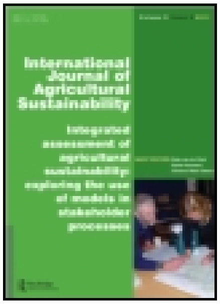

International Journal of Agricultural Sustainability

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tags20

Climate adaptation imperatives: untapped global maize yield opportunities

David I. Gustafson[a], James W. Jones[b], Cheryl H. Porter[b], Glenn Hyman[c], Michael D. Edgerton[d], Tom Gocken[d], Jereme Shryock[d], Michael Doane[d], Katie Budreski[e], Chris Stone[e], David Healy[e] & Nathan Ramsey[f]

[a] Center for Integrated Modeling of Sustainable Agriculture & Nutrition Security (CIMSANS), International Life Sciences Institute Research Foundation, 1156 15th St NW, Suite 200, Washington, DC 20005

[b] Agricultural & Biological Engineering, University of Florida, 103 Frazier Rogers Hall, PO Box 110570, Gainesville FL 32611-0570

[c] International Center for Tropical Agriculture (CIAT), Cali, Colombia

[d] Monsanto Company, 800 N. Lindbergh Blvd, St. Louis, MO 63167

[e] Stone Environmental Inc, 535 Stone Cutters Way, Montpelier, VT 05602

[f] The Context Network, 4401 Westtown Parkway, Suite 214, West Des Moines, IA 50266

Published online: 31 Jan 2014.

To cite this article: David I. Gustafson, James W. Jones, Cheryl H. Porter, Glenn Hyman, Michael D. Edgerton, Tom Gocken, Jereme Shryock, Michael Doane, Katie Budreski, Chris Stone, David Healy & Nathan Ramsey , International Journal of Agricultural Sustainability (2014): Climate adaptation imperatives: untapped global maize yield opportunities, International Journal of Agricultural Sustainability, DOI: 10.1080/14735903.2013.867694

To link to this article: http://dx.doi.org/10.1080/14735903.2013.867694

International Journal of Agricultural Sustainability, 2014
http://dx.doi.org/10.1080/14735903.2013.867694

Climate adaptation imperatives: untapped global maize yield opportunities

David I. Gustafson[a*], James W. Jones[b], Cheryl H. Porter[b], Glenn Hyman[c], Michael D. Edgerton[d], Tom Gocken[d], Jereme Shryock[d], Michael Doane[d], Katie Budreski[e], Chris Stone[e], David Healy[e] and Nathan Ramsey[f]

[a]*Center for Integrated Modeling of Sustainable Agriculture & Nutrition Security (CIMSANS), International Life Sciences Institute Research Foundation, 1156 15th St NW, Suite 200, Washington, DC 20005;* [b]*Agricultural & Biological Engineering, University of Florida, 103 Frazier Rogers Hall, PO Box 110570, Gainesville FL 32611-0570;* [c]*International Center for Tropical Agriculture (CIAT), Cali, Colombia;* [d]*Monsanto Company, 800 N. Lindbergh Blvd, St. Louis, MO 63167;* [e]*Stone Environmental Inc, 535 Stone Cutters Way, Montpelier, VT 05602;* [f]*The Context Network, 4401 Westtown Parkway, Suite 214, West Des Moines, IA 50266*

Climate change represents an unavoidable and growing challenge to food security, imposing new adaptation imperatives on all farmers. Maize is arguably the world's most productive grain crop, as measured by grain yield. However, maize yields vary dramatically due to many factors, including soils, climate, pests, disease, agronomic practices, and seed quality. The difference between observed yields and those achievable by optimized crop production methods is called the yield gap. In this work we quantified the current yield gap for 44 countries through the use of a large private-sector data set recently made available to the crop modelling community. The yield gap was quantified for three groups of countries, categorized by level of intensification. Observed yield gaps for high, medium, and low levels of intensification are 23%, 46%, and 68%, respectively. If all maize production countries were able to shrink their yield gap to 16.5% (as in the USA) an additional 335 million metric tons (MMT) of maize grain would be produced. This represents a 45% increase over the 741 MMT produced by these countries in 2010. These data demonstrate that a major untapped maize yield opportunity exists, especially in those countries where intensification has not kept pace with the rest of the world.

Keywords: climate change; food security; nutrition security; sustainable intensification

Introduction

Global demand for maize, the world's most heavily traded grain, continues to rise sharply (Diffenbaugh et al. 2012). Although the majority (>50%) of the world's maize is consumed by livestock (Teheripour et al. 2009), the growth in demand is also due to the many other uses which have been found for the components of maize grain: its oil is used in foods and soaps; corn flour is used in bakery products; cornstarch is a common baking ingredient and is used in numerous industrial products (abrasive papers, adhesives, ceramics, disinfectants, pharmaceuticals, plastics, tires, etc.); and corn sugar from the starch becomes fructose in foods and beverages, glucose in foods, paper products, and textiles, or it can be fermented to become the ethanol in both fuels and alcoholic beverages (Paasche 2012). In addition to grain, the maize plant produces an approximately equal amount of so-called crop residue (stover), a relatively small portion

*Corresponding author. Email: dgustafson@ilsi.org

(<10%) of which becomes soil organic matter or is actually necessary for conservation of soil and water resources, but the majority of which may be sustainably harvested and utilized as feed, energy, or renewable building material (Mueller et al. 2012a). This multiplicity of maize uses has been spurred on by a generally stable growth in supply of the crop, enabled by continuing advances in plant breeding, agronomics (agricultural management), and the advances of agricultural biotechnology (Castleberry et al. 1984, Duvick 2005, Edgerton et al. 2012).

However, despite these maize productivity advances, global demand now appears to be outstripping supply (Diffenbaugh et al. 2012). The high volatility of global food prices during the last few years has brought attention to the very real threats to future global food security (Nelson et al. 2010). The food price spike in 2008, the 2010 drought in Russia, massive floods in Pakistan, and the 2012 drought in the USA are examples of a potentially new, unwanted trend in real food prices after a century during which real global food prices continually decreased. Nelson et al. (2010) suggested that agricultural prices are likely to increase during the next several decades due to higher incomes and a growing population as well as the negative productivity effects of climate change, driven by sensitivity of crop production to climate variability (Easterling et al. 2007). This trend seems likely to increase in the future as world population grows from the current 7 billion to an estimated 9 billion by mid-century (Foresight 2011, Beddington et al. 2012a). The demand for maize will not only be driven by population growth but also by changes in dietary preferences of a burgeoning middle class (Wik et al. 2008). Ray et al. (2013) tracked four key global crops – maize, rice, wheat, and soybean – that currently produce nearly two-thirds of global agricultural calories. They found that yields in these top four crops are increasing at 1.6%, 1.0%, 0.9%, and 1.3% per year non-compounding rates, respectively, which is less than the 2.4% per year rate required to double global production by 2050. Although increasing global trade can help to mitigate some of these shortfalls, the increasing dependence upon food imports means that the poorest consumers in many countries are increasingly exposed to variations in yields, production and export prices in the major food-producing regions of the world (Iizumi et al. 2013). This will increase the risk of hunger and malnutrition, including micronutrient malnutrition, through a number of direct and indirect causal pathways including declines in agricultural productivity gains and price increases for maize and other crops (Cline and Zhu 2008, Nelson et al. 2009, UNSCN 2010).

These and other factors led Beddington et al. (2012b) to conclude that we are operating the planet outside of its 'safe operating space'. Indeed, the Ehrlichs have asked (2013) whether a 'collapse of global civilization can be avoided'. Others (Foley et al. 2011, Tomlinson 2013) have questioned whether productivity advances alone are required to meet future food and nutrition needs, pointing out that tremendous progress could be made by shifting diets and reducing waste. Still others have raised concerns about the rapidly increasing proportion of global net primary productivity that is now being appropriated by humanity, and that these increases cannot continue (Krausman et al. 2013).

There is also a growing recognition that climate change and resource constraints (especially water) may significantly decrease future crop yield gains (Lobell et al. 2008, 2011, Parry et al. 2009). In addition to the direct impacts of climate change on crop production, there are expected increases in pest and disease pressure (Bebber et al. 2013, Dwivedi et al. 2013). The specific challenges of climate change to maize and bean production in East Africa have been examined in detail through the use of computer simulation models (Thornton et al. 2010). The same authors highlighted the considerable climatic and topographic variability across this region, leading to substantial between-country and within-system differences in crop yield response through 2050. But it is not only variations in climate that make crop production variable and challenging: social and economic factors are possibly even more important (Garnett et al. 2013). These same authors point out that sustainability and food security have multiple environmental, social, and ethical dimensions. Increases in productivity must be accompanied by reductions in consumption of inputs, less waste, and improve governance. Fortunately, some improvements in the efficiency of input utilization (land, water, energy, greenhouse gas emissions) are occurring (Gustafson et al. 2013). Despite these daunting challenges and the increasing awareness about the urgency of boosting maize yields to meet the growing global demand, there has been surprisingly little progress in achieving full maize yield potential in many areas of the world. The difference between observed yields and what might be achieved using optimized crop production methods has come to be known as the yield gap. Several previous researchers have examined global yield gaps for maize and other crops (*Boyd*-Orr 1950, Cassman 1999, Ewert et al. 2005, Lobell et al. 2009, Licker et al. 2010, Liu *et al.* 2010, Neumann et al. 2010, Waddington et al. 2010, Johnston et al. 2011, Liu et al. 2011, Nin-Pratt et al. 2011, Richardson et al. 2011, Tilman et al. 2011, Lauer et al. 2012, Mueller et al. 2012b, Nolan and Santos 2012, Vermeulen et al. 2012, Wani et al. 2012, van Wart et al. 2013). However, all of these previous analyses have been based on some form of simulation modelling or statistical regression. In this work, we have chosen a data-driven empirical approach. The global maize yield gap has been quantified by comparing observed national average maize yields to the average yields observed in a large, private-sector data set comprising properly managed maize breeding trials within these same countries. We acknowledge that a number of factors would lead such maize yields to be higher than the national averages. For instance, access to inputs and irrigation water will be economically limited in poorer countries, especially in light of climate change. However, we show in this work that yield gaps so defined are relatively small in high-intensification countries. We believe this demonstrates the relevance of such properly managed breeding trials as a way to estimate achievable yield elsewhere in the world. The results are presented in a number of ways, focusing on the major impact of irrigation on maize yields and also examining the importance of national agricultural intensification levels, based on a method for categorizing intensification recently developed by Context (2012), which defines three levels of intensification based on agronomic practices, use of high-quality seed, and deployment of modern agricultural technology. This paper is one of a planned series of publications looking at various climate adaptation imperatives as they are impacted by the level of agricultural intensification. Here, we consider the impact of intensification on crop yield. A separate paper examined the eco-efficiency of natural resource utilization (Gustafson et al. 2013), and yet another seeks to quantify the global economic impact of the adoption of modern maize technology.

Materials and methods

Maize breeding trial data set

Irrigated and rainfed maize yield potentials were determined for each country by calculating average annual maize yields for the period 2007–2011 from a large, private-sector maize breeding trial data set. Representative maize breeding trial data from this data set have been posted to the AgTrials database maintained by CIAT (AgTrials 2012) and a database maintained by the University of Florida on behalf of AgMIP (AgMIP 2012). The data reported for each trial are the average observed maize yields for all varieties included in the trial. All of the field trial sites were well managed, and therefore represent experimental potential yields that could have been attained by commercial growers in that region, if they had used similar inputs. As noted above, there may be economic limitations to gaining access to such inputs.

The breeding trial data set utilized in this analysis is large, including a total of 21,293 observations, each of which is the average across multiple hybrids tested at a particular field location, for the years 2007–2011. Breeding yield trials typically employ small (4 rows wide by 7 m long) plots as their basic experimental unit. Row spacing is typically 0.76 m, for a total area of about 20 m^2 per plot, with some variations of plot size and configuration across geographies and years. Each breeding trial may have between 10 and 50 hybrids, typically organized in some form of randomized block design. Crop rotations, tillage, and the use of irrigation vary by field and region and typically reflect the practices that are common for the area. Commercial yield trials are larger, with approximately 12–20 hybrids planted side by side in long strips, usually running the length of a field. The width of each strip is determined by the size of locally available planting and harvesting machinery. Strip width typically ranges from 8 to 16 rows wide for a total area of 0.25–0.5 ha per hybrid tested. Commercial yield trials use the same management practices as the farm they are grown on, which is advantageous as they more closely replicate local farming practices than research breeding trials. The breeding trial sites are distributed throughout the representative maize-growing regions within each country, as is necessary to adapt varieties to local climate conditions and soil types.

Selected soils and weather data are collected at these breeding trials, however the types of data collected within each region vary widely and were not judged to be of sufficient quality for this form of global analysis. These data were therefore not utilized here, nor are they part of the information that has been posted to the AgTrials or AgMIP databases. However, as noted in the Appendix, sufficient geographic locational data have been posted in order for crop modelling researchers to associate either climate (Ramierez-Villegas and Challinor 2012) or soils (Hiederer and Köchy 2011) information with each particular maize yield observation.

National average maize yields

National average maize yields were extracted directly from the US Department of Agriculture (USDA) Foreign Agricultural Service's Production, Supply, and Distribution database (USDA 2012).

Categorizing intensification level

The intensification level of each country was categorized as high, medium, or low according to the procedures defined by Context (2012). Using its own data and input from a panel of leading industry experts, Context developed and applied an empirical, crop-specific, intensification scoring system for four crops: canola, cotton, maize, and soybeans. Their system scored three different sub-categories of intensification: breeding intensity, biotechnology adoption, and agronomic practices. For each of these indicators, Context systematically ranked each country as having either a high, medium, or low level of intensification for the particular crop (Table 1).

In order to apply the Context methodology for this report, we developed an aggregate measure of overall intensification for the production of maize, from its individual sub-category rankings. Numerical values of 1, 2, or 3 were assigned to each sub-category ranking of low, medium, and high, respectively. We then summed the three sub-category scores for each country and classified each by its sum as follows: high (8–9); medium (5–7); and low (3–4).

Results

Shown in Table 2 are the national average and breeding trial yields (MT/HA) for the years 2007–2011, in all 44 countries where comparative data were available (USDA 2012). The table is sorted alphabetically by level of intensification. The yield gap has been calculated for each country by comparing the national average yield with a weighted average of the breeding trial yields, with the rainfed and irrigated yields weighted by the amount of irrigated maize production in each country

Table 1. Technology and sub-factors considered by context (2012).

Country by crop rating criteria – high, medium, and low	High = 3	Medium = 2	Low = 1
Agronomic practice	3	2	1
Use of irrigation where natural precipitation is limiting	●	△	◆
High degree of mechanization (combination of tractors and low use of labour/unit output)			
Use of fertilizers and pesticides			
Ability to consolidate land to take advantage of scale economies			
High level of experience and management acumen growing a crop in a given geography			
Availability of support systems and services			
Breeding	3	2	1
Corn – High adoption of hybrid technology	●	△	◆
Soybean – High percentage of proprietary OP and limited saved seed			
Cotton – High percentage of proprietary OP and limited saved seed			
Biotechnology	3	2	1
High levels of adoption	●	△	◆
High trait intensity			
Efficiently functioning regulatory approval process and multiple approvals			
Ability to protect and enforce protection for intellectual property			

Table 2. Maize yield gaps for all forty four countries with comparable data from the USDA-PSD database (2012) and the breeding trials.

				Observed maize yields (MT/HA)				Yield gap			
					Breeding trials			Observed			
Country	Level of intensification	Production of maize in 2010 (MMT)	Percent of maize irrigated	National averages	Rainfed	Irrigated	Wgt-Avg	(MT/HA)	(%)	Closable (MT/HA)	Production opportunity (MMT)
Argentina	High	10.7	1	6.70	9.69	10.97	9.71	3.01	31.0%	1.40	2.24
Brazil	High	58.2	0	4.04	10.26	12.19	10.26	6.22	60.6%	4.53	65.20
Canada	High	10.7	1	8.92	10.97		10.97	2.05	18.7%	0.24	0.29
Chile	High	1.4	77	10.96	10.00		10.00	0.00		0.00	0.00
South Africa	High	12.3	2	4.09	6.31	12.33	6.43	2.34	36.4%	1.28	3.85
Spain	High	3.4	54	10.15	12.00	14.40	13.30	3.15	23.7%	0.95	0.32
United States of America	High	320.9	11	9.66	11.44	12.65	11.57	1.91	16.5%	0.00	0.00
Austria	Medium		0	10.21	13.31		13.31	3.10	23.3%	0.90	
China	Medium	177.7	9	5.44	9.10	8.85	9.08	3.64	40.1%	2.14	69.89
Colombia	Medium	1.5	0	2.87	7.48	7.51	7.48	4.61	61.6%	3.37	1.76
Czech Republic	Medium	0.8	0	7.24	11.56	14.68	11.56	4.32	37.4%	2.41	0.27
Ecuador	Medium	0.4	20	2.86	7.49		7.49	4.63	61.8%	3.39	0.49
El Salvador	Medium	0.6	0	3.21	6.04	6.92	6.04	2.83	46.9%	1.83	0.35
France	Medium	14.7	18	9.11	13.34	13.36	13.34	4.23	31.7%	2.03	3.28
Germany	Medium		0	9.45	12.34	11.46	12.34	2.89	23.4%	0.85	
Greece	Medium		51	10.07		14.62	14.62	4.55	31.1%	2.14	
Honduras	Medium	0.6	1	1.48	7.32	6.82	7.31	5.83	79.8%	4.63	1.88
Hungary	Medium		0	6.06	10.63	13.20	10.63	4.57	43.0%	2.82	
India	Medium	19.7	4	2.34	9.42	9.03	9.40	7.06	75.1%	5.51	46.39
Indonesia	Medium	7.3	3	2.51	8.08	7.84	8.07	5.56	68.9%	4.23	12.30
Italy	Medium		21	9.24	13.17	14.54	13.46	4.22	31.3%	1.99	
Kenya	Medium	2.7	0	1.52	7.83		7.83	6.31	80.6%	5.02	8.91
Mexico	Medium	20.7	3	3.17	9.65	14.44	9.80	6.63	67.7%	5.02	32.75
Paraguay	Medium	1.6	0	2.67	6.00	7.11	6.00	3.33	55.5%	2.34	1.42
Philippines	Medium	6.9	0	2.63	6.60	7.73	6.60	3.97	60.2%	2.88	7.56
Poland	Medium	1.7	1	6.09	10.81	10.92	10.81	4.72	43.7%	2.94	0.82
Portugal	Medium	0.7	63	6.44	16.54	13.87	14.86	8.42	56.7%	5.97	0.65
Romania	Medium	8.5	2	3.09	10.13	9.11	10.11	7.02	69.4%	5.35	14.72
Russian Federation	Medium	4.6	36	3.02	5.38		5.38	2.36	43.9%	1.47	2.24

Slovakia	Medium	1.1	6	6.32	11.11	12.95	11.22	4.90	43.7%	3.04	0.53
Thailand	Medium	4.1	0	4.08	7.78	7.35	7.78	3.70	47.6%	2.42	2.43
Turkey	Medium	3.7	24	7.55	11.97	12.73	12.15	4.60	37.9%	2.60	1.27
Ukraine	Medium	15.0	8	4.91	7.82	9.05	7.91	3.00	38.0%	1.70	5.18
Uruguay	Medium	0.4	1	4.34	5.24		5.24	0.90	17.2%	0.03	0.00
Vietnam	Medium	5.0	0	4.13	6.88		6.88	2.75	40.0%	1.61	1.95
Bolivia	Low	0.7	3	2.26	7.32		7.32	5.06	69.1%	3.85	1.19
Guatemala	Low	1.1	0	1.70	6.80	6.88	6.80	5.10	75.0%	3.98	2.57
Malawi	Low	3.0	0	1.99	7.53		7.53	5.54	73.6%	4.30	6.48
Pakistan	Low	3.0	26	2.87	7.87	9.53	8.30	5.43	65.4%	4.06	4.25
Peru	Low	1.6	14	2.89		10.82	10.82	7.93	73.3%	6.14	3.40
Serbia	Low	6.5		4.80	13.46		13.46	8.66	64.3%	6.44	8.72
Tanzania	Low	3.4	1	1.13	7.20		7.20	6.07	84.3%	4.88	14.69
Venezuela	Low	1.7	3	3.68	7.82		7.82	4.14	52.9%	2.85	1.32
Zambia	Low	2.6	0	2.03	5.63	9.06	5.64	3.61	64.0%	2.68	3.43
Global totals (MMT)		741.2									334.98
	High	417.6									
	Medium	300.0									
	Low	23.6									

(Mekonnen and Hoekstra 2011). The closable yield gap is calculated based on the assumption that that yield gap could be reduced to the same percentage amount observed in the USA (16.5%). The production opportunity is defined as the additional maize grain that could be produced at this higher yield value, while maintaining the total harvested area constant at 2010 levels.

These same data are displayed in much richer detail in Figure 1, which compares observed irrigated and rainfed maize yields at breeding trial locations (histograms and green and blue cumulative frequency curves) vs. national average yields during this same period. Vertical lines compare the median yields of each group. The histograms of breeding trial results are scaled according to the number of trials in each group.

As evidenced by the shift in the yield distributions in Figure 1, irrigation is able to drive significantly higher maize yields. In Figure 2, we show the water-limited yield potential for rainfed trials and the much higher potential yield for irrigated trials. Each symbol compares the observed national average maize yield (MT/HA) in a given year (*Y*-axis) vs. the average maize yield in breeding trials for that country in the same year (*X*-axis), with the chart on the left based on rainfed breeding trials and the chart on the right based on irrigated breeding trials.

In Figure 3, we further explored the impact of irrigation on maize yields in the USA, where additional data are available from USDA (USDA 2012). The solid lines show USDA-reported

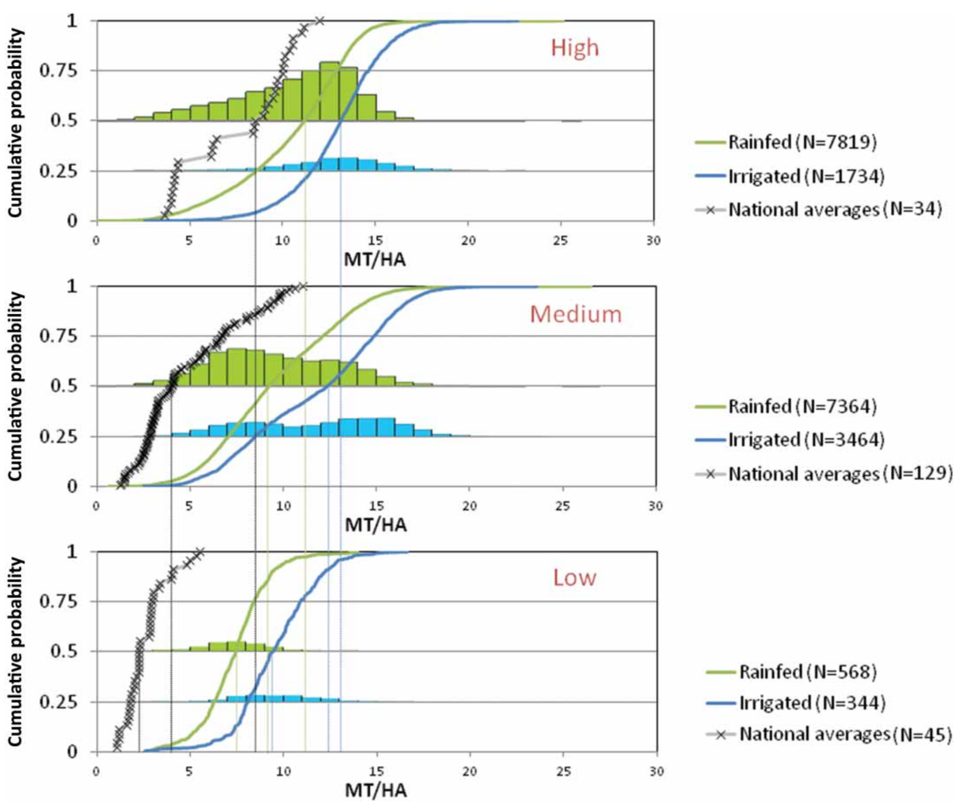

Figure 1. Comparison of observed maize yields (2007–2011) at breeding trial locations (histograms and green and blue cumulative frequency curves) vs. national average yields during the same years. Vertical lines compare the median yields of each group. The histograms of breeding trial results are scaled according to number in each group. The level of agricultural intensification of each country has been categorized using the method presented in this paper. Available in colour online.

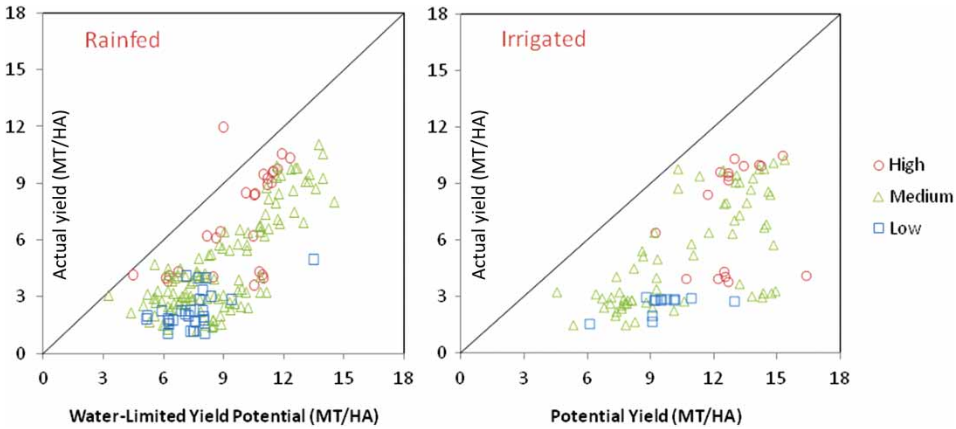

Figure 2. Each symbol compares the observed national average maize yield (MT/HA) in a given year (*Y*-axis) vs. the average maize yield in breeding trials for that country in the same year (*X*-axis), with the chart on the left based on rainfed breeding trials and the chart on the right based on irrigated breeding trials. The level of intensification of each country has been categorized using the method presented in this paper.

average yields (MT/HA) for irrigated maize in four US states: Colorado (CO), Kansas (KS), Nebraska (NE), and Texas (TX). The dashed lines show USDA-reported average rainfed maize yields in those same states. The filled symbols at the right side of the chart show average maize yields for the breeding trials in these four states for the period 2008–2011, as a blue circle (irrigated) and a green circle (rainfed). The box and whiskers symbols to the right of the graph indicate percentile levels of the full distributions of irrigated (blue) and rainfed (green) breeding trial yields for these states and years. It is notable that irrigated maize yields continue to increase in a linear manner, at a greater rate of increase and with less annual variation than the rainfed yields. The difference between farmer average yields and breeding trial yields is larger for rainfed than for irrigated maize.

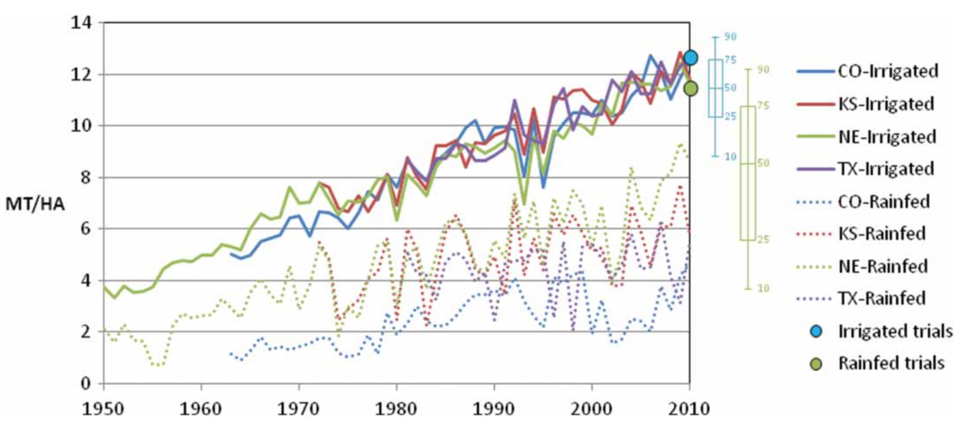

Figure 3. The solid lines show USDA-reported average yields (MT/HA) for irrigated maize in four US states: Colorado (CO), Kansas (KS), Nebraska (NE), and Texas (TX). The dashed lines show USDA-reported average rainfed maize yields in those same states. The filled symbols at the right side of the chart show average maize yields for the breeding trials for all four states for the period 2007–2011, as a blue circle (irrigated) and a green circle (rainfed). The box and whiskers symbols to the right of the graph indicate percentile levels of the full distributions of irrigated (blue) and rainfed (green) breeding trial yields for these states and years. Available in colour online.

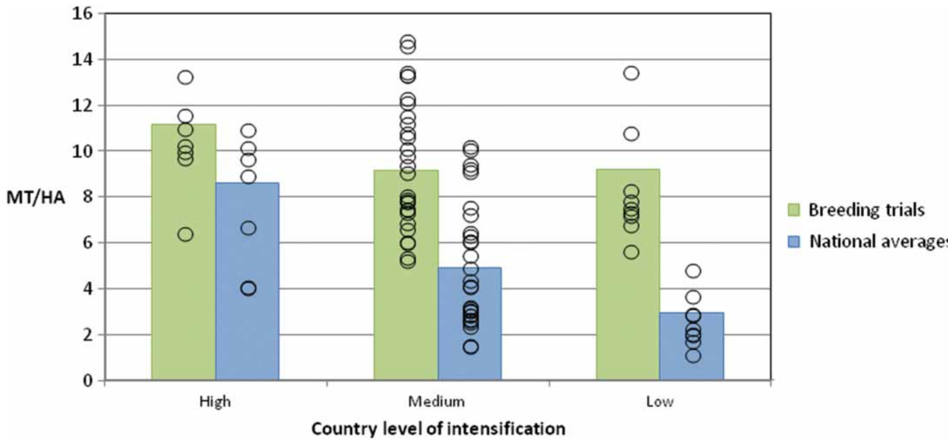

Figure 4. The global maize yield gap. The bars show production-weighted average maize yields (MT/HA) for the period 2007–2011, comparing national average yields to those obtained in breeding trials (with the rainfed and irrigated breeding trial yields weighted by the amount of irrigated maize production in each country). The level of intensification of each country has been categorized using the method presented in this paper. Individual country averages are shown as open circles.

Looking at the global scale, the gap between national average maize yields and yields seen in the breeding trials is large (Figure 4). The bars show production-weighted average maize yields (MT/HA) for the period 2007–2011. As before, the rainfed and irrigated yields have been weighted by the amount of irrigated maize production in each country. The level of intensification of each country has been categorized using the method presented by Context. Individual country averages are shown as open circles. The yield gap is largest for the low-intensification countries. This is hardly surprising based on previous literature, but (unlike previous work) we demonstrate through real experimental data that maize yields of the indicated level are achievable in properly managed fields. The effect of level of intensification on the size of the closable yield gap is of very high statistical significance by both the Student's *t*-test (*p* .0001) and the Tukey Kramer HSD (*p* .0004).These same data are presented in a map form in Figure 5, where the maize-growing regions within each country are coloured according to the size of the maize yield gap in that nation.

Discussion

Based on the values shown in Table 2, the seven high-intensification countries produced 417.6 millions metric tons (MMT) of maize grain in 2010, and had a production-weighted average yield of 8.62 MT/HA, 23% less than the average yield seen in breeding trials in those same countries. The 28 medium-intensification countries produced 300.0 MMT of maize in 2010, and had an average yield of 4.91 MT/HA, 46% less than seen in those nations' breeding trials. The nine low-intensification countries produced 23.6 MMT of maize in 2010, and yielded 2.93 MT/HA, 68% less than in breeding trials. If all of these maize production countries were able to shrink their yield gap to the closable value of 16.5% (the level now seen in the USA), an additional 335 MMT of maize grain would be produced (holding maize harvest area constant). This represents a 45% increase over the 741 MMT produced by these countries in 2010. These data demonstrate that a major untapped maize yield opportunity exists, especially in those countries where intensification has not kept pace with the rest of the world.

As noted earlier in this paper, climate change represents a major challenge to meet current and future growing global demand for all crops, including maize. The results presented here

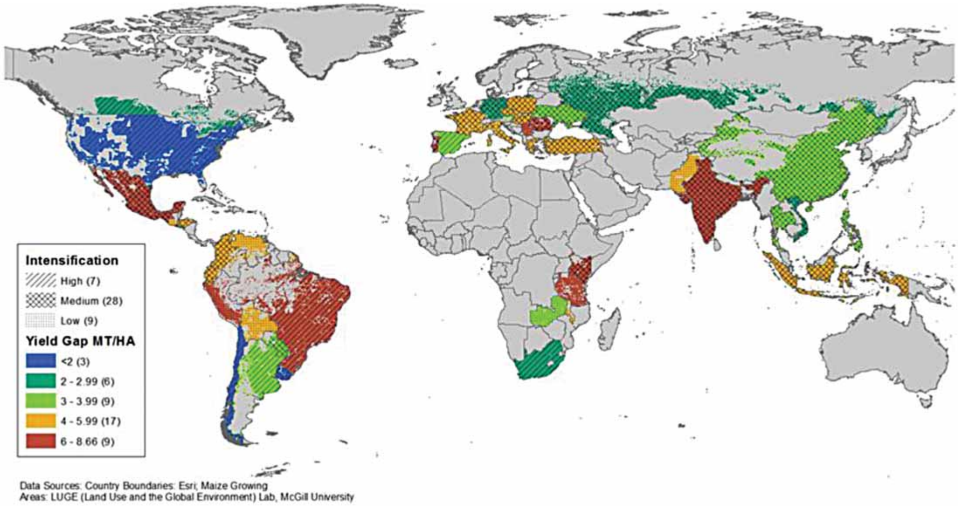

Figure 5. Mapping the global maize yield gap. The maize-growing regions within each country are coloured according to the size of the maize yield gap in that nation, defined as the difference between national average yields and the average yields obtained in breeding trials for that country (with the rainfed and irrigated breeding trial yields weighted by the amount of irrigated maize production in each country). The level of intensification of each country is indicated by cross-hatching and has been categorized using the method presented in this paper. The numbers in parentheses are the number of countries in each category. Available in colour online.

demonstrate that one adaptation strategy for meeting that challenge would be for medium- and low-intensification countries to adopt the practices that are being so successfully deployed in high-intensification countries, where national average maize yields continue to increase and yield gaps are relatively small. Although it is not the subject of this paper to describe specific adaptive actions that could be taken in these countries, the practices listed in Table 1 would be a place to start. Similarly, there has been no attempt to link specific causes for the size of the yield gap in any particular country or region, but we nevertheless feel that our work provides a useful estimate for the size of the global yield gap. Ongoing climate change and economic pressures will restrict the availability of irrigation water and access to inputs in the poorer, drier parts of the world. We therefore recommend the use of integrated modelling – combining climate, crop, and economic models – to help determine what particular actions would be most cost-effective in order to close the global maize yield gap.

Acknowledgements

We acknowledge the support of our various host organizations, and especially the positive attitude of our management towards this productive form of public–private collaboration. We also express appreciation for the very helpful and constructive reviewer comments on the original version of this manuscript.

References

AgTrials – The Global Agricultural Trial Repository. 2012. Available from: http://www.agtrials.org [Accessed 3 September 2013].

Bebber, D.P., Ramotowski, M.A.T., and Gurr, S.J., 2013. Crop pests and pathogens move polewards in a warming world. *Nature climate change*, 3, 985–988.

Beddington, J.R., *et al.*, 2012a. The role for scientists in tackling food insecurity and climate change. *Agriculture and food security*, 1, 10–18.

Beddington, J.R., *et al.*, 2012b. What next for agriculture after Durban? *Science*, 335 (6066), 289–290.
Boyd-Orr, J., 1950. The food problem. *Scientific American*, 183(1), 43–47.
Cassman, K.G., 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. *Proceedings of the national academy sciences*, 96 (11), 5952–5959.
Castleberry, R.M., Crum, C.W., and Crull, C.F., 1984. Genetic yield improvement of US maize cultivars under varying fertility and climatic environments. *Crop science*, 24(1), 33–36.
Cline, S.A. and Zhu, T., 2008. *International model for policy analysis of agricultural commodities and trade (IMPACT): Model description* [online]. Washington, DC: International Food Policy Research Institute. Available from: http://www.ifpri.org/themes/impact/impactwater.pdf [Accessed 3 September 2013].
Context. 2012. *Global crop production systems and technology: an assessment of top producing countries in corn, cotton, soybeans and canola* [online]. West Des Moines, IA: The Context Network, 46. Available from: http://www.contextnet.com/120420 Global Crop Production Systems.pdf [Accessed 1 September 2013].
Diffenbaugh, N.S., *et al.*, 2012. Response of corn markets to climate volatility and alternative energy futures. *Nature climate change*, 2, 514–518.
Duvick, D.N., 2005. The contribution of breeding to yield advances in maize. *Advances in agronomy*, 86 (1), 83–145.
Dwivedi, S., *et al.*, 2013. Food, nutrition and agrobiodiversity under global climate change. *Advances in agronomy*, 120, 1–128.
Easterling, W., *et al.*, 2007. Food, fibre and forest products, *In*: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, and C.E. Hanson, eds. *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press, 273–313.
Edgerton, M., *et al.*, 2012. Transgenic insect resistance traits increase corn yield and yield stability. *Nature biotechnology*, 30, 493–496.
Ehrlich, P.R. and Ehrlich, A.H., 2013. Can a collapse of global civilization be avoided? *Proceedings of the royal society B*, 280, 1–9.
Ewert, F., *et al.*, 2005. Future scenarios of European agricultural land use I. Estimating changes in crop productivity. *Agriculture, ecosystems and environment*, 107, 101–116.
Foley, J.A., *et al.*, 2011. Solutions for a cultivated planet. *Nature*, 478, 337–342.
Foresight. The Future of Food and Farming. 2011. *Final project report*. London: The Government Office for Science.
Garnett, T., *et al.*, 2013. Sustainable intensification in agriculture: premises and policies. *Science*, 341, 31–34.
Gustafson, D.I., *et al.*, 2013. Climate adaptation imperatives: global sustainability trends and eco-efficiency metrics in four major crops: canola, cotton, maize, and soybeans. *International journal of agricultural sustainability*. Available from: http://dx.doi.org/10.1080/14735903.2013.846017 [Accessed 3 December 2013].
Hiederer, R. and Köchy, M., 2011. *Global soil organic carbon estimates and the harmonized world soil database*, EUR 25225 EN. Publications Office of the European Union, 79.
Hunt, L.A., *et al.*, 2006. *ICASA Version 1.0 data standards for agricultural research and decision support* [online]. International Consortium for Agricultural System Applications, Honolulu, HI. Available from: http://dssat.net/data/standards [Accessed 25 July 2012].
Hyman, G., Hodson, D., and Jones, P., 2013. Spatial analysis to support geographic targeting of genotypes to environments. *Frontiers in physiology*, 4 (40), 1–13.
Iizumi, T., *et al.*, 2013. Prediction of seasonal climate-induced variations in global food production. *Nature climate change*, 3, 904–908.
Johnston, M., *et al.*, 2011. Closing the gap: global potential for increasing biofuel production through agricultural intensification. *Environmental research letters* 6, 034028 (11 pp).
Krausman, F., *et al.*, 2013. Global human appropriation of net primary production doubled in the 20th century. *Proceedings of the national academy sciences*, 110 (25), 10324–10329.
Lauer, J.G., *et al.*, 2012. The scientific grand challenges of the 21st century for the Crop Science Society of America. *Crop science*, 52, 1003–1010.
Licker, R., *et al.*, 2010. Mind the gap: how do climate and agricultural management explain the 'yield gap' of croplands around the world? *Global ecology and biogeography*, 19 (6), 769–782.
Liu, H.L., *et al.*, 2010. Using the DSSAT-CERES-maize model to simulate crop yield and nitrogen cycling in fields under long-term continuous maize production. *Nutrient cycling in agroecosystems*, 89 (3), 313–328.

Liu, X., *et al.*, 2011. Yield gaps, indigenous nutrient supply, and nutrient use efficiency of wheat in China. *Agronomy journal*, 103, 1452–1463.

Lobell, D.B., *et al.*, 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science*, 319, 607–610.

Lobell, D.B., Cassman, K.G., and Field, C.B., 2009. Crop yield gaps: their importance, magnitudes, and causes. *Annual review of environment and resources*, 34(1), 179–204.

Lobell, D.B., Schlenker, W., and Costa-Roberts, J., 2011. Climate trends and global crop production since 1980. *Science*, 333, 616–620.

Mekonnen, M.M. and Hoekstra, A.Y., 2011. *National water footprint accounts: the green, blue and grey water footprint of production and consumption*. Value of Water Research Report Series No. 50, UNESCO-IHE, Delft, the Netherlands.

Monfreda, C., Ramankutty, N., and Foley, J.A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global biogeochemical cycles*, 22, GB1022, doi:10.1029/2007GB002947.

Mueller, N.D., *et al*., 2012a. *Low carbon intensity corn ethanol: new pathways based on sustainable stover utilization* [online]. Tacoma, WA: LCA XII. Available from: http://lcacenter.org/lcaxii/final-presentations/656.pdf [Accessed 3 September 2013].

Mueller, N.D., *et al.*, 2012b. Closing yield gaps through nutrient and water management. *Nature*, 490, 254–257.

Nelson, G.C., *et al.*, 2009. *Climate change: impact on agriculture and costs of adaptation*. Washington, DC: Food Policy Report. International Food Policy Research Institute.

Nelson, G.C., *et al.*, 2010. *Food security, farming, and climate change to 2050: scenarios, results, policy options*. Washington: IFPRI Research Monograph, IFPRI, doi: 10.2499/9780896291867.

Neumann, K., *et al.*, 2010. The yield gap of global grain production: a spatial analysis. *Agricultural systems*, 103, 316–326.

Nin-Pratt, A., *et al.*, 2011. *Yield gaps and potential agricultural growth in west and central Africa*. Washington: IFPRI Research Monograph, IFPRI.

Nolan, E. and Santos, P., 2012. The contribution of genetic modification to changes in corn yield in the United States. *American journal of agricultural economics*, 94, 1171–1188.

Paasche, C., 2012. The many many uses for corn, *Fortune Magazine*, 3 Sep, p. 15.

Parry, M., *et al.*, 2009. *Climate change and hunger: responding to the challenge*. Rome: World Food Program.

Ramankutty, N., *et al.*, 2002. The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. *Global ecology and biogeography*, 11 (5), 377–392.

Ramirez-Villegas, J., and Challinor, A., 2012. Assessing relevant climate data for agricultural applications. *Agricultural and forest meteorology*, 161, 26–45.

Ray, D.K., *et al*., 2013. Yield trends are insufficient to double global crop production by 2050. *PLoS one*, 8 (6), 1–8.

Richardson, A.E., *et al.*, 2011. Plant and microbial strategies to improve the phosphorus efficiency of agriculture. *Plant soil*, 349, 121–156.

Shrestha, R., *et al.*, 2012. Bridging the phenotypic and genetic data useful for integrated breeding through a data annotation using the crop ontology developed by the crop communities of practice. *Frontiers in physiology*, 3, 326, doi: 10.3389/fphys.2012.00326.

Stoorvogel, J. 2012. *S-World: towards a global soil property map*. Presented at the *CIMSANS round-table on opportunities for new public–private collaborations on the science of integrated modeling,* Rome, 9 October. Available from: https://www.ilsiextra.org/rf/CIMSANS/SitePages/Home.aspx

Taheripour, F., *et al.*, 2009. *Introducing liquid biofuels into the GTAP Data Base* [online]. GTAP Research Memorandum No. 11. Available from: https://www.gtap.agecon.purdue.edu/resources/download/3939.pdf [Accessed 14 January 2012].

The Agricultural Model Intercomparison and Improvement Project (AgMIP), 2012. Available from: http://www.agmip.org [Accessed 1 September 2013].

Thornton, P.K., *et al.*, 2010. Adapting to climate change: agricultural system and household impacts in East Africa. *Agricultural systems* 103, 73–82.

Tilman, D., *et al.*, 2011. Global food demand and the sustainable intensification of agriculture. *Proceedings of the national academy sciences*, 108, 20260–20264.

Tomlinson, I. 2013. Doubling food production to feed the 9 billion: a critical perspective on a key discourse of food security in the UK. *Journal of rural studies*, 29, 81–90.

UNSCN, 2010. *Climate Change and Nutrition Security. The United Nations System Standing Committee on Nutrition (UNSCN)*. Geneva: UNSCN.

USDA NASS Irrigated and Rainfed CropYields, 2012. Available from: http://www.nass.usda.gov [Accessed 3 September 2013].
USDA-PSD Database, 2012. Available from: http://www.fas.usda.gov/psdonline/psdDownload.aspx [Accessed 3 September 2013].
USDA/NRCS, 2012. *Soil survey staff, Natural Resources Conservation Service, United States Department of Agriculture*. Soil Survey Geographic (SSURGO) Database. Available from: http://soildatamart.nrcs.usda.gov [Accessed March 1, 2012].
Vermeulen, S.J., Campbell, B.M., and Ingram, J.S.I., 2012. Climate change and food systems. *Annual reviews of environmental resources*, 37, 195–222.
Villalobos, C., 2012. Using JSON & Riak for AgMIP. Available from: http://research.agmip.org/download/attachments/1212592/using_json_and_riak.pdf?version=1&modificationDate=1339620113767 [Accessed 25 July 2012].
Waddington, S.R., *et al.*, 2010. Getting the focus right: production constraints for six major food crops in Asian and African farming systems, *Food security*, 2, 27–48.
Wani, S.P., *et al.*, 2012. *Bhoochetana: Mission to boost productivity of rainfed agriculture through science-led interventions in Karnataka*. International Crops Research Institute for the Semi-Arid Tropics. Patancheru 502 324, Andhra Pradesh, India, ISBN 978-92-9066-548-9. BOE 058. 84.
van Wart, J., *et al.*, 2013. Use of agro-climatic zones to upscale simulated crop yield potential. *Field crops research*, 143, 44–55.
Wik, *et al.*, 2008. *Global agricultural performance: past trends and future prospects.* Background Paper for the World Development Report 2008, World Bank, Washington, DC.

Appendix. Description of private-sector data set

Maize breeding trial data set. Irrigated and rainfed maize yield potentials were determined for each country by calculating average annual maize yields for the period 2007–2011 from a large, private-sector maize breeding trial data set. Representative maize breeding trial data from this data set have been posted to the AgTrials database maintained by CIAT (AgTrials 2012) and a database maintained by the University of Florida on behalf of AgMIP (AgMIP 2012). The data reported for each trial are the average observed maize yields for all varieties included in the trial. All of the field trial sites were well managed, and therefore represent experimental potential yields that could have been attained by commercial growers in that region, if they had used similar inputs. This Appendix provides details on how the location for each trial was posted, how soils data were provided for US trial sites, and the identification of nearby weather stations (for use by crop modellers and others). The private-sector source of the data is disclosed within the publicly available databases.

Location data. For breeding yield trials, the term location refers to one or more fields located within driving distance of a breeding station. The specific field or part of the field planted may vary from year to year as crops are rotated.

Locations of research breeding trials and commercial strip plots were posted as the latitude and longitude of the nearest grid centroid to the true trial location. A 5 min by 5 min raster grid (approximately 10 km by 10 km) of the globe was developed to represent trial locations. The global grid is based on the same origin as grids used in similar global agricultural modelling efforts (Ramankutty *et al.* 2002, Monfreda *et al.* 2008). The posted field trial coordinates are the latitude and longitude, in decimal degrees, of the 5 min by 5 min grid centroid of the grid cell that the field trial is located.

There are cases when the true field location was unavailable in the breeding trial database. In these cases an effort was made to match the administrative unit name recorded in the breeding trial database to a country-based administrative data set to determine a location. In cases where there was a match, the coordinate for the trial is posted based on the 5 min by 5 min grid centroid of the grid cell that the administrative boundary centroid is located. These trials have been flagged in the Location Source attribute of the trial record. Additionally, the area in square kilometres of the administrative unit in which the location is based upon is provided in the Administrative Area attribute of the trial record, where applicable.

For both research breeding trials and commercial strip plots, yield values are averaged across all hybrids and replicates at the location to derive a yield Test Mean, which is the value reported in the database.

Soils data. The soil texture at the trial location is reported and uploaded to the CIAT and AgMIP databases. In many cases the soil information is a single texture and is assumed to be the surface layer. In some cases no soil information is provided at all. If more detailed soil data are necessary, they can be derived from other sources. S-World, a global digital soils database is being developed for use in crop growth simulation models and AgMIP, in particular (Stoorvogel 2012). This database pulls from many best-available digital soils databases and incorporates elevation, climate, and land cover data to enhance the data. Once completed, this database will be a prime resource for digital soils data and can be used in conjunction with the breeding trial data such as these for agricultural modelling. While the S-World database is being compiled using many of the 'best-available' soils databases, there are no current plans to incorporate the Soil Survey Geographic (SSURGO) Database (USDA/NRCS 2012), with digital coverage of soils in the USA. For this reason, SSURGO data were extracted for trial locations within the USA. The true latitude and longitude recorded in the breeding trial data set were used to extract the SSURGO map unit and associated soil profiles attributes relevant to agricultural modelling. For each trial, the soil profile for the component with the same soil texture, as recorded in the breeding trial data set, was extracted. If there were two components with a matching soil texture, the profile of the component with the highest component percent in SSURGO was extracted. If there were no matching soil textures for the map unit components, the profile of the primary component, or highest component percent, was extracted. See Table A1 for a listing of SSURGO attributes extracted.

Table A1. Soil attributes extracted from ssurgo for posting with the breeding trial data set.

Breeding trial attribute	SSURGO table	SSURGO attribute	SSURGO label
SOIL_ID	Component	Cokey	Component key
SOIL_NAME	Component	Compname	Component name
CLASSIFCATION	Component	Taxclname	Taxonomic class
SOIL_ELEV	Component	elev_r	Elevation – representative value
SLOPE_PCT	Component	slope_r	Slope gradient – representative value
SALB	Component	albedodry_r	Albedo dry – representative value
DRAINAGE	Component	Drainagecl	Drainage class
SLMH	Chorizon	Hzname	Designation
SLBDM	Chorizon	Partdensity	Dp
SLCLY	Chorizon	claytotal_r	Total clay – representative value
SLSND	Chorizon	sandtotal_r	Total sand – representative value
SLSIL	Chorizon	silttotal_r	Total silt – Representative value
SLCF	Chorizon	Coarse fraction = 100*((100– 'sieveno10_r')/(100 + ('fraggt10_r' + 'frag3to10_r')))	#10 – Representative value, rock >10 – representative value, and Rock 3–10 – representative value
SKSAT	Chorizon	ksat_r	Ksat – Representative value
SLOC	Chorizon	om_r	OM – Representative value
SLPHW	Chorizon	ph1to1h2o_r	pH H_2O – Representative value
SLLT	Chorizon	hzdept_r	Top depth – Representative value
SLLB	Chorizon	hzdepb_r	Bottom depth – Representative value
SLFC1	Chorizon	wthirdbar_r	0.33 bar H_2O – Representative value
SLFC2	Chorizon	wtenthbar_r	0.1 bar H_2O – Representative Value
SLWP	Chorizon	wfifteenbar_r	15 bar H_2O – Representative Value

Weather data. In order to facilitate the assignment of appropriate weather data to a particular location, the true latitude and longitude recorded in the breeding trial data set were used to extract the nearest three weather station identifiers from the Global Summary of the Day (GSOD) and Global Historic Climatology Network (GHCN) databases, both maintained by the National Climate Data Center (NCDC). These identifiers can be used to search and download weather data observations from the GSOD and GHCN databases. There may be cases where weather data are missing at the nearest weather station for some portions of the breeding trial growing season. In these cases, the weather observation records from the other two stations can be extracted. Distance ranges, in kilometres, for trial locations to weather stations have also been posted.

AgMIP database. The Agricultural Model Improvement and Intercomparison Project (AgMIP; www.agmip.org) is a distributed modelling effort that seeks to improve the capability of models to characterize the effects of climate change on agricultural production. AgMIP has adopted the ICASA data standards (Hunt *et al*. 2006), as a means of harmonizing the data used by the numerous participating crop modelling groups around the world. The AgMIP Crop Experiment (ACE) database contains data from detailed field experiments as well as the less detailed data collected in variety trials by international agricultural research centres, universities, and the private sector. Because the quality and content of the data do not easily fit a rigid schema, a less-structured, non-relational architecture was selected (Hyman *et al*. 2013). The ACE database uses a Riak platform (wiki.basho.com/), which is an open source, key-value system designed to be deployed in a clustered fashion where data are distributed across multiple nodes. For ACE, data are divided into buckets of information, representing individual experiments, each of which is assigned a unique key. A separate metadata table stores and indexes a searchable subset of the experiment data, enabling fast queries within a large database. Since information from a given experiment is stored in a single bucket, rather than multiple tables as in a relational database, fast retrieval times for large amounts of data are possible. Data are imported and stored in ACE using JSON (JavaScript Object Notation, www.json.org) structures.

AgTrials database. AgTrials (http://www.agtrials.org) is an online database and file repository of cultivar trials and other agricultural technology evaluations. The initiative aims to standardize trial data from multiple sources for studies of the effects of genotype by environment interactions and climate change on crop production. One aim of the project is to link time- and location-specific environmental data to its corresponding trial data. The information resource can subsequently be used to support geographic targeting of genotypes to their environmental niches (Shrestha *et al*. 2012). Cultivar names are standardized by a validation process requiring names to be checked against existing variety names. Traits and variables measured in the trials are standardized using crop-specific ontologies (Villalobos 2012). The online information resource includes utilities for file storage and batch upload of trial data. Users and producers of information can characterize trial sites, link weather and soil data to trials and navigate trial sites using a spatial data viewer.