INVESTING IN PUBLIC R&D FOR A COMPETITIVE AND SUSTAINABLE US AGRICULTURE

Commissioned by The Breakthrough Institute

Authors: Uris Baldos (Purdue University), Dan Blaustein-Rejto (Breakthrough Institute)

SUMMARY

- Public agricultural R&D is a major source of agricultural productivity growth.
- We model the effects of future investments in US public agricultural R&D on global and domestic crop production, land use, input use, and greenhouse gas emissions.
- We find that increasing US public agricultural R&D spending would increase US cropland area and greenhouse gas emissions, but reduce global land use and emissions by a greater amount.
- Sharing technological developments from R&D internationally amplifies the global benefits of increased US public agricultural R&D spending.

INTRODUCTION

Sustained productivity growth of the US agricultural sector is crucial to ensure global competitiveness and improve the efficiency of land and other farm input use. Productivity growth, associated with the adoption of new technologies such as crop varieties, has driven more than a two-fold increase in US production since the 1950s, while US agricultural land use has fallen (Bigelow & Borchers, 2017; USDA ERS, 2015).

It is well-established that publicly funded agricultural research and development (R&D), primarily conducted in universities and government institutions, is a major source of new agricultural technologies and knowledge and is economically beneficial (Alston et al., 2011; Andersen & Song, 2013; Jin & Huffman, 2016). It also complements other agricultural extension, private R&D, and other productivity-enhancing activities (Heisey, Wang & Fuglie 2011). Yet funding for US public agricultural R&D has stagnated in recent decades, a sharp contrast with funding growth in other world regions, particularly China, where total public agricultural R&D has surpassed that of the US since 2008 (Clancy et al. 2016). This trend could erode US competitiveness in world agricultural markets, prompting economists to call for at least doubling US public agricultural R&D (Alston 2018).

It is less firmly established what effect increasing US public R&D spending and productivity growth would have on global environmental impacts from agriculture, particularly greenhouse gas (GHG) emissions. Several studies have estimat-

ed that global yield increases and R&D have historically reduced cropland area and GHG emissions (Burney, Davis & Lobell 2011; Stevenson et al. 2013). Other studies at the global level have projected that increasing average global yields in the future would reduce the amount of land and other farm input use as well as their associated GHG emissions (Valin et al. 2013; Jones & Sands 2013; Lobell et al. (2013) consider). For the US specifically, Villoria (2019) estimated that raising productivity, and thus global competitiveness, has historically increased domestic cropland area — a 'rebound effect' — but reduced global land use. However, this and other studies did not specifically estimate the effects of US public agricultural R&D spending on global GHGs.

This study contributes to the literature by assessing domestic and global GHG, cropland, and crop production impacts from increased crop productivity growth due to increased US public R&D investments. To the best of our knowledge, this is the first such study conducted. This study also builds upon previous work by using the latest data and parameter estimates on the historical gains from US R&D spending (Baldos et al., 2018) and technological spillovers to the rest of the world (Fuglie, 2017) to calculate the implied growth in agricultural productivity from R&D spending increases. In contrast to several similar studies, our analysis is limited to crop production; however we plan to extend the analysis to include livestock.

Our results indicate that US productivity growth alone cannot reduce cropland, input use, and associated emissions in the US, which would all rise as domestic production increases with greater international competitiveness. At the same time, global environmental impacts would fall thanks to US agriculture improving its GHG intensity and taking up a greater share of global production. Ensuring that technological advances from US R&D "spill over" to the rest of the world, as they historically have, amplifies the global benefit. We also find that strictly constraining US cropland and farm input use — though decreasing global cropland, and GHG emissions — would decrease production and substantially increase crop prices.

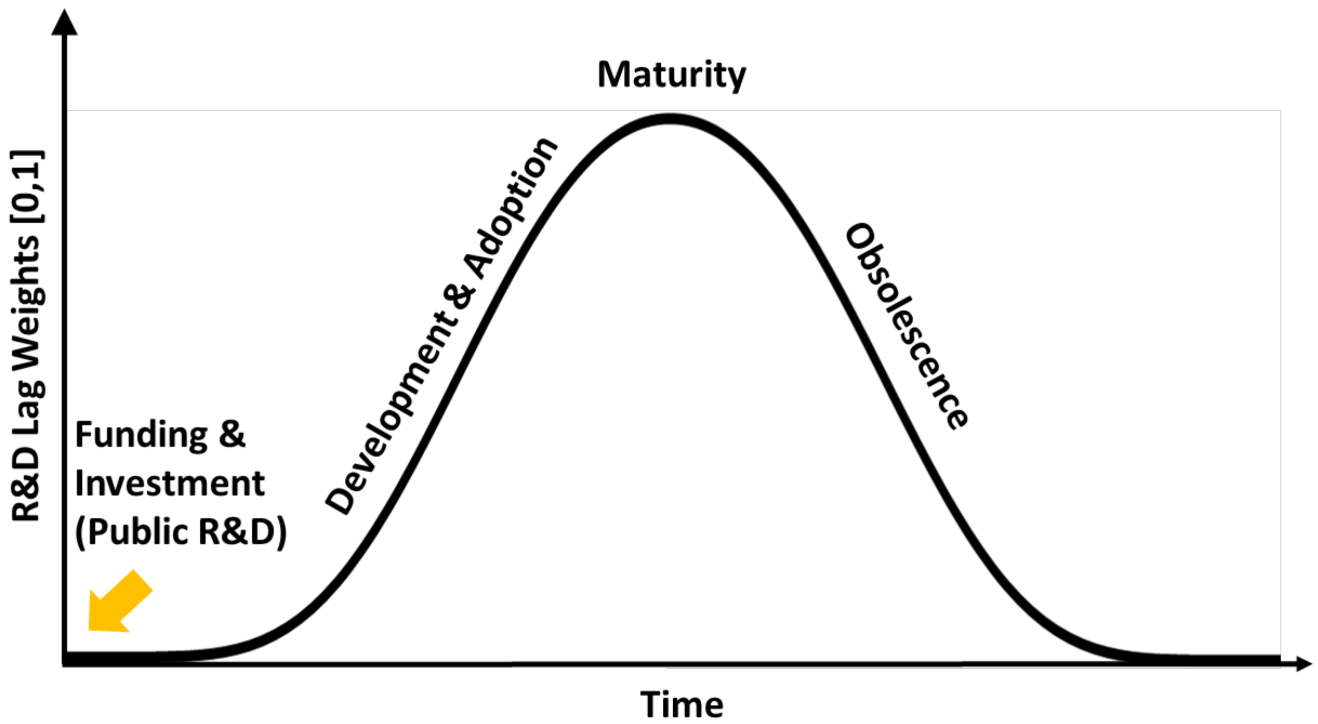
METHODS

Modelling R&D investments and knowledge stock accumulation

The empirical literature on the linkages between the flow of R&D spending, the stock of accumulated knowledge capital and subsequent productivity growth is well established (Alston et al., 2011; Griliches, 1979; P. Heisey et al., 2011; Huffman, 2009). The framework involves two main stages. In the first stage, knowledge capital stocks are constructed from the stream of R&D spending using R&D lag

weights (Figure 1). Knowledge capital consists of the technological and human capital needed to develop and propagate high-yielding crop varieties as well as modern farm management techniques and machineries. More importantly, how R&D spending today contributes to the R&D knowledge stock in the future is summarized by the R&D lag weights. Initially, the R&D spending contributes little to knowledge capital accumulation, but its effect builds over time as technology arising from that research becomes mature and is eventually disseminated to farmers. Eventually, the effects peak when technology is fully disseminated, but then wane due to technology obsolescence. In the second stage, after converting the R&D spending flows to knowledge capital stocks, the growth in stocks are then linked to growth in agricultural total factor productivity (TFP) growth via elasticities which describe the percent rise in TFP given a 1 percent rise in knowledge capital stock.

Figure 1. R&D Lag Weights



Our analysis borrows heavily from the data and parameter estimates from Baldos et al (2018) which examines the historical gains in US R&D spending using Bayesian econometrics. The authors compiled annual public agricultural R&D expenditures (in billion 2005 USD) from spending data by USDA intramural research agencies in particular the Agricultural Research Service (ARS) and the Economic Research Service (ERS), State Agricultural Experiment Stations (SAES), and Schools

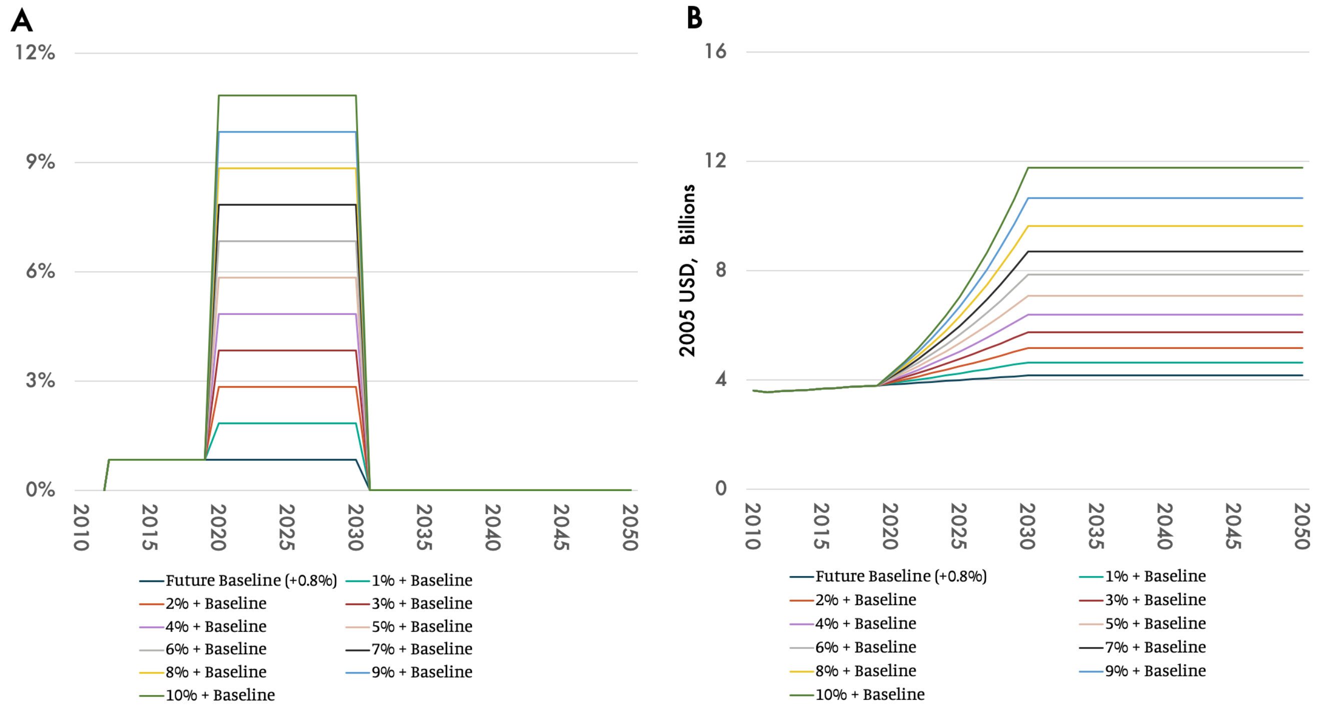
of Veterinary Medicine. Following the authors, we adapt the gamma structure with a 50-year lag span when calibrating the R&D lag weights. Furthermore, the R&D lag weight structure is parametrized by $\delta = 0.74$ and $\lambda = 0.86$ which Baldos et al (2018) estimated. Note that the sum of the weights (i.e. $\beta_{RD,0} \cdots \beta_{RD,49}$) is equal to 1 due to normalization.

$$\beta_{RD,i} = (i+1)^{\delta/1-\delta} (\lambda)^{i} \Big/ \sum_{i=0}^{L} (i+1)^{\delta/1-\delta} \lambda^{i} \; ; \; \sum_{i=0}^{49} \beta_{RD,i} = 1$$

We use an R&D stock TFP elasticity of 0.34, as estimated in Baldos et al (2018). In other words, we assume that there is a 0.34 percent rise in TFP given a 1 percent rise in knowledge capital stock.

We explore the productivity implications from increased US R&D spending increases from 2020 to 2030. Specifically, we develop 10 growth rate scenarios with annual R&D spending growth ranging from 1% to 10% (Figure 2). Note that these increases are added to the assumed Future Baseline growth in US R&D spending which is around 0.8% per year from 2011 to 2030.

Figure 2. Future Annual R&D Spending Growth Rate (A) and Absolute Annual Values (B)



To explore the technological spillovers to the rest of the world from increased US R&D spending, we use the methods and parameters from Fuglie (2017). The author reviewed the literature on the estimated R&D stock TFP elasticities as well as R&D spillover elasticities for key world regions. The author also calculated the international R&D stocks — which generate R&D spillovers — from the knowledge capital stocks in the developed world specifically in Western Europe, North America, Oceania + S Africa and Developed Asia. Since the full data used by Fuglie (2017) is not publicly available, side calculations are necessary to calculate the international R&D stocks from the available US data. Shares of R&D stocks for US and other key regions from Fuglie (2017) are combined with the computed US R&D knowledge capital stocks in this study in order to derive the total international R&D stocks. We assume that the contribution of R&D stocks from non-US regions are fixed (i.e. international R&D stocks are mainly driven by R&D stocks from the US). Regions which historically benefited from R&D spillovers include Western Europe, Oceania + S Africa, Developed Asia and Latin America. Actual agricultural TFP data for these regions for the year 2011 are taken from USDA-ERS (2019) and are projected to 2050 using the year-on-year change in international R&D stocks and R&D spillover TFP elasticities from Fuglie (2017) (Table 1).

Table 1. Average Agricultural R&D Elasticities for Key Regions from Fuglie (2017)

Region	TFP R&D Elasticity from International R&D stocks
Developed	0.210
Western Europe	0.240
Australia-NZ-S Africa	0.120
Japan-Korea-Taiwan	0.210*
Developing	0.070
Latin America	0.360

Projecting global agriculture using the simple model

To quantify economic and environmental benefits from increased US R&D spending, we employ the SIMPLE model (a Simplified International Model of agricultural Prices, Land use and the Environment) — a global economic model of agriculture (Appendix 3). We estimate future changes in TFP growth, food demand, crop production, crop prices, and other key variables under a business-as-usual scenario, referred to as the 'Future Baseline.' We also simulate scenarios which incorporate R&D driven productivity growth from increased US R&D spending, with and without international R&D spillovers. These are implemented as additions to the baseline increase in crop TFP. In addition, we model scenarios with "input constraints", in which cropland use is fixed to current areas and non-cropland input use is taxed by 20%. These constraints reflect efforts to curb GHG emissions from input use in the crop sector. We simulate constraints in the US only ("Constraints-US") and in the US as well as the regions which indirectly benefit from increased R&D spending in the US via R&D spillovers ("Constraints - Spillovers").

RESULTS

We primarily report results in terms of percentage change between 2011 and 2050 for the scenario in which R&D spending grows by an additional 7% over 2020-2030 — referred to as 7% annual R&D growth or the 7% scenario. In this scenario, R&D spending roughly doubles between 2020 and 2030. We present results for scenarios accounting for international R&D spillovers from US agricultural R&D investments except where noted, since spillovers have been observed in the past. See Appendix 1 for results in terms of absolute change, results for other scenarios, and results without spillovers.

Projections of R&D driven US TFP growth

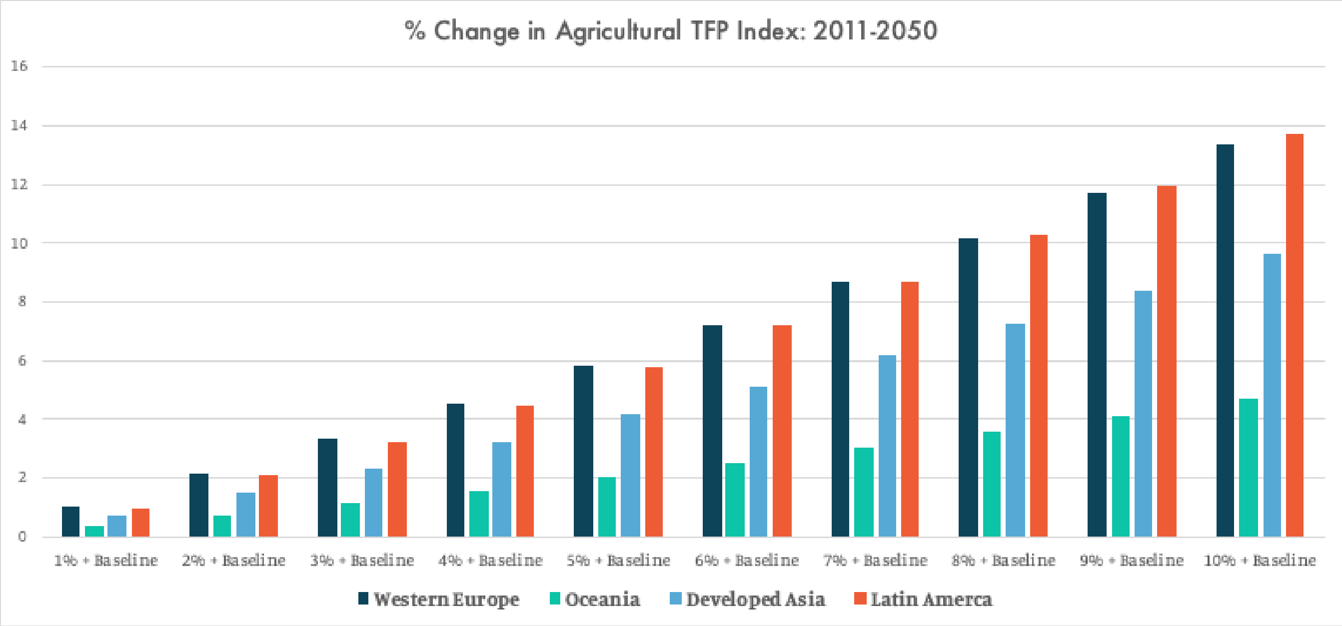
Gains in crop TFP growth increase at higher R&D growth rate scenarios, though with declining marginal gains (Table 2). For example, under 1% annual R&D growth, For every 1% rise in total R&D spending, there is a 0.27% increase in TFP. But under the 7% scenario, for each 1% rise in spending, there is a 0.23% increase in TFP on average.

Table 2. US R&D Spending and Crop TFP Changes for Each R&D Investment Scenario Relative to Future Baseline

Annual US R&D expenditure growth rate: 2020-2030	US R&D spending: 2020-2050			Additional US Crop TFP Growth over Future Baseline (in %, 2011-2050):
	Total Cost	Annual Average Cost	Relative to Future Baseline R&D Spending	
	in Billion 2005 USD		in %	
1% per yr	12.3	0.4	9.7	2.6
2% per yr	25.7	0.9	20.2	5.4
3% per yr	40.5	1.3	31.8	8.2
4% per yr	56.6	1.9	44.5	11.2
5% per yr	74.2	2.5	58.4	14.3
6% per yr	93.5	3.1	73.5	17.5
7% per yr	114.5	3.8	90.1	20.8
8% per yr	137.5	4.6	108.2	24.3
9% per yr	162.5	5.4	127.9	27.9
10% per yr	189.9	6.3	149.4	31.6

Increased US R&D investments also result in productivity growth outside the US via technological spillovers (Figure 3). Across each region, Western Europe and Latin America tend to gain more from the technological spillovers from increased US R&D spending. For example, under 7% annual R&D growth, productivity in Western Europe and Latin America is projected to rise around 10%. Note that the gains in productivity growth from technological spillovers across regions reflect the relative values of the R&D spillover elasticities in Table 1; hence, Oceania and South Africa benefit the least in terms of the R&D spillovers from increased US R&D spending.

Figure 3. Crop TFP Growth in the Rest of the World Due to Technological Spillovers from US R&D Investments (Relative to Future Baseline Growth)



Global implications of R&D driven US TFP growth in future projections

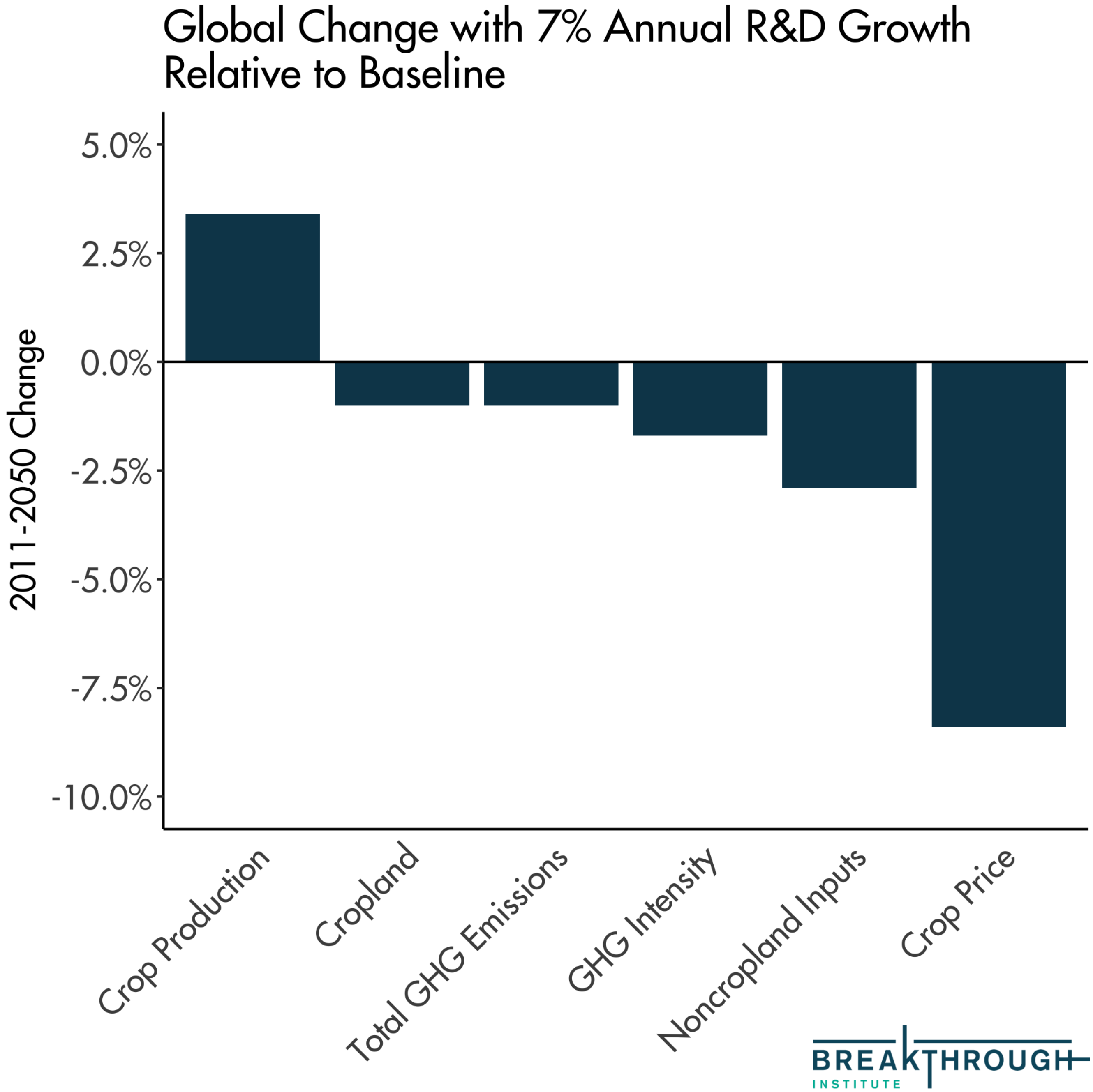
Under the increased R&D spending scenarios, global crop production rises sharply while greenhouse gas emissions, cropland area, and crop prices fall relative to the Future Baseline scenario. These effects are magnified at higher levels of R&D spending scenarios.

Since the US is a major world exporter of agricultural crops, greater productivity growth of the US crop sector due to R&D investments results in greater US exports which in turn reduces global crop price, cropland and noncropland input use, and increases global crop production relative to the Future Baseline scenario (Figure 4). Under the Future Baseline, global crop price is expected to decline by 16% while global crop production is expected to increase by 74%. Under the 7% scenario, we project global crop prices fall 24.3% and production rises 77.5%. The additional rise in global crop production is relatively smaller than the additional reduction in global crop prices, suggesting that global demand for crops does not respond much to changes in crop price (i.e. it is price inelastic).

R&D-driven productivity growth also reduces global use of cropland and noncropland inputs (Figure 5). Future Baseline cropland growth is 12%, or 184.6 million hectares (Mha), and noncropland input growth is 30%, or $590.6 billion. The rise in global cropland and input use is much less at higher R&D spending lev-

els: 10.9% (168.2 Mha), and 26.8% ($531.6 billion), respectively, under the 7% scenario.

Figure 4



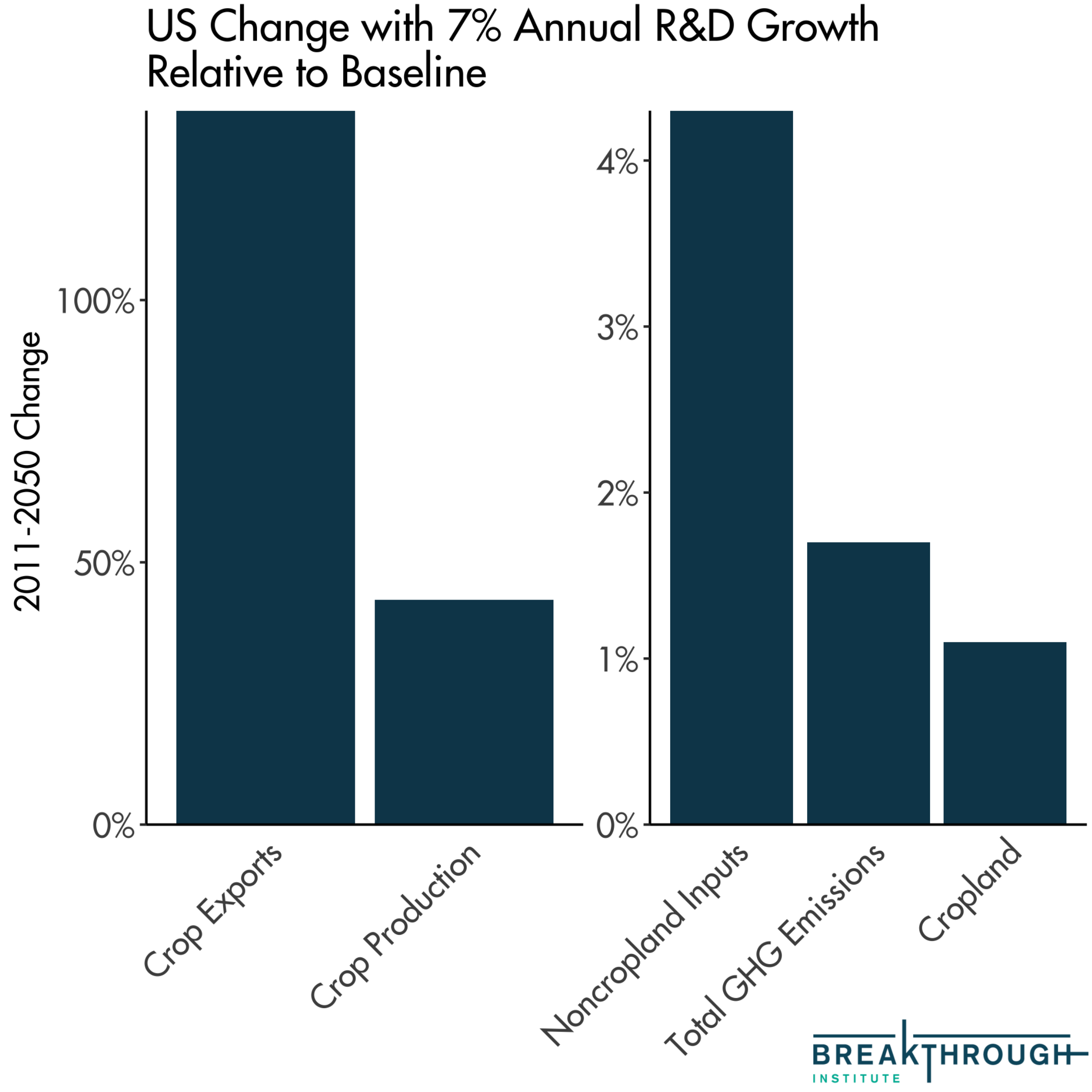
R&D-driven productivity growth also reduces GHG emissions associated with land use change, fertilizer, and energy (Figure 4 & Appendix 1). Under the Future Baseline, global 2050 GHG emissions are expected to rise 1,126 MMT CO2 eq/yr. Note that these estimates are smaller than estimates from other studies which consider

emissions from crops as well as livestock (see Appendix 2). Under the 7% annual R&D growth, total GHG emissions in 2050 rise 109 MMT less, with land use change emissions declining the most relative to the Future Baseline. Global GHG intensity also declines by 38%, more than the Future Baseline projected decline of 37%.

US implications of R&D driven US TFP growth in future projections

The productivity gains from greater US R&D make US farmers more competitive in world markets, driving expansion of US crop production and exports and the global results described above (Figure 5). Under the Future Baseline scenario, US crop producer price declines 25.6% between 2011-2050, while crop production and crop exports increase by 50% and 116.8%, respectively. Under 7% annual R&D growth, US producer prices fall more — by 38.1% — driving dramatic increases in US crop production and exports of 92.8% and 252.9%, respectively.

Figure 5



Given access to global markets, improvements in US crop productivity not only result in increases in domestic crop output but also expansion in land (i.e. extensification), noncropland input use (i.e. intensification), and associated GHG emissions (Figures 5). These increases do not offset or negate the global reductions in cropland, input use or emissions, and are factored into the global results above. US noncropland input use is projected to grow faster than cropland expansion which suggest greater intensity of crop production (i.e. more noncropland inputs per unit of cropland). Under the Future Baseline, US cropland, noncropland input use, and related GHG emissions expand by 1.9% (2.9 Mha), 6.9% ($108 billion), and 2.8% (40 MMT CO2e/yr), respectively. Under 7% annual R&D growth, they expand 3% (4.7 Mha), 11.2% ($176 billion), and 4.5% (64.8 MMT CO2e/yr), respectively. Emissions related to cropland expansion account for the majority of emissions growth across scenarios, illustrating the large role that limiting extensification can play in climate mitigation.

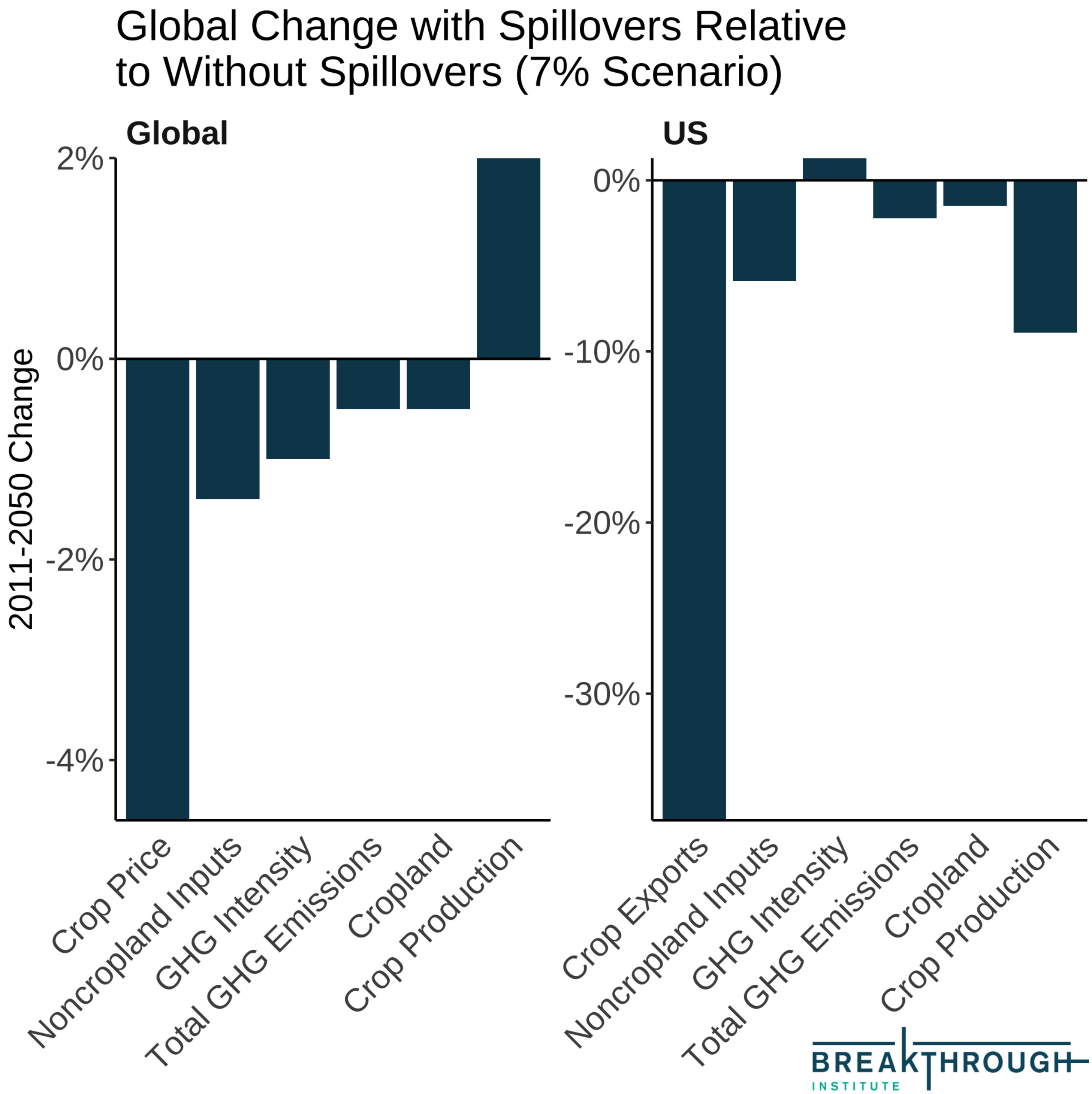
Although US crop GHG emissions increase with greater R&D investment rates, GHG intensity declines (Figure 5). Under 7% annual R&D growth, US crop GHG intensity falls 46%, more than the 31% decline projected under the Future Baseline scenario.

It is important to highlight the observed reduction in global cropland and noncropland use since within the US both cropland and noncropland use expands at greater levels of R&D investment. This suggests that farm input use in the rest of the world is declining faster than it is rising in the US given productivity growth from R&D investments.

R&D international spillovers

The global effects of increased US R&D spending are magnified when R&D spillovers to key regions are accounted for. Without R&D spillovers, global crop price declines less and global crop production increases less (Figure 6). Likewise, global cropland and total greenhouse gas emissions increase more, by 177.6 Mha and 1,076 MMT CO2 eq /yr., respectively, under the 7% scenario.

Figure 6

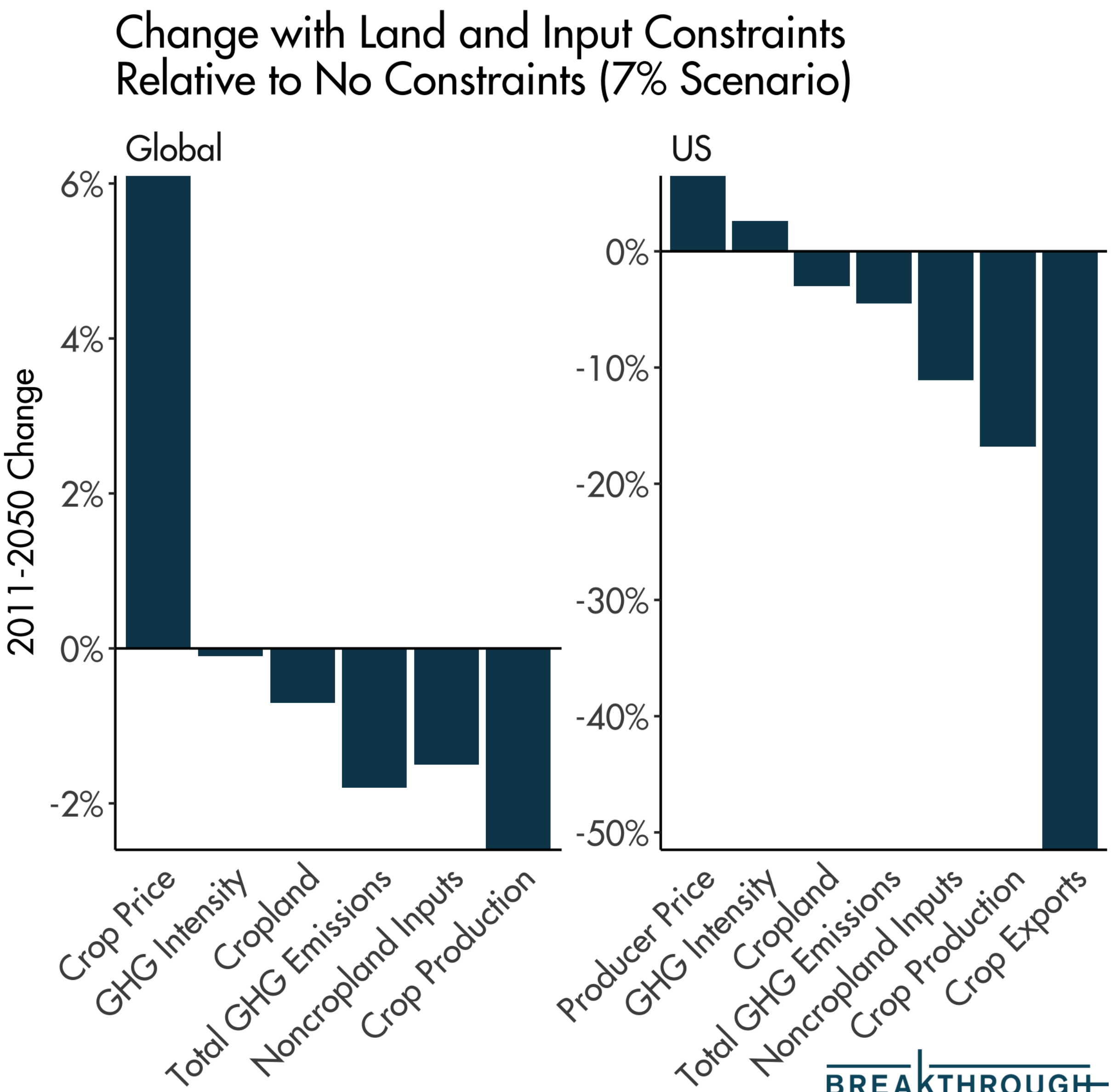


R&D spillovers further increase farm productivity growth in other regions, indirectly reducing the competitiveness of US crop exports in the world market. Without R&D spillovers, we project greater US crop production, greater US exports, and less reduction in US crop producer prices than with spillovers included. We also project greater US cropland expansion, noncropland input use, and associated GHG emissions.

Input constraints

We also project global and US results under "input constraints", holding cropland area constant at 2011 levels and levying a tax of 20% on farm inputs in the US and in regions which benefit from US R&D spillovers. Compared to the Future Baseline, imposing input constraints without substantially increasing US R&D results in less global cropland, input use and GHG emissions, but at the cost of higher global crop prices and less crop production. For example, with input constraints and minimal R&D investment of 1% annual growth, we project global crop prices would fall 12.5% vs. 15.9% under the Future Baseline and 24.3% under 7% annual R&D growth (Appendix 1).

Figure 7



When R&D spending grows at higher rates, imposing input constraints reduces the global food production benefits and increases the GHG benefits compared to a scenario with R&D growth and no constraints (Figure 7). For example, the global crop price reduction is 24.3% under the 7% scenario with spillovers and no constraints while the reduction is only 18.2% under the 7% scenario with constraints. Global crop production rises less, prices fall less, and global GHGs and cropland rise less with input constraints.

In the US, input constraints have similar effects as they do globally. Compared to scenarios with similar or greater R&D growth, all scenarios with input constraints result in substantially lower cropland expansion, input use, and GHG emissions, but with the tradeoff of less internationally competitive US production and lower crop production and exports (Appendix 1).

CONCLUSIONS

These results suggest that increasing US R&D investments between 2020-2030 increases US crop productivity and international competitiveness, thereby expanding US exports. This reduces global crop prices, cropland, input use and associated GHG emissions. We project that doubling US R&D spending — equivalent to a 7% annual increase over 2020-2030 — would approximately cut in half global crop prices in 2050 and reduce cropland use and crop-related greenhouse gas emissions 16.4 Mha and 109 MMT CO2 eq/yr, respectively, compared to business-as-usual.

The global benefits of increased US R&D come at the cost of increased cropland, input use, and GHG emissions within the US, exemplifying how productivity growth can result in a local rebound effect, but global land sparing and GHG mitigation. Policies that restrict cropland and input use can reduce US and global emissions, but reduce the competitiveness of US crop exports. Other regions take advantage of these restrictions by producing more crops and selling it to the world market. This increases global food prices and reduces global food production, especially when there are only small increases in US R&D spending. In a world with rising food demand and increasing external pressures on crop production such as those caused by climate change, the negative impacts on food production of input constraints must carefully be considered.

Whether or not policies are enacted to constrain cropland and input use, our results suggest that significant reduction in global GHG emissions can only be achieved with growth in US R&D spending and widespread technological spillovers from R&D to other countries.

Appendix 1: Detailed Results

Appendix Table 1. Changes in key US crop production and GHG emissions variables from 2011 to 2050 under different US R&D investment scenarios and farm input constraints (in % changes)

Regional Variables	Units	Future Baseline	US R&D 2020-30																			
			US only										w/ RD Spillovers									
			1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
US Crop Price	%	-25.6	-28.5	-29.7	-30.9	-32.1	-33.3	-34.4	-35.6	-36.7	-37.8	-38.9	-29.5	-31.0	-32.4	-33.9	-35.3	-36.7	-38.1	-39.5	-40.9	-42.2
US Crop Production	%	50.0	62.0	67.8	73.8	80.2	87.0	94.2	101.7	109.6	118.0	126.8	59.5	64.5	69.7	75.1	80.8	86.7	92.8	99.2	105.9	112.8
US Cropland	%	1.9	2.5	2.8	3.1	3.4	3.8	4.1	4.5	4.8	5.2	5.6	2.0	2.1	2.3	2.5	2.6	2.8	3.0	3.2	3.3	3.5
US Noncropland inputs	%	6.9	9.3	10.4	11.6	12.9	14.2	15.6	17.1	18.6	20.1	21.7	7.3	7.9	8.6	9.2	9.9	10.5	11.2	11.9	12.6	13.2
US GHG Emissions																						
Energy Use	%	6.9	9.3	10.4	11.6	12.9	14.2	15.6	17.1	18.6	20.1	21.7	7.3	7.9	8.6	9.2	9.9	10.5	11.2	11.9	12.6	13.2
Fertilizer Use	%	6.9	9.3	10.4	11.6	12.9	14.2	15.6	17.1	18.6	20.1	21.7	7.3	7.9	8.6	9.2	9.9	10.5	11.2	11.9	12.6	13.2
Cropland Use	%	1.9	2.5	2.8	3.1	3.4	3.8	4.1	4.5	4.8	5.2	5.6	2.0	2.1	2.3	2.5	2.6	2.8	3.0	3.2	3.3	3.5
Total	%	2.8	3.7	4.2	4.6	5.1	5.6	6.2	6.7	7.3	7.9	8.5	2.9	3.2	3.4	3.7	3.9	4.2	4.5	4.7	5.0	5.2
US GHG Intensity | Total	%	-31.5	-36.0	-37.9	-39.8	-41.7	-43.5	-45.3	-47.1	-48.8	-50.5	-52.2	-35.5	-37.3	-39.0	-40.8	-42.5	-44.2	-45.8	-47.4	-49.0	-50.5
US Crop Exports	%	116.8	155.5	174.4	194.7	216.3	239.4	264.1	290.3	318.0	347.5	378.6	145.4	161.1	177.7	195.1	213.5	232.7	252.9	274.0	296.1	319.0

Regional Variables	Units	Future Baseline	US R&D 2020-30 + Input Constraints																			
			US only										w/ RD Spillovers									
			1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
US Crop Price	%	-25.6	-23.6	-25.0	-26.3	-27.7	-28.9	-30.2	-31.4	-32.6	-33.8	-35.0	-22.0	-23.7	-25.3	-26.9	-28.5	-30.1	-31.6	-33.2	-34.7	-36.2
US Crop Production	%	50.0	43.1	47.9	53.0	58.4	64.1	70.1	76.5	83.2	90.3	97.7	46.1	50.5	55.2	60.0	65.1	70.4	76.0	81.7	87.7	93.9
US Cropland	%	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
US Noncropland inputs	%	6.9	-5.6	-4.7	-3.8	-2.8	-1.7	-0.6	0.5	1.7	3.0	4.3	-3.2	-2.7	-2.1	-1.6	-1.0	-0.4	0.1	0.7	1.3	1.9
US GHG Emissions																						
Energy Use	%	6.9	-5.6	-4.7	-3.8	-2.8	-1.7	-0.6	0.5	1.7	3.0	4.3	-3.2	-2.7	-2.1	-1.6	-1.0	-0.4	0.1	0.7	1.3	1.9
Fertilizer Use	%	6.9	-5.6	-4.7	-3.8	-2.8	-1.7	-0.6	0.5	1.7	3.0	4.3	-3.2	-2.7	-2.1	-1.6	-1.0	-0.4	0.1	0.7	1.3	1.9
Cropland Use	%	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	%	2.8	-1.0	-0.8	-0.7	-0.5	-0.3	-0.1	0.1	0.3	0.5	0.8	-0.6	-0.5	-0.4	-0.3	-0.2	-0.1	0.0	0.1	0.2	0.3
US GHG Intensity | Total	%	-31.5	-30.8	-33.0	-35.1	-37.2	-39.3	-41.3	-43.3	-45.2	-47.2	-49.0	-31.9	-33.9	-35.8	-37.7	-39.5	-41.4	-43.2	-44.9	-46.6	-48.3
US Crop Exports	%	116.8	94.9	110.0	126.2	143.7	162.3	182.3	203.7	226.4	250.7	276.3	106.5	120.3	134.8	150.2	166.4	183.5	201.4	220.2	239.8	260.3

Appendix Table 2. Changes in key US crop production and GHG emissions variables from 2011 to 2050 under different US R&D investment scenarios and farm input constraints (in absolute changes)

Regional Variables	Units	Future Baseline	US R&D 2020-30																			
			US only										w/ RD Spillovers									
			1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
US Crop Price	USD / MT	-58	-64	-67	-70	-73	-75	-78	-80	-83	-85	-88	-67	-70	-73	-77	-80	-83	-86	-89	-92	-95
US Crop Production	M MT	423.8	525.4	574.0	625.3	679.6	737.0	797.6	861.5	928.7	999.4	1073.7	504.0	546.0	590.0	635.9	684.0	734.1	786.3	840.5	897.0	955.4
US Cropland	k Ha	2939.5	3937.5	4408.4	4900.5	5412.7	5945.2	6496.6	7065.0	7648.6	8246.9	8856.2	3130.6	3387.7	3649.8	3915.8	4185.8	4456.4	4729.6	5000.7	5271.2	5538.1
US Noncropland inputs	B USD	10779.5	14557.9	16361.8	18261.9	20255.2	22345.2	24527.7	26797.9	29149.8	31583.8	34085.9	11498.2	12468.8	13462.2	14475.1	15507.5	16546.5	17600.4	18650.3	19702.9	20745.9
US GHG Emissions																						
Energy Use	M MT CO2 eq.	9.7	13.0	14.7	16.4	18.1	20.0	22.0	24.0	26.1	28.3	30.5	10.3	11.2	12.1	13.0	13.9	14.8	15.8	16.7	17.6	18.6
Fertilizer Use	M MT CO2 eq.	8.2	11.1	12.5	13.9	15.4	17.0	18.7	20.4	22.2	24.1	26.0	8.8	9.5	10.3	11.0	11.8	12.6	13.4	14.2	15.0	15.8
Cropland Use	M MT CO2 eq.	22.1	29.6	33.2	36.9	40.7	44.7	48.9	53.1	57.5	62.0	66.6	23.6	25.5	27.5	29.5	31.5	33.5	35.6	37.6	39.7	41.7
Total	M MT CO2 eq.	40.0	53.8	60.3	67.1	74.3	81.8	89.5	97.6	105.9	114.4	123.1	42.6	46.2	49.8	53.5	57.2	61.0	64.8	68.5	72.3	76.1
US GHG Intensity | Total	M MT CO2 eq. / M MT	-0.541	-0.617	-0.650	-0.683	-0.715	-0.746	-0.777	-0.808	-0.837	-0.866	-0.895	-0.608	-0.639	-0.670	-0.700	-0.729	-0.758	-0.786	-0.814	-0.841	-0.867
US Crop Exports	M MT	237.4	316.1	354.6	395.8	439.7	486.7	536.8	590.0	646.5	706.4	769.6	295.5	327.5	361.2	396.6	433.9	473.1	514.2	557.0	601.8	648.4
Regional Variables	Units	Future Baseline	US R&D 2020-30 + Input Constraints																			
			US only										w/ RD Spillovers									
			1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
US Crop Price	USD / MT	-58	-53	-56	-60	-62	-65	-68	-71	-74	-76	-79	-50	-54	-57	-61	-64	-68	-72	-75	-78	-82
US Crop Production	M MT	423.8	364.7	405.6	448.9	494.6	543.0	594.1	648.0	704.8	764.7	827.5	390.1	427.8	467.2	508.4	551.5	596.4	643.3	692.1	742.9	795.5
US Cropland	k Ha	2939.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
US Noncropland inputs	B USD	10779.5	-8809.4	-7420.5	-5945.9	-4386.1	-2736.9	-1000.0	822.7	2727.4	4716.1	6778.8	-4985.7	-4173.2	-3335.4	-2474.9	-1591.4	-695.6	219.3	1137.0	2063.2	2986.8
US GHG Emissions																						
Energy Use	M MT CO2 eq.	9.7	-7.9	-6.6	-5.3	-3.9	-2.5	-0.9	0.7	2.4	4.2	6.1	-4.5	-3.7	-3.0	-2.2	-1.4	-0.6	0.2	1.0	1.8	2.7
Fertilizer Use	M MT CO2 eq.	8.2	-6.7	-5.7	-4.5	-3.3	-2.1	-0.8	0.6	2.1	3.6	5.2	-3.8	-3.2	-2.5	-1.9	-1.2	-0.5	0.2	0.9	1.6	2.3
Cropland Use	M MT CO2 eq.	22.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total	M MT CO2 eq.	40.0	-14.6	-12.3	-9.9	-7.3	-4.5	-1.7	1.4	4.5	7.8	11.2	-8.3	-6.9	-5.5	-4.1	-2.6	-1.2	0.4	1.9	3.4	5.0
US GHG Intensity | Total	M MT CO2 eq. / M MT	-0.541	-0.528	-0.565	-0.602	-0.638	-0.673	-0.708	-0.743	-0.776	-0.809	-0.841	-0.548	-0.581	-0.614	-0.646	-0.678	-0.710	-0.740	-0.770	-0.799	-0.828
US Crop Exports	M MT	237.4	192.9	223.6	256.6	292.0	330.0	370.7	414.1	460.3	509.5	561.7	216.6	244.5	274.1	305.3	338.3	372.9	409.4	447.5	487.5	529.1

Appendix Table 3. Changes in key global crop production and GHG emissions variables from 2011 to 2050 under different US R&D investment scenarios and farm input constraints (in % changes)

Global Variables	Units	Future Baseline	US R&D 2020-30																			
			US only										w/ RD Spillovers									
			1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Global Crop Price	%	-15.9	-16.8	-17.2	-17.6	-18.1	-18.6	-19.2	-19.7	-20.3	-20.9	-21.6	-18.6	-19.5	-20.4	-21.3	-22.3	-23.3	-24.3	-25.4	-26.5	-27.6
Global Crop Production		74.1	74.4	74.6	74.7	74.9	75.1	75.3	75.5	75.7	75.9	76.1	75.2	75.5	75.9	76.2	76.6	77.1	77.5	78.0	78.5	79.0
Global Cropland		11.9	11.8	11.8	11.7	11.6	11.6	11.5	11.4	11.3	11.2	11.1	11.6	11.5	11.4	11.3	11.1	11.0	10.9	10.7	10.6	10.4
Global Noncropland inputs		29.7	29.4	29.2	29.1	28.9	28.7	28.5	28.2	28.0	27.8	27.5	28.8	28.5	28.2	27.9	27.5	27.2	26.8	26.4	25.9	25.5
Global GHG Emissions																						
Energy Use		19.8	19.7	19.6	19.5	19.4	19.3	19.1	19.0	18.9	18.7	18.6	19.2	18.9	18.7	18.5	18.2	17.9	17.7	17.4	17.0	16.7
Fertilizer Use		16.1	15.9	15.8	15.7	15.6	15.5	15.4	15.3	15.2	15.0	14.9	15.6	15.4	15.2	15.0	14.8	14.5	14.3	14.0	13.7	13.4
Cropland Use		8.7	8.6	8.6	8.5	8.5	8.4	8.3	8.3	8.2	8.1	8.1	8.4	8.3	8.3	8.2	8.1	8.0	7.9	7.8	7.7	7.6
Total		10.5	10.4	10.3	10.2	10.2	10.1	10.0	10.0	9.9	9.8	9.7	10.1	10.0	9.9	9.8	9.7	9.6	9.5	9.3	9.2	9.0
Global GHG Intensity | Total		-36.6	-36.7	-36.8	-36.9	-37.0	-37.1	-37.2	-37.3	-37.4	-37.6	-37.7	-37.1	-37.3	-37.5	-37.7	-37.9	-38.1	-38.3	-38.6	-38.8	-39.1

Global Variables	Units	Future Baseline	US R&D 2020-30 + Input Constraints																			
			US only										w/ RD Spillovers									
			1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Global Crop Price	%	-15.9	-15.3	-15.7	-16.1	-16.5	-16.9	-17.4	-17.8	-18.3	-18.9	-19.4	-12.5	-13.4	-14.3	-15.2	-16.2	-17.2	-18.2	-19.3	-20.4	-21.6
Global Crop Production		74.1	74.0	74.1	74.2	74.4	74.5	74.7	74.8	75.0	75.2	75.4	72.9	73.2	73.5	73.8	74.2	74.6	74.9	75.4	75.8	76.3
Global Cropland		11.9	11.9	11.8	11.7	11.6	11.5	11.4	11.3	11.2	11.1	11.0	10.9	10.8	10.7	10.6	10.5	10.4	10.2	10.1	10.0	9.8
Global Noncropland inputs		29.7	29.1	28.9	28.8	28.6	28.4	28.3	28.1	27.9	27.6	27.4	27.2	26.9	26.6	26.3	26.0	25.7	25.3	24.9	24.5	24.1
Global GHG Emissions																						
Energy Use		19.8	18.5	18.4	18.3	18.2	18.1	18.0	17.9	17.8	17.6	17.5	16.4	16.1	15.9	15.7	15.4	15.2	14.9	14.6	14.3	14.0
Fertilizer Use		16.1	14.8	14.7	14.6	14.5	14.4	14.3	14.2	14.1	14.0	13.9	12.5	12.4	12.2	12.0	11.8	11.5	11.3	11.1	10.8	10.5
Cropland Use		8.7	8.5	8.5	8.4	8.3	8.2	8.1	8.0	7.9	7.8	7.7	6.9	6.8	6.8	6.7	6.6	6.5	6.4	6.4	6.3	6.2
Total		10.5	10.1	10.0	9.9	9.9	9.8	9.7	9.6	9.5	9.4	9.2	8.3	8.3	8.2	8.1	8.0	7.8	7.7	7.6	7.5	7.3
Global GHG Intensity | Total		-36.6	-36.7	-36.8	-36.9	-37.0	-37.1	-37.2	-37.3	-37.4	-37.6	-37.7	-37.3	-37.5	-37.7	-37.8	-38.0	-38.2	-38.4	-38.6	-38.9	-39.1

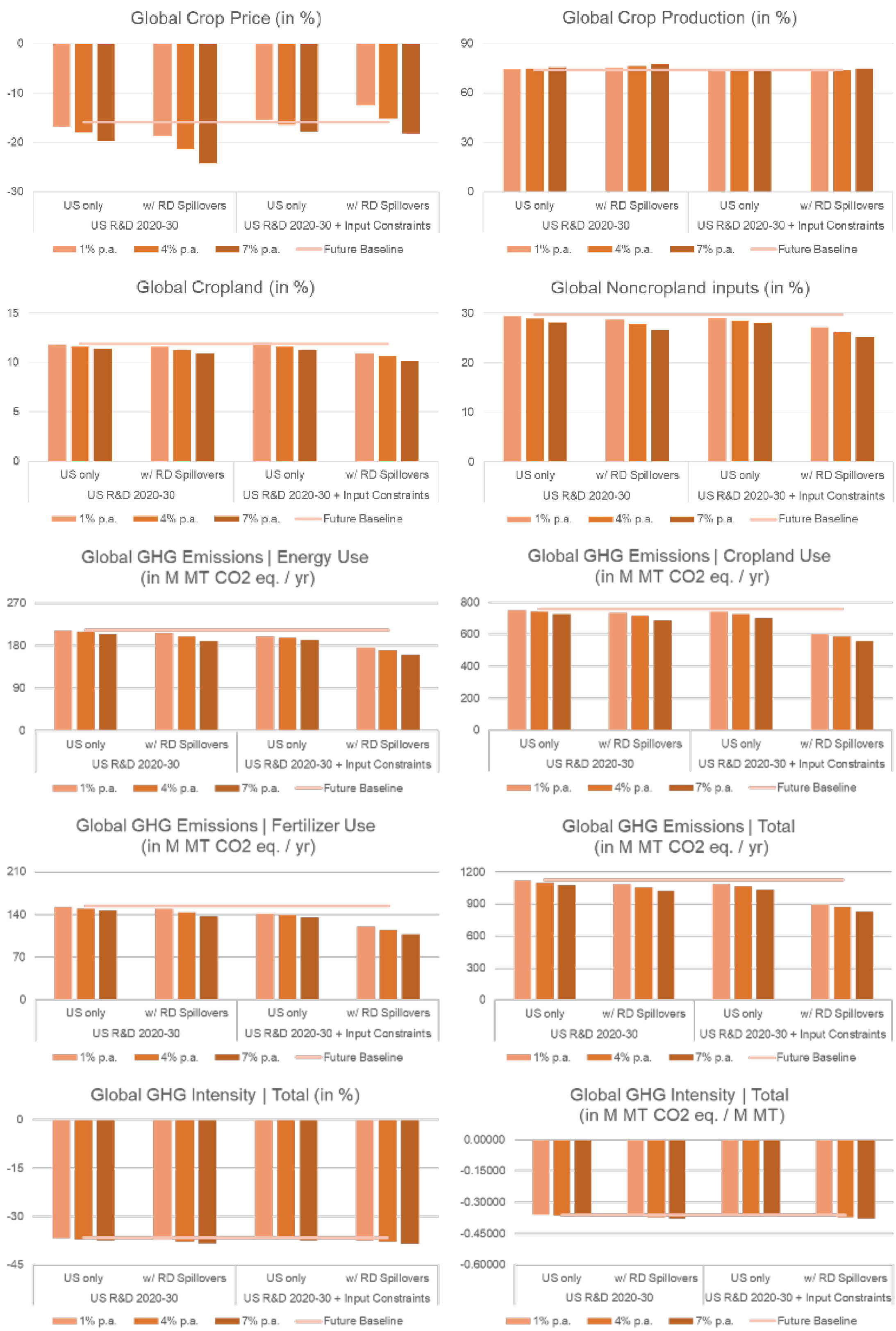
Appendix Table 4. Changes in key global crop production and GHG emissions variables from 2011 to 2050 under different US R&D investment scenarios and farm input constraints (in absolute changes)

Global Variables	Units	Future Baseline	US R&D 2020-30																			
			US only										w/ RD Spillovers									
			1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Global Crop Price	USD / MT	-36	-38	-39	-40	-41	-42	-43	-45	-46	-47	-49	-42	-44	-46	-48	-50	-53	-55	-57	-60	-62
Global Crop Production	M MT	8.1	8.1	8.2	8.2	8.2	8.2	8.2	8.3	8.3	8.3	8.3	8.2	8.3	8.3	8.3	8.4	8.4	8.5	8.5	8.6	8.6
Global Cropland	M Ha	184.6	182.8	181.9	180.9	179.9	178.8	177.6	176.4	175.1	173.7	172.1	179.5	177.8	176.1	174.3	172.4	170.3	168.2	166.0	163.7	161.3
Global Noncropland inputs	B USD	590.6	583.8	580.5	577.1	573.4	569.5	565.4	561.0	556.3	551.4	546.1	572.8	566.8	560.4	553.7	546.7	539.3	531.6	523.5	515.1	506.2
Global GHG Emissions																						
Energy Use	M MT CO2 eq.	213.6	211.6	210.6	209.6	208.5	207.3	206.0	204.7	203.2	201.6	200.0	206.3	204.0	201.4	198.8	196.0	193.1	190.0	186.8	183.4	179.9
Fertilizer Use	M MT CO2 eq.	153.6	151.9	151.1	150.3	149.4	148.4	147.4	146.3	145.1	143.9	142.5	149.0	147.2	145.3	143.2	141.1	138.8	136.4	133.9	131.2	128.5
Cropland Use	M MT CO2 eq.	758.5	750.4	746.5	742.2	737.7	732.9	727.7	722.1	716.2	709.7	702.9	735.2	728.7	721.9	714.7	707.2	699.3	691.0	682.2	673.1	663.6
Total	M MT CO2 eq.	1125.6	1113.9	1108.2	1102.1	1095.6	1088.6	1081.1	1073.1	1064.5	1055.3	1045.4	1090.5	1079.9	1068.6	1056.8	1044.3	1031.2	1017.4	1002.9	987.8	971.9
Global GHG Intensity | Total	M MT CO2 eq. / M MT	-0.360	-0.361	-0.362	-0.363	-0.364	-0.365	-0.366	-0.367	-0.368	-0.370	-0.371	-0.365	-0.367	-0.369	-0.371	-0.373	-0.375	-0.377	-0.380	-0.382	-0.385

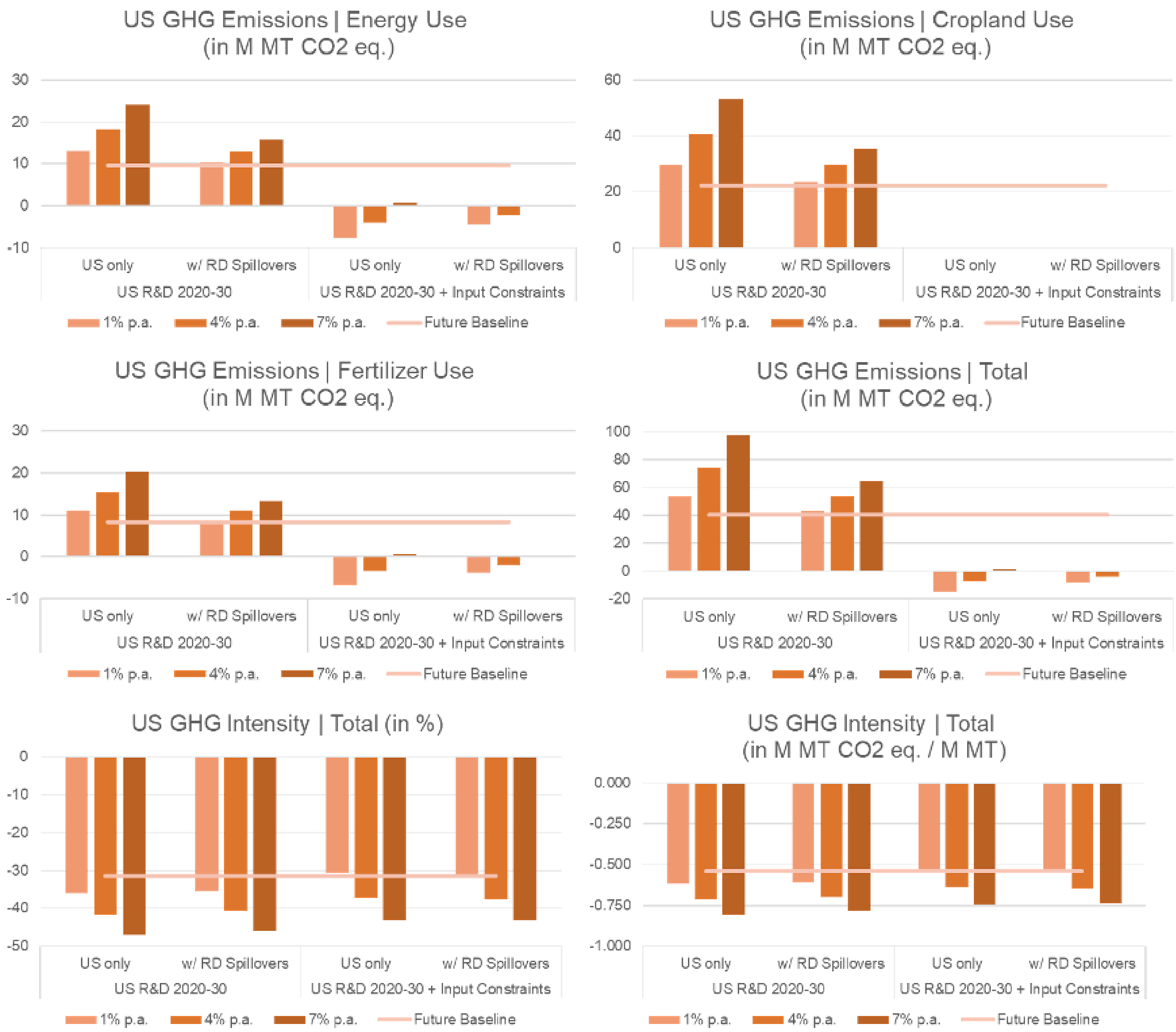
Global Variables	Units	Future Baseline	US R&D 2020-30 + Input Constraints																			
			US only										w/ RD Spillovers									
			1%	2%	3%	4%	5%	6%	7%	8%	9%	10%	1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
Global Crop Price	USD / MT	-36	-35	-35	-36	-37	-38	-39	-40	-41	-43	-44	-28	-30	-32	-34	-37	-39	-41	-44	-46	-49
Global Crop Production	M MT	8.1	8.1	8.1	8.1	8.1	8.1	8.2	8.2	8.2	8.2	8.2	8.0	8.0	8.0	8.1	8.1	8.2	8.2	8.2	8.3	8.3
Global Cropland	M Ha	184.6	183.3	182.2	181.0	179.7	178.3	176.9	175.4	173.8	172.1	170.3	168.3	166.8	165.3	163.7	162.0	160.2	158.3	156.4	154.4	152.2
Global Noncropland inputs	B USD	590.6	577.1	574.3	571.2	568.0	564.6	561.1	557.3	553.2	549.0	544.5	540.3	534.8	528.9	522.8	516.3	509.5	502.3	494.8	487.0	478.8
Global GHG Emissions																						
Energy Use	M MT CO2 eq.	213.6	199.2	198.3	197.3	196.2	195.1	194.0	192.7	191.4	190.0	188.5	176.1	173.8	171.4	168.9	166.3	163.6	160.7	157.6	154.4	151.1
Fertilizer Use	M MT CO2 eq.	153.6	141.3	140.5	139.7	138.8	137.9	137.0	136.0	134.9	133.8	132.5	120.0	118.2	116.4	114.5	112.4	110.3	108.0	105.7	103.2	100.6
Cropland Use	M MT CO2 eq.	758.5	745.4	739.1	732.5	725.5	718.0	710.2	701.9	693.1	683.9	674.2	602.0	596.2	590.2	583.9	577.2	570.2	562.9	555.3	547.4	539.1
Total	M MT CO2 eq.	1125.6	1085.9	1077.9	1069.5	1060.6	1051.1	1041.1	1030.6	1019.4	1007.7	995.3	898.0	888.3	878.0	867.3	856.0	844.1	831.6	818.6	805.0	790.8
Global GHG Intensity | Total	M MT CO2 eq. / M MT	-0.360	-0.361	-0.362	-0.363	-0.364	-0.365	-0.366	-0.367	-0.368	-0.370	-0.371	-0.367	-0.369	-0.370	-0.372	-0.374	-0.376	-0.378	-0.380	-0.382	-0.385

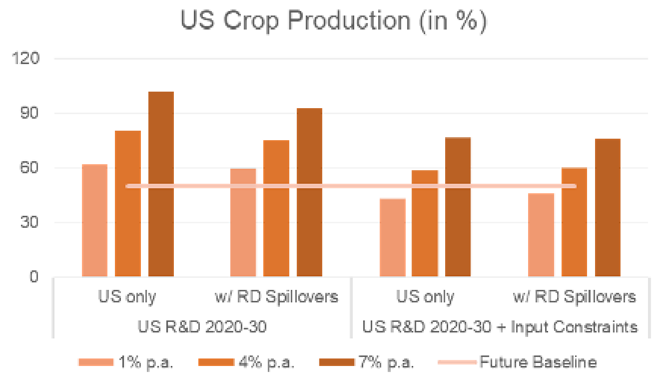
Supplementary Figures

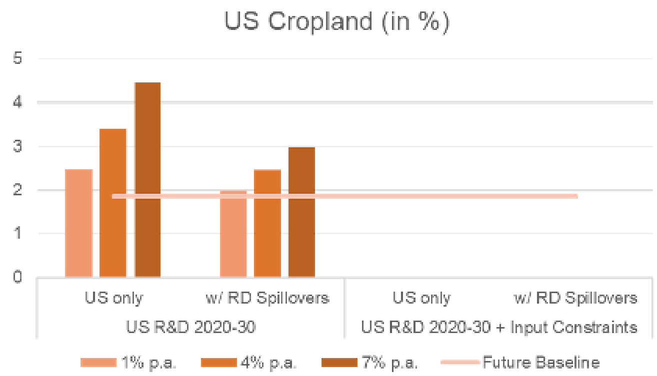
Supplementary Figure 1: Global Results

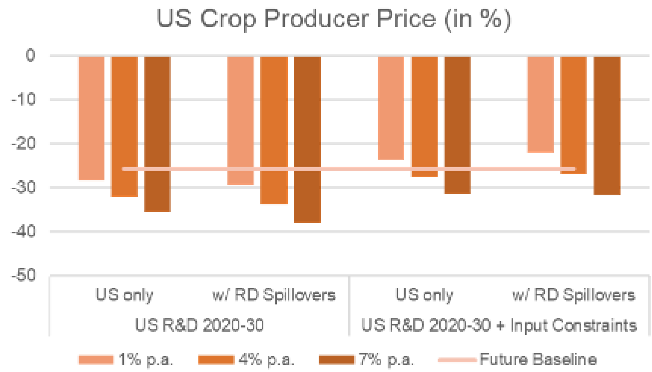


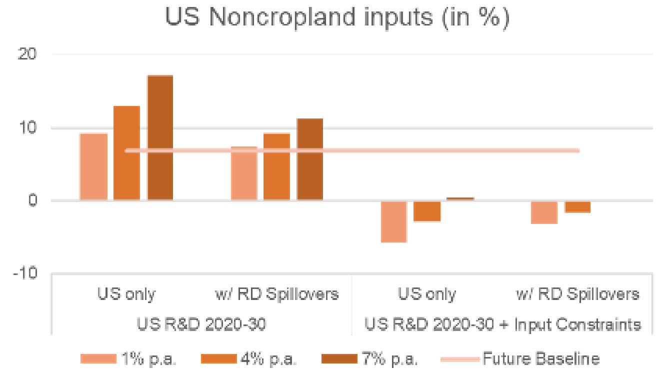
Supplementary Figure 2: US Results

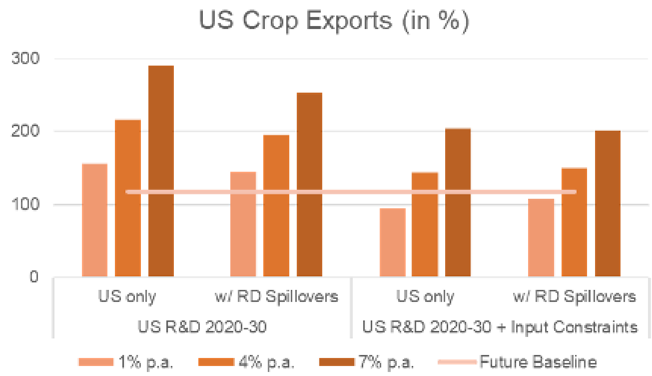



US Crop Production (in %)
120
90
60
30
0
US only
w/ RD Spillovers
US only
w/ RD Spillovers
US R&D 2020-30
US R&D 2020-30 + Input Constraints
1% p.a.
4% p.a.
7% p.a.
Future Baseline


US Cropland (in %)
5
4
3
2
1
0
US only
w/ RD Spillovers
US only
w/ RD Spillovers
US R&D 2020-30
US R&D 2020-30 + Input Constraints
1% p.a.
4% p.a.
7% p.a.
Future Baseline


US Crop Producer Price (in %)
0
-10
-20
-30
-40
-50
US only
w/ RD Spillovers
US only
w/ RD Spillovers
US R&D 2020-30
US R&D 2020-30 + Input Constraints
1% p.a.
4% p.a.
7% p.a.
Future Baseline


US Noncropland inputs (in %)
20
10
0
-10
US only
w/ RD Spillovers
US only
w/ RD Spillovers
US R&D 2020-30
US R&D 2020-30 + Input Constraints
1% p.a.
4% p.a.
7% p.a.
Future Baseline


US Crop Exports (in %)
300
200
100
0
US only
w/ RD Spillovers
US only
w/ RD Spillovers
US R&D 2020-30
US R&D 2020-30 + Input Constraints
1% p.a.
4% p.a.
7% p.a.
Future Baseline

Appendix 2. Estimates of agricultural GHG emissions by 2050

Long-run projections on the GHG emissions of agriculture typically rely on economic models as well as input-output accounting methods. Often these estimates are generated using assumed growths in food demand (due to population, income and changing diets) and food supply (driven by productivity growth and technical change).

Using a global partial equilibrium model of agriculture, FAO (2018) examined how global agriculture evolves to 2050 given different assumptions on food demand drivers such as population, incomes, diets and bioenergy needs as well as food supply drivers such as cropping intensity and productivity growth in both the crops and livestock sectors. Three main scenarios are explored in the study namely stratified societies (SSS), business as usual (BAU) and towards sustainability scenarios (TSS). GHG emissions are computed from the changes in agricultural production. Emissions reported in the study include those from paddy rice, crop residues, and fertilizer use as well as animal specific emissions from the livestock sector. The results show that global gross agricultural production is expected to increase by 53%, 50% and 40% from 2012 to 2050 under SSS, BAU and TSS, respectively. US gross agricultural production is expected to increase by around 40%, 33% and 4% respectively. Globally, agricultural GHG emissions are expected to increase by around 20% and 38% under BAU and SSS (around 5.2 and 5.9 GtCO2-eq /yr, respectively) while they will decrease by around 17% under TSS (3.6 GtCO2-eq /yr). For the US, agricultural GHG emissions under BAU and TSS are expected to fall by around 31% and 68% (from 0.36 GtCO2-eq /yr in 2012 to 0.24 and 0.11 GtCO2-eq /yr, respectively) while they will increase by around 10% under SSS (0.39 GtCO2-eq /yr).

WRI (2019) used a global accounting model to calculate future changes in agricultural production, land use and greenhouse gas emissions between 2010 and 2050. Several scenarios are estimated in the report using different assumptions regarding future diets, food waste mitigation, productivity and emission reduction in crops and livestock animals. Findings from these initial model runs are used to craft three key alternative scenarios which consist of "Coordinated Effort" "Highly Ambitious" and "Breakthrough Technologies" scenarios. These are ranked according to the level of effort to drastically reduce agricultural GHG emissions. The estimates show that under business as usual, global GHG emissions from agricultural production are expected to rise by 32% from 6.8 to 9.0 GtCO2-eq /yr between 2010 and 2050 while land use change emissions are expected to increase by around 15% (or from 5.2 to 6.0 GtCO2-eq /yr). In total, global agricultural GHG emissions are expected to increase by around 25% (15 GtCO2-eq /yr). Estimates of the alternative

scenarios show a significant reduction in GHG emissions from global agriculture between 2010 to 2050. Agricultural emissions under the "Coordinated Effort", "Highly Ambitious" and "Breakthrough Technologies" scenarios are expected to decline by 39%, 61% and 69%, respectively relative to 2010 values.

Frank et al (2018) examined how technical and structural mitigation options, as well as consumer preferences, can reduce methane and nitrous oxide emissions in global agriculture by 2050 using a global partial equilibrium model of agriculture. Technical improvements considered by the authors include fertilizer management, better rice cultivation practices, manure management and livestock supplements. Structural adjustments in the study consist of shifts in production systems, reallocation of international trade, and changes in consumer preferences. The results show that in their baseline scenario, without mitigation, global agricultural non-CO_2 emissions are expected to grow from 4.8 GtCO2-eq/yr in 2010 to around 6.8 GtCO2-eq/yr by 2050 (around 42%). Around 80% of the global increase in methane and nitrous oxide emissions are in Asia, Latin America and Africa. The authors find that combined structural, technical, and food demand mitigation strategies could reduce global agricultural non-CO2 emissions by up to 2.6 GtCO2-eq/yr in 2050 at the 100 $/tCO2eq carbon price — around 38% of global emissions under the future baseline. Furthermore, the authors find that there is no single set of policies that could be adopted globally. Each region has its own unique set of policies which will yield the most effective reduction in non-CO_2 emissions in agriculture.

Bennetzen, Smith and Porter (2016b) used global GHG accounting methods in order to assess historical as well as future global GHG emissions from agriculture. Unlike model-based estimates, the authors used identity-based analysis to deconstruct the primary elements of agricultural GHG emissions. GHG emissions considered in the study include those from the livestock and crop sector. The authors applied their approach in order to calculate the GHG emissions from past projections by UN FAO. The authors found that under business as usual — wherein emissions per crop and livestock follow historical trends — global agricultural GHG emissions are expected to increase by around 2.6 GtCO2-eq/yr between 2007 to 2050 (11.9 and 14.5 GtCO2-eq /yr, respectively). Overall contribution of crops and livestock production to the total change is around 0.8 and 1.8 GtCO2-eq/yr, respectively. Emissions for crop production can be further decomposed to contribution of energy use (1.3 GtCO2-eq/yr), soil emissions (0.2 GtCO2-eq/yr) as well as land use change emissions (-0.7 GtCO2-eq/yr).

A 2013 study estimated that under a business as usual scenario, world agricultural GHG emissions will increase by about 1 GtCO2-eq/ yr between 2000 and 2050, primarily due to increased livestock methane emissions and emissions from

fertilizer use (Valin et al. 2013). With increased crop and livestock yields, however, the increase is dampened to 0.324 - 0.456 GtCO2e/yr (56 - 69% less), depending on whether increasing yields costs farmers extra or technological advances enabled them to increase at no cost. Another study found similar climate benefits from productivity growth. It projected that without productivity growth, global agricultural GHG emissions would increase by 47% (from 5.1 GtCO2-eq/yr to 7.5 GtCO2-eq/yr) between 2004 and 2034, whereas it would increase about 66% less if productivity for crops and livestock grew (Jones & Sands, 2013).

Appendix 3: SIMPLE Model Description

As the name suggests, SIMPLE focuses on the key drivers and economic responses which govern long run developments in the farm and food system (U.L.C. Baldos & Hertel, 2013). In the SIMPLE model, per capita food demands are driven by exogenous per capita income growth and respond to endogenous changes in food prices with these responses varying by income level. Consumers in wealthy regions are less responsive to price and income changes than those residing in low income regions. Aggregated food commodities in SIMPLE include crops, livestock products, and processed foods, and consumption patterns evolve to reflect observed shifts in dietary preferences — moving away from crops towards livestock and processed foods as incomes rise.

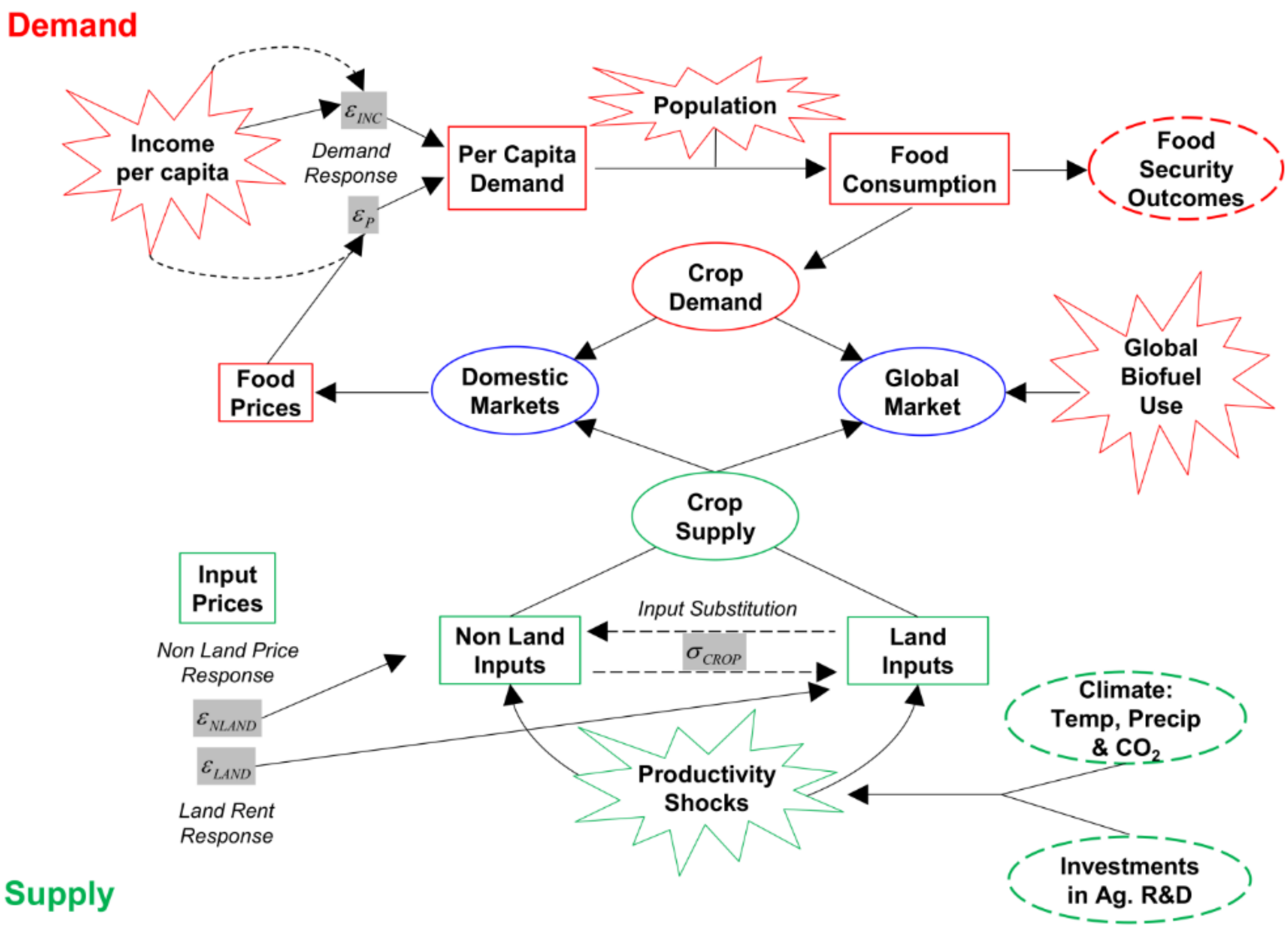


Figure A1. Schematic of the SIMPLE Model

Regional production systems in SIMPLE are modelled using a constant elasticity of substitution (CES) production framework. Crops are produced by combining land and an aggregate noncropland input, with the latter input representing all other factors of production — excluding land — which are used by the crops

sector, including fertilizer, labor, and machinery, among other farm inputs. Crop outputs are demanded in four uses, namely: direct food consumption, feed use in the livestock sectors, raw input use in the processed food industries, and feedstocks in the global biofuel sector. The capacity for input substitution between land and noncropland inputs makes it possible to endogenously increase crop yields. The evolution of the global farm system is also driven by exogenous productivity trend effects owing to climate change as well as endogenous productivity responses to past and future investments in agricultural R&D.

Future projections for the period 2011 to 2050 using the SIMPLE model require future growth rates in the population, income, biofuel demand, and total factor productivity in the crops, livestock and processed food sectors. In this study, sources of these future growth rates are as follows. 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., 2012). 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). 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). With the "Current policies" scenario, all energy policies for the power and transportation sectors enacted as of mid-2012 are taken into account. In this study, estimates of total factor productivity (TFP) growth rates — a measure of productivity which accounts for total output given over-all input use — are used in future projections. Regional TFP growth rates for the crops and livestock sectors are based on adjusted historical estimates from Fuglie (2012) and projections from Ludena et al. (2007), respectively. Lacking detailed TFP projections for the processed food sector, historical rates from Griffith et al. (2004) are used, assuming that these rates apply in the future and across all regions. SIMPLE was also modified to include CO2 GHG emissions from noncropland inputs (fuel and energy GHG intensities (Bennetzen et al., 2016a) as well as one-time cropland use change emission — soil and above ground biomass from potential vegetation cover (West et al., 2010).

REFERENCES

Alston, J. M., Andersen, M. A., James, J. S., & Pardey, P. G. (2011). The Economic Returns to U.S. Public Agricultural Research. American Journal of Agricultural Economics, 93(5), 1257—1277. https://doi.org/10.1093/ajae/aar044

Alston, J. M. (2018). Reflections on agricultural R&D, productivity, and the data constraint: unfinished business, unsettled issues. American Journal of Agricultural Economics, 100(2), 392-413.

Andersen, M. A., & Song, W. (2013). The Economic impact of public agricultural research and development in the United States. Agricultural Economics, 44(3), 287—295. https://doi.org/10.1111/agec.12011

Baldos, U.L.C., & Hertel, T. W. (2013). Looking back to move forward on model validation: Insights from a global model of agricultural land use. Environmental Research Letters, 8(3), 034024. https://doi.org/10.1088/1748-9326/8/3/034024

Baldos, Uris Lantz C, Viens, F. G., Hertel, T. W., & Fuglie, K. O. (2018). R&D Spending, Knowledge Capital, and Agricultural Productivity Growth: A Bayesian Approach. American Journal of Agricultural Economics, 101(1), 291—310.

Bennetzen, E. H., Smith, P., & Porter, J. R. (2016a). Agricultural production and greenhouse gas emissions from world regions—The major trends over 40 years. Global Environmental Change, 37, 43—55. https://doi.org/10.1016/j.gloenvcha.2015.12.004

Bennetzen, E. H., Smith, P., & Porter, J. R. (2016b). Decoupling of greenhouse gas emissions from global agricultural production: 1970—2050. Global Change Biology, 22(2), 763—781. https://doi.org/10.1111/gcb.13120

Bigelow, D., & Borchers, A. (2017). Major uses of land in the United States, 2012 (No. 1476-2017-4340).

Burney, J., Davis, S., & Lobell, D. B. (2010). Greenhouse gas mitigation by agricultural intensification. Proceedings of the National Academy of Sciences, 107(26), 12052—12057. www.pnas.org/cgi/doi/10.1073/pnas.0914216107

Clancy, M., Fuglie, K., & Heisey, P. (2016). US Agricultural R&D; in an Era of Falling Public Funding (No. 1490-2016-128541).

FAO. (2018). The future of food and agriculture — Alternative pathways to 2050 (p. 228). UN FAO.

Frank, S., Beach, R., Havlík, P., Valin, H., Herrero, M., Mosnier, A., Hasegawa, T., Creason, J., Ragnauth, S., & Obersteiner, M. (2018). Structural change as a key component for agricultural non-CO 2 mitigation efforts. Nature Communications, 9(1), 1—8. https://doi.org/10.1038/s41467-018-03489-1

Fuglie, K. (2017). R&D Capital, R&D Spillovers, and Productivity Growth in World Agriculture. Applied Economic Perspectives and Policy. https://doi.org/10.1093/aepp/ppx045

Fuglie, K. O. (2012). Productivity growth and technology capital in the global agricultural economy. In K. O. Fuglie, S. L. Wang, & V. E. Ball (Eds.), Productivity Growth In Agriculture: An International Perspective (pp. 335—368). CAB International; CABDirect2.

García, V. R., Gaspart, F., Kastner, T., & Meyfroidt, P. (2020). Agricultural intensification and land use change: assessing country-level induced intensification, land sparing and rebound effect. Environmental Research Letters, 15(8), 085007. https://doi.org/10.1088/1748-9326/AB8B14

Griliches, Z. (1979). Issues in Assessing the Contribution of Research and Development to Productivity Growth. The Bell Journal of Economics, 10(1), 92—116. https://doi.org/10.2307/3003321

Heisey, P. W., & Fuglie, K. O. (2018). Agricultural Research Investment and Policy Reform in High-Income Countries (ERR-249). U.S. Department of Agriculture, Economic Research Service.

Heisey, P., Wang, S. L., & Fuglie, K. (2011). Public Agricultural Research Spending and Future U.S. Agricultural Productivity Growth: Scenarios for 2010-2050 (Economic Brief EB-17). Economic Research Service, U.S. Department of Agriculture.

Huffman, W. E. (2009). Measuring Public Agricultural Research Capital and Its Contribution to State Agricultural Productivity (No. 09022). Department of Economics, Iowa State University.

IEA. (2008). World Energy Outlook. OECD Publishing. http://www.oecd-ilibrary.org/content/book/weo-2008-en

IEA. (2012). World Energy Outlook. OECD Publishing. http://www.oecd-ilibrary.org/content/book/weo-2012-en

Jin, Y., & Huffman, W. E. (2016). Measuring public agricultural research and extension and estimating their impacts on agricultural productivity: New insights from U.S. evidence. Agricultural Economics, 47(1), 15—31. https://doi.org/10.1111/agec.12206

Jones, C. A., & Sands, R. D. (2013). Impact of Agricultural Productivity Gains on Greenhouse Gas Emissions: A Global Analysis. American Journal of Agricultural Economics, 95(5), 1309—1316. https://doi.org/10.1093/ajae/aat035

Jones, C. A., Nickerson, C. J., & Heisey, P. W. (2013). New Uses of Old Tools? Greenhouse Gas Mitigation with Agriculture Sector Policies. Applied Economic Perspectives and Policy, 35(3), 398—434. https://doi.org/10.1093/aepp/ppt020

Kriegler, E., O'Neill, B. C., Hallegatte, S., Kram, T., Lempert, R. J., Moss, R. H., & Wilbanks, T. (2012). The need for and use of socio-economic scenarios for climate change analysis: A new approach based on shared socio-economic pathways. Global Environmental Change, 22(4), 807—822. https://doi.org/10.1016/j.gloenvcha.2012.05.005

Lobell, D. B., Baldos, U. L. C., & Hertel, T. W. (2013). Climate adaptation as mitigation: The case of agricultural investments. Environmental Research Letters. https://doi.org/10.1088/1748-9326/8/1/015012

Ludena, C. E., Hertel, T. W., Preckel, P. V., Foster, K., & Nin, A. (2007). Productivity growth and convergence in crop, ruminant, and nonruminant production: Measurement and forecasts. Agricultural Economics, 37(1), 1—17. https://doi.org/10.1111/j.1574-0862.2007.00218.x

O'Neill, B. C., Ren, X., Jiang, L., & Dalton, M. (2012). The effect of urbanization on energy use in India and China in the iPETS model. The Asia Modeling Exercise: Exploring the Role of Asia in Mitigating Climate Change, 34, Supplement 3(0), S339—S345. https://doi.org/10.1016/j.eneco.2012.04.004

SSP Database (v 0.93). (2013). ttps://secure.iiasa.ac.at/web-apps/ene/SspDb

Stevenson, J. R., Villoria, N., Byerlee, D., Kelley, T., & Maredia, M. (2013). Green Revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production. Proceedings of the National Academy of Sciences of the United States of America, 110(21), 8363—8368. https://doi.org/10.1073/pnas.1208065110

USDA ERS. (2015). Agricultural Productivity in the U.S. http://www.ers.usda.gov/data-products/agricultural-productivity-in-the-us.aspx

USDA ERS. (2019). International Agricultural Productivity [On-line database.]. https://www.ers.usda.gov/data-products/international-agricultural-productivity/

Valin, H., Havlík, P., Mosnier, A., Herrero, M., Schmid, E., & Obersteiner, M. (2013). Agricultural productivity and greenhouse gas emissions: Trade-offs or synergies between mitigation and food security? Environmental Research Letters, 8(3), 035019. https://doi.org/10.1088/1748-9326/8/3/035019

Villoria, N. B. (2019). Technology Spillovers and Land Use Change: Empirical Evidence from Global Agriculture. American Journal of Agricultural Economics, 101(3), 870—893. https://doi.org/10.1093/ajae/aay088

West, P. C., Gibbs, H. K., Monfreda, C., Wagner, J., Barford, C. C., Carpenter, S. R., & Foley, J. A. (2010). Trading carbon for food: Global comparison of carbon stocks vs. crop yields on agricultural land. Proceedings of the National Academy of Sciences. https://doi.org/10.1073/pnas.1011078107

WRI. (2019). Creating a sustainable food future (p. 564). WRI.

ABOUT

Uris Lantz Baldos is a research assistant professor from the Department of Agricultural Economics at Purdue University. He co-developed the Simplified International Model of agricultural Prices, Land use and the Environment (SIMPLE), a computational economic model of global agriculture which he extensively use in his research. Uris co-authored a textbook on global food sustainability and published several peer reviewed journal articles in the American Journal of Agricultural Economics, Proceedings of the National Academy of Sciences and Nature Communications. Uris' research interests are on the broad issues surrounding the global farm-food-environment nexus, local-global telecoupling and on computational economic modelling.

Dan analyzes the economics and potential of sustainable agriculture policies and practices. He has conducted research with the Environmental Defense Fund, International Center for Tropical Agriculture, and Farmers Market Coalition. Originally from New York's Hudson Valley, Dan joined Breakthrough in 2017 after completing a Masters of Public Policy from University of California, Berkeley where he researched the air pollution implications of Cap-and-Trade. Dan earned his BA in Environmental Studies from Brown University. Out of the office, you can find him hiking the Berkeley hills or rock climbing.

THE BREAKTHROUGH INSTITUTE
436 14TH ST
SUITE 820
OAKLAND, CA 94612

WWW.THEBREAKTHROUGH.ORG
TWITTER: @TheBTI