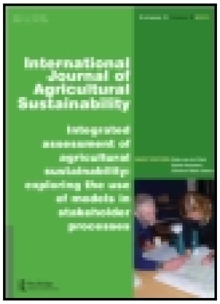

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Climate adaptation imperatives: global sustainability trends and eco-efficiency metrics in four major crops – canola, cotton, maize, and soybeans

David I. Gustafson[a], Michael Collins[b], Jonna Fry[b], Saori Smith[b], Marty Matlock[c], David Zilberman[d], Jereme Shryock[e], Michael Doane[e] & Nathan Ramsey[f]

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

[b] Environmental Resources Management (ERM), 33 St. Mary Axe, London, EC3A 8AA, UK

[c] Biological and Agricultural Engineering, College of Engineering, University of Arkansas, 233 Engineering Hall, Fayetteville, AR 72701, USA

[d] Department of Agricultural and Resource Economics, University of California, 207 Giannini Hall, Berkeley, CA 94720, USA

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

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

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Climate adaptation imperatives: global sustainability trends and eco-efficiency metrics in four major crops – canola, cotton, maize, and soybeans

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[a]*International Life Sciences Institute Research Foundation, Center for Integrated Modeling of Sustainable Agriculture & Nutrition Security (CIMSANS), 1156 15th St NW, Suite 200, Washington, DC 20005, USA;* [b]*Environmental Resources Management (ERM), 33 St. Mary Axe, London, EC3A 8AA, UK;* [c]*Biological and Agricultural Engineering, College of Engineering, University of Arkansas, 233 Engineering Hall, Fayetteville, AR 72701, USA;* [d]*Department of Agricultural and Resource Economics, University of California, 207 Giannini Hall, Berkeley, CA 94720, USA;* [e]*Monsanto Company, 800 N. Lindbergh Blvd, St. Louis, MO 63167, USA;* [f]*The Context Network, 4401 Westtown Parkway, Suite 214, West Des Moines, IA 50266, USA*

Supplying our world's growing nutrition needs in more sustainable ways has become an urgent global imperative, given the constraints of finite resources and the challenges of accelerating climate change. We present national-level eco-efficiency metrics in several representative production countries during the most recent decade (2000–2010) for four important crops: canola, cotton, maize, and soybeans. The metrics address greenhouse gas emissions and the utilization of land, water, and energy – all calculated per unit of production. We group countries based on their level of agricultural intensification and find that high-intensification countries are achieving the highest and yet still increasing levels of eco-efficiency, with these decadal gains: canola (26%), cotton (23%), maize (17%), and soybeans (18%). By stark contrast, low-intensification countries had no change in eco-efficiency during this same decade. Overall, our results suggest large opportunities for additional improvements in the developing world, and that cumulative resource savings through intensification have been significant. For instance, in the case of irrigated maize, if the high- and medium-intensification production countries had only achieved the same irrigation water-use efficiency as in the low-intensification countries, approximately 4 quadrillion (4×10^{15}) more litres of irrigation water would have been consumed during the period 2000–2010.

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

Introduction

We find ourselves in a race to prove Malthus wrong – that we can meet the resource demands of exponential growth and through our common prosperity bring population into equilibrium with our resources, without the predicted plagues of famine, disease, and war over control of the dwindling inputs required to feed ourselves. To meet the demand expectations for food, feed, and fibre production from a growing global population in the twenty-first century, significant increases in agricultural productivity will be required (Boyd-Orr 1950, Tilman *et al.* 2011). Climate change will greatly exacerbate the scale and scope of this challenge (Smith *et al.* 2007, Lobell *et al.* 2008, 2011, Wik *et al.* 2008, Beddington *et al.* 2012). Adoption of the

*Corresponding author. Email: dgustafson@ilsi.org

best-available production practices and new technology will be critical for the agricultural industry around the world to deliver on this increase in productivity in a sustainable manner (Cassman 1999, Richardson *et al.* 2011). In recent years, several prominent global organizations have highlighted the magnitude of the challenge facing the world's agricultural industry to meet the nutritional demands for a growing population in the next 30–50 years (Field to Market 2009, 2012, *Foresight. The future of food and farming* 2011). Meeting this demand sustainably will require increased productivity from the finite natural resources that exist around the world while balancing demands for environmental protection and social benefit (Waddington *et al.* 2010, Beddington *et al.* 2012). 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 halting agricultural expansion, closing yield gaps on underperforming lands, increasing cropping efficiency, shifting diets, and reducing waste.

Fortunately, there are now signs that agricultural production can be intensified in a sustainable manner (Castleberry *et al.* 1984, Duvick 2005, Edgerton *et al.* 2012, Nolan and Santos 2012, Wani *et al.* 2012). Some of these references include the advances that have come through the adoption of systems based on the application of agricultural biotechnology, the sustainability of which has attracted some public debate (Edgerton *et al.* 2012). This current paper does not focus on the sustainability of agricultural biotechnology itself. Instead, we present national-level eco-efficiency metrics in several relevant and representative production countries during the most recent decade (2000–2010) for four important crops: canola, cotton, maize, and soybeans.

The World Business Council for Sustainable Development (WBCSD) has defined eco-efficiency as a:

> management philosophy and the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earth's estimated carrying capacity. In short, it is concerned with creating more value with less impact. (WBCSD 2000)

This objective, when applied here, is to achieve increased value from lower inputs of materials and energy and with reduced emissions, which are expressed in this paper via particular eco-efficiency metrics. These metrics, each based on accepted methods of Life Cycle Analysis, address greenhouse gas (GHG) emissions and the utilization of land, water, and energy – all calculated per unit of production. We group the national-level metrics based on the level of agricultural intensification currently practiced in the countries of production. The level of intensification of each country was categorized based on a method presented by Context (2012). The Context method represents a broad initial effort to better quantify the level of sophistication and technology adoption in the crop production environment for top field crops in all significant production countries around the world.

Materials and methods

The following ecological indicators were considered:

- land use (m^2),
- irrigation water consumption (m^3),
- energy consumption (MJ) and,
- climate change (GHG emissions, kg CO_2e).

Table 1. Key data requirements for the eco-efficiency assessment.

Data	Example unit	Indicator to which it applies
Crop yield	kg per hectare	All
Total agricultural land area	Hectares	All
Total area harvested for crop	Hectares	All
Seed consumption	kg seeds per hectare	Energy, climate change
N fertilizer consumption	kg (as N) per hectare	Energy, climate change
P fertilizer consumption	kg (as P_2O_5) per hectare	Energy, climate change
K fertilizer consumption	kg (as K_2O)per hectare	Energy, climate change
Organic fertilizer consumption (manure)	kg per hectare	Climate change
N_2O emissions	kg N_2O per hectare	Climate change
Pesticide use	kg a.i. per hectare	Energy, climate change
Irrigation water use	m^3 per hectare	Irrigation water consumption
Fuel consumption	litres per hectare	Energy, climate change
Electricity use	kWh per hectare	Energy, climate change
GHG dLUC emissions	kg CO_2 per hectare	Climate change

Soil loss was also initially considered; however, this was excluded due to lack of available data for the countries assessed. With this exception, these indicators are the same as those assessed in the Field to Market reports (Field to Market 2009, 2012), which document eco-efficiency trends for crop production systems in the USA. The results were presented across a timeline on a per unit of production basis, showing the indicator (use or impact) against production achieved (e.g. kg CO_2e per kg maize grain). The measures show changes in the use or impact over time relative to the ability to meet productivity demands, normalized to a common unit of comparison (per kg of the harvested raw agricultural commodity).

Annual statistics were sought, from national and international agencies, on production of the crops and for the countries assessed. The data identified varied considerably from crop to crop and from country to country. To enable consistency in the calculations between different countries, simplified approaches had to be adopted for some indicators (e.g. the tillage method was not accounted for due to lack of data for a number of countries).

Listed in Table 1 are the details of the key data requirements that were available for most of the countries assessed and which were identified as being the most significant, or sole, drivers for the eco-efficiency indicators.

Land use

The change over time in the land required per unit of production (i.e. the inverse of yield) for each crop is a measure of agricultural efficiency which provides a more immediate representation of demand for an increasingly constrained resource.

Due to the lack of consistent statistics for *planted* area for the countries and crops appraised, *harvested* area has been used instead. This is a limitation and introduces some uncertainty with regard to the efficiency of land use (crops lost due to drought, etc.).

Irrigation water consumption

Water consumption and scarcity have become a local environmental issue of international concern. Demands on water are many and without an adequate and timely supply of water, crop yield, and agricultural efficiency are affected. For water consumption, we have calculated irrigated water use. Indirect water use associated with other parts of the supply chain have not been calculated or reported.

Energy use

The energy indicator analysis is an assessment of change over time in the energy use for the production of different crops. The time series can express efficiency drives within farming aiming at reducing fuel and electricity use, and can also be an indicator for industrialization of crop production.

Both direct energy use (electricity and fuel consumption on farm) and indirect energy use (energy resources consumed in the production of fuels, agro-chemicals and electricity) were considered. Data for direct energy use by crop were not identified. Instead, national statistics for energy use in agriculture as a whole were used, assuming no variability in energy use by the different crops produced. This demonstrates a significant limitation in the data for the application to a study of this nature and a degree of uncertainty is, therefore, associated with the results calculated.

Climate change (GHG)

GHG emissions are an indicator for climate change impacts over time for the production of crops. Climate change affects agricultural production through the changes in temperature and weather patterns impacting on yield and crop quality. However, agriculture itself contributes to anthropogenic GHG emissions. In 2005, direct emissions were reported as 5.1–6.1 GtCO2-eq/yr (Smith *et al*. 2006; IPCC 2006). We estimated GHG emissions associated with direct land-use change (dLUC), but have not reported them here. Those results are available from the authors by direct request. When land-use change (LUC) is considered, the loss of soil and above ground carbon, through conversion to- and from- agriculture, has been demonstrated to dramatically increase the emissions attributed to agriculture (IFEU 2007, FAOSTAT 2012).

The PAS 2050 method (2011) for GHG emissions assessment was used to define cradle to field gate, and the characterization of GHG emissions into CO_2 equivalents. Cradle to field gate captures agrochemical, fuel and electricity production, transport, field activities, and harvesting. Other studies (IFEU 2007, CropLife International 2012, FAOSTAT 2012, Gan *et al.* 2012) have identified dLUC, fertilizer production, fertilizer N_2O emissions from soil, and farm energy use, as being the primary drivers of GHG emissions with fertilizer and LUC being the most critical. For this reason, the research focused on obtaining, or calculating, crop-specific fertilizer consumption and dLUC GHG emissions. The GHG emission calculations do not consider differences in tillage systems, biogenic carbon dioxide emissions, or field burning.

A dLUC calculator tool was created that implemented guidance in the Greenhouse Gas Protocol Product Life Cycle Accounting and Reporting Standard (Greenhouse Gas Protocol, 2012). The calculator applied:

- If the land occupied by a crop constitutes a larger area than the land occupied by that crop 20 years earlier, dLUC must be considered.
- Where crop land has been made available over the 20-year period through the decrease in land used by other crops, this crop land is assumed to be used for the crop being studied and no LUC is assumed to have occurred.
- Where available crop land (another crop has decreased) is not sufficient to meet the need for land by the crop being studied, this need for land is assumed to be met by converting either forest land or grass land to crop land.
- The split between forest land and grass land is based on national land coverage data (source: US Geological Survey (USGS) EarthTrend data (Schmitt *et al*. 2008)).
- The emission factors for land conversion are based on the factors provided in PAS 2050 (2011).

Table 2. Data sources utilized for this study.

Data	Sources
Crop yield	Beer *et al.* (2007), Central Statistical Agency of Ethiopia (2012), Canola Council of Canada (2012), FAOSTAT (2012), NASS (2012), PBS (2012), AOF (2012), and USDA-PSD Database (2012)
Total agricultural land area	Central Statistical Agency of Ethiopia (2012), FAOSTAT (2012), National Bureau of Statistics of China (2012), NASS (2012), PBS (2012), and USDA-PSD Database (2012)
Total area harvested for crop	Central Statistical Agency of Ethiopia (2012), FAOSTAT (2012), NASS (2012), PBS (2012), and USDA-PSD Database (2012)
Seeds	FAOSTAT (2012) and PBS (2012)
N fertilizer	Central Statistical Agency of Ethiopia (2012), FertiStat (2012), IFA (2012), PBS (2012), and Rosas (2012)
P fertilizer	Central Statistical Agency of Ethiopia (2012), FertiStat (2012), IFA (2012), PBS (2012), and Rosas (2012)
K fertilizer	Central Statistical Agency of Ethiopia (2012), IFA (2012), FertiStat (2012), PBS (2012), and Rosas (2012)
Manure	IPCC (2006) and FAOSTAT (2012)
Pesticides	CropLife International (2012), Panichelli *et al.* (2009), and SEEP (2010)
Irrigation water use	Australian Bureau of Statistics (2012), AQUASTAT (2012), SIAP (2012), and USDA (2009)
Diesel	PBS (2012) and UNSD (2012)
Electricity	PBS (2012) and UNSD (2012)

Data sources and data gaps

As described above, annual statistics from national and international agencies were used as the data sources for this project. The reason for using these data sources was that they provide data over time and should ensure some commonality in the data collection method.

The availability of data varied considerably from crop to crop and from country to country. Some, developed, countries had considerable data (in some cases data were more detailed than that were used, e.g. soil loss), while other countries had limited statistical data available.

Although more detailed data were available for some regions, or for specific enterprises for specific crops, simplified approaches were adopted for some indicators in order to enable consistency in the calculation method across the countries and on a national scale.

The data sources are summarized in Table 2 and the following approaches for calculating the indicators were employed:

- Specific data representing the specific crop, country, and year.
- Estimated based on another data point (e.g. data point for previous year and data point for another country in a similar climatic area and with farming at a similar level of intensification).
- Data representing total agricultural production for a specific country and year.
- Theoretical data calculated using documented internationally accepted methods (this was used for calculating manure use, N conversion to N_2O and dLUC emissions).

The importance of fertilizer consumption for the indicators meant that crop-specific consumption statistics was essential for each country. Fertilizer consumption data, by crop, for each country were extracted from research by the Center for Agricultural and Rural Development at Iowa State University (Rosas 2012). The reported annual fertilizer use was either crop-specific data published by the Food and Agriculture Organization of the United Nations (FAO) for the years where crop-specific data were available, or was an estimate based on total fertilizer use by types and crop requirements.

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 primary data from published studies 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.

In order to apply the Context methodology for this report, we developed an aggregate measure of overall intensification for the production of each crop, 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). However, in applying this methodology for canola and soybeans, we found that all countries were ranked as either high or medium, with none in the low category of intensification.

Results

Due to data availability constraints (see Materials and methods) we were not able to include all major production countries for all four of the chosen crops. However, we were able to include representative countries (Table 3) which collectively represent a significant proportion of global production as follows: canola (100%); cotton (76.6%); maize (77.7%); and soybean (90.9%). As indicated in Table 3, the countries included in the analysis also provided good representation of each relevant intensification category (note that no countries were found to belong in the low-intensification category for either canola or soybean). The least represented crop intensification categories were the low-intensification categories for both cotton and maize, which is a consequence of data availability, and the relatively large number of low-production countries in these categories. Nevertheless, we believe that the chosen countries well represent the unselected countries in those categories, and that our overall analysis is, therefore, useful for drawing inferences about the global patterns of production for these crops.

In Table 4, eco-efficiency metrics for land (m^2), irrigation water (m^3), energy (MJ), and GHG (kg CO_2e) – all per unit of crop production (kg) for the period 2000–2010, for all four crops, and for each intensification category – are calculated. The numerator and denominator for land, energy, and GHG's include all crop production (irrigated and non-irrigated), whereas the denominator for irrigation water only includes irrigated crop production in those countries, based on the data reported by Mekonnen and Hoekstra (2011). Several interesting facts emerge from the data in Table 4. Comparing crops, maize has the highest eco-efficiency for land, water, and energy, followed by either canola or soybeans depending on which metric is selected, with cotton having the highest relative inputs (due to its much lower yield, when measured on a kg/m^2 basis). For GHG's, soybeans have the highest efficiency, since they do not generally require the use of nitrogenous fertilizers. Comparing intensification categories, greater eco-efficiencies are generally seen for high-intensification countries, though there are some notable exceptions. For instance, low-intensity maize production is relatively efficient with respect to use of energy

Table 3. Agricultural intensification categories and production levels (2010) for the selected crop production countries.

	Production levels (2010) as a percentage of global production and as a percentage of agricultural intensification class									
Crop	High	Pct of world (%)	Pct of class (%)	Medium	Pct of world (%)	Pct of class (%)	Low	Pct of world (%)	Pct of class (%)	Overall pct of world (%)
Canola	Canada	79.6	92.0	Australia	100	100				
	US	6.9	8.0							
Totals			100			100			n/a	100
Cotton	China	26.5	34.4	Argentina	1.1	8.5	Uzbekistan	3.6	51.0	
	India	22.1	28.7	Pakistan	7.6	58.9				
	US	15.7	20.4							
Totals			83.6			67.4			51.0	76.6
Maize	Argentina	2.7	5.4	China	21.4	55.4	Ethiopia	0.5	11.2	
	Brazil	6.9	13.7	India	2.6	6.7	Nigeria	1.1	22.2	
	South Africa	1.4	2.8	Mexico	2.5	6.4	Tanzania	0.4	9.2	
	US	38.2	75.4							
Totals			97.4			68.5			42.5	77.7
Soybean	Brazil	28.6	44.1	Argentina	18.6	58.0				
	US	34.3	52.9	China	5.7	17.9				
				India	3.7	11.6				
Totals			97.0			87.4			n/a	90.9

Table 4. Eco-efficiency metrics (per unit of production) for countries (Table 2) with varying levels of intensification for canola, cotton, maize, and soybeans.

			Crop production year										
Crop	Resource	Intensification	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Canola	Land	High	5.57	6.26	6.84	5.89	5.17	4.68	4.94	5.58	4.42	4.37	4.61
	m^2/kg	Medium	7.23	7.45	13.69	6.22	7.50	5.67	17.12	9.95	7.51	7.52	6.67
	Water	High	0.59	0.71	0.76	0.58	0.47	0.45	0.46	0.52	0.39	0.38	0.45
	m^3/kg	Medium	0.16	0.16	0.30	0.14	0.16	0.12	0.37	0.22	0.16	0.16	0.15
	Energy	High	3.48	4.07	4.51	4.02	3.66	2.97	3.49	3.91	3.13	2.80	3.72
	MJ/kg	Medium	4.86	5.27	9.04	4.35	6.21	4.05	12.09	5.99	4.57	3.55	4.27
	GHG	High	0.51	0.63	0.71	0.63	0.58	0.45	0.56	0.63	0.50	0.42	0.63
	kg CO_2e/kg	Medium	0.84	0.92	1.59	0.76	1.13	0.72	2.11	1.01	0.79	0.61	0.77
Cotton	Land	High	16.99	15.42	14.90	14.58	12.64	12.76	11.80	11.39	11.79	12.60	12.63
	m^2/kg	Medium	16.65	17.55	16.36	17.81	13.86	14.93	16.15	16.42	16.09	15.42	15.65
		Low	14.88	13.68	14.20	15.70	12.53	11.85	12.27	12.27	14.18	15.31	14.56
	Water	High	4.99	4.64	4.36	4.72	4.71	4.89	3.77	3.56	3.65	4.11	4.33
	m^3/kg	Medium	6.55	6.55	6.55	6.55	6.55	6.55	6.54	6.76	6.55	6.26	6.25
		Low	8.35	8.35	8.35	8.35	8.35	8.35	7.49	7.49	8.66	9.35	8.88
	Energy	High	30.25	28.58	24.02	24.66	23.31	20.94	20.33	20.99	20.29	21.35	24.13
	MJ/kg	Medium	22.31	25.61	20.69	25.45	22.80	22.40	22.68	25.38	22.58	22.06	26.91
		Low	33.51	31.27	28.59	34.57	26.71	23.66	24.82	24.76	31.22	33.03	34.57
	GHG	High	3.82	3.70	2.78	3.29	3.32	2.72	2.73	2.89	2.74	2.78	3.41
	kg CO_2e/kg	Medium	3.74	4.41	3.27	4.16	3.95	3.64	3.62	4.26	3.61	3.52	4.69
		Low	5.13	4.80	4.02	5.14	3.86	3.37	3.50	3.54	4.71	4.84	5.35

Maize	Land	High	1.54	1.51	1.59	1.45	1.30	1.37	1.38	1.31	1.31	1.24	1.26
	m^2/kg	Medium	2.71	2.62	2.53	2.57	2.44	2.34	2.31	2.31	2.16	2.28	2.18
		Low	6.66	5.71	5.37	8.26	7.27	6.61	5.50	6.17	5.69	5.54	5.07
	Water	High	0.18	0.17	0.19	0.17	0.15	0.16	0.16	0.16	0.15	0.15	0.15
	m^3/kg	Medium	0.26	0.27	0.26	0.27	0.26	0.26	0.24	0.25	0.23	0.24	0.23
		Low	2.71	2.25	2.17	2.32	2.38	2.65	2.08	2.30	2.08	1.96	1.78
	Energy	High	1.56	1.46	1.59	1.48	1.34	1.30	1.49	1.38	1.29	1.28	1.22
	MJ/kg	Medium	3.35	3.30	3.29	3.42	3.49	3.03	3.13	3.19	2.95	2.93	2.82
		Low	0.81	0.78	0.77	0.86	0.96	0.77	0.68	0.81	0.84	0.83	0.88
	GHG	High	0.26	0.24	0.27	0.25	0.22	0.23	0.27	0.25	0.23	0.23	0.22
	kg CO_2e/kg	Medium	0.54	0.53	0.54	0.56	0.58	0.50	0.52	0.53	0.49	0.46	0.45
		Low	0.09	0.10	0.08	0.10	0.12	0.10	0.08	0.10	0.12	0.12	0.14
Soybean	Land	High	3.98	3.70	3.88	4.03	3.82	3.84	3.75	3.56	3.66	3.54	3.41
	m^2/kg	Medium	5.97	5.44	5.13	4.87	5.63	4.98	5.05	4.72	4.89	6.38	4.62
	Water	High	1.16	1.11	1.15	1.19	1.03	1.01	1.01	1.02	1.14	0.99	0.98
	m^3/kg	Medium	1.48	1.46	1.47	1.42	1.45	1.42	1.43	1.51	1.38	1.49	1.31
	Energy	High	1.55	1.54	1.50	1.86	1.69	1.58	1.38	1.50	1.47	1.35	1.36
	MJ/kg	Medium	4.30	3.71	3.53	3.47	4.24	3.71	3.78	3.63	3.92	5.06	3.65
	GHG	High	0.11	0.11	0.11	0.14	0.13	0.11	0.10	0.10	0.10	0.09	0.10
	kg CO_2e/kg	Medium	0.43	0.37	0.34	0.35	0.45	0.38	0.38	0.36	0.40	0.50	0.37

Table 5. Eco-efficiency metric trends for canola, cotton, maize, and soybeans for high-intensification countries (based on least-squares regression fits to observed data).

Crop	Metric	Eco-efficiency gain (2000–2010) (%)	P^a	Overall eco-efficiency gain (2000–2010) (%)
Canola	Land	29	0.0043	26
	Water	43	0.0022	
	Energy	19	0.1209	
	GHG	14	0.3661	
Cotton	Land	28	0.0015	23
	Water	22	0.0243	
	Energy	26	0.0112	
	GHG	18	0.1060	
Maize	Land	20	0.0001	17
	Water	18	0.0021	
	Energy	20	0.0018	
	GHG	11	0.1023	
Soybean	Land	12	0.0024	18
	Water	24	0.0002	
	Energy	16	0.0539	
	GHG	19	0.0531	

[a]Significance of linear fits to observed trend (with logarithmic *Y*-axis, as in Figures 1–4).

and GHG emissions, but this comes at the expense of much greater land and irrigation water requirements. Looking across time, most crop categories show improvements in eco-efficiency over the decade, particularly countries with high intensification.

Tables 5–7 investigate these temporal trends in greater detail. In each case, a simple log-linear regression line has been fit to the temporal data for each of the individual eco-efficiency metrics (log (metric) vs. time). The significance of each regression fit is indicated, and then the resulting

Table 6. Eco-efficiency metric trends for canola, cotton, maize, and soybeans for medium intensification countries (based on least-squares regression fits to observed data).

Crop	Metric	Eco-efficiency gain (2000–2010) (%)	P^a	Overall eco-efficiency gain (2000–2010) (%)
Canola	Land	4	0.9163	14
	Water	4	0.9163	
	Energy	24	0.4700	
	GHG	24	0.4569	
Cotton	Land	8	0.2509	0
	Water	3	0.1320	
	Energy	−6	0.5191	
	GHG	−5	0.6920	
Maize	Land	20	0.0001	17
	Water	14	0.0004	
	Energy	16	0.0015	
	GHG	17	0.0051	
Soybean	Land	8	0.3993	0
	Water	5	0.1506	
	Energy	−7	0.5661	
	GHG	−8	0.5302	

Note: Negative values indicate losses in eco-efficiency.
[a]Significance of linear fits to observed trend (with logarithmic *Y*-axis, as in Figures 1–4).

Table 7. Eco-efficiency metric trends for cotton and maize in low-intensification countries (based on least-squares regression fits to observed data).

Crop	Metric	Eco-efficiency gain (2000–2010) (%)	P^a	Overall eco-efficiency gain (2000–2010) (%)
Cotton	Land	2	0.8743	0
	Water	−5	0.4502	
	Energy	1	0.9501	
	GHG	1	0.9480	
Maize	Land	18	0.1705	−1
	Water	23	0.0132	
	Energy	−4	0.6694	
	GHG	−43	0.0194	

Note: Negative values indicate losses in eco-efficiency.
[a]Significance of linear fits to observed trend (with logarithmic *Y*-axis, as in Figures 1–4).

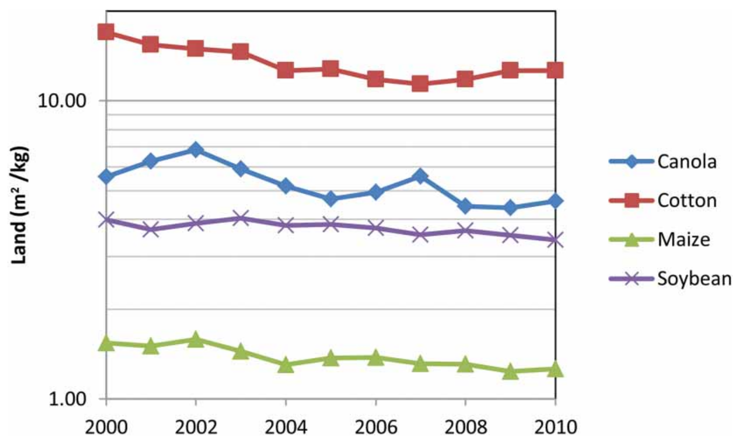

Figure 1. Land-use efficiency trends for canola, cotton, maize, and soybean production in high-intensification countries.

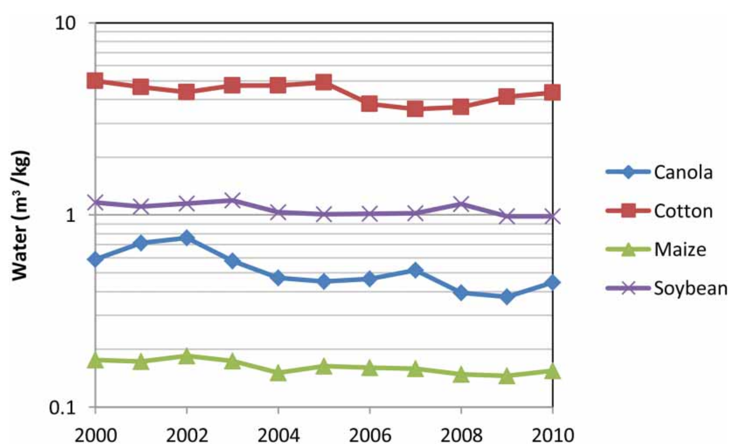

Figure 2. Irrigation water-use efficiency trends for canola, cotton, maize, and soybean production in high-intensification countries.

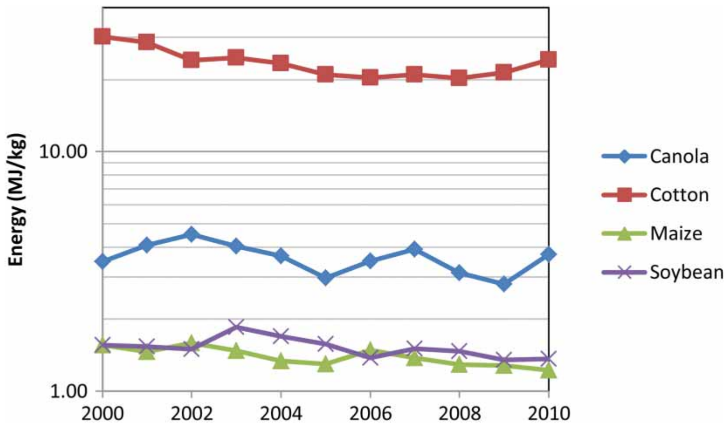

Figure 3. Energy-use efficiency trends for canola, cotton, maize, and soybean production in high-intensification countries.

slope is used to estimate the overall eco-efficiency gain for the period (2000–2010). A negative value indicates that eco-efficiency actually worsened over the decade, as observed in a handful of examples, though only one of these trends was significant ($P < .05$): increasing GHG emissions for maize production in low-intensification countries. Tables 5–7 also include a simple average of the decadal percentage gains in each of the four eco-efficiency metrics to derive what we define to represent the overall eco-efficiency gain for each crop intensification category. Overall eco-efficiency gains for all four crops are greatest for the high-intensification countries: canola (26%), cotton (23%), maize (17%), and soybeans (18%). Overall gains for medium-intensification countries are generally lower, especially for canola and soybean, neither of which showed any gains for the decade. Gains for maize in medium-intensification countries are the same as in the high-intensification maize countries (17%). No gains in overall eco-efficiency were achieved for low-intensification cotton or maize countries.

In Figures 1–4, the eco-efficiency trends in high-intensification countries for land, irrigation water, energy, and GHG emissions are shown. These charts reflect the same observations made in

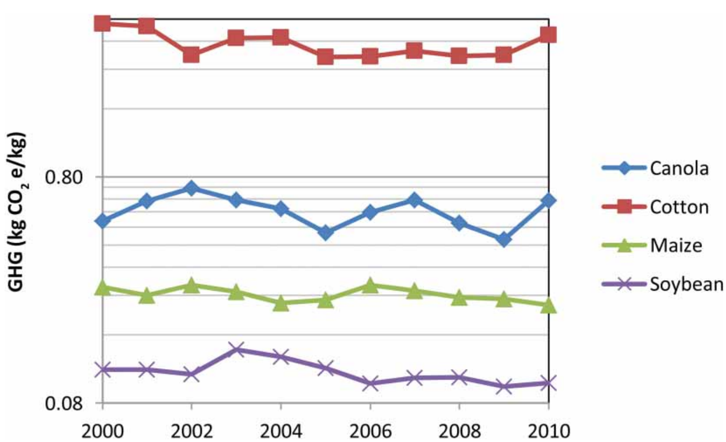

Figure 4. GHG emission trends for canola, cotton, maize, and soybean production in high-intensification countries.

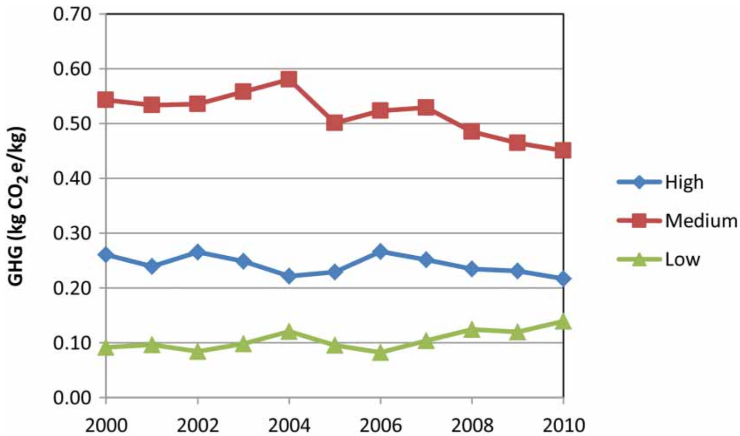

Figure 5. GHG emissions for maize production countries with varying levels of agricultural intensification. Illustration of Kuznets Curve behavior.

the previous paragraph, but also give an additional insight into the degree of annual variation, which we believe is largely due to weather-related impacts on crop yield. Maize is again seen as having the highest eco-efficiency for most inputs, followed by either canola or soybeans. Cotton has the highest relative inputs. As was noted in the discussion of Tables 5–7, steady gains in efficiency are evident in these high-intensification countries for most individual metrics. Figure 5 explores the trends in maize GHG emissions in greater detail, this time showing all three intensification categories. Interestingly, GHG emissions are lowest for the low-intensification countries and highest for the medium-intensification countries (dominated by China and India). This observation appears to be a corollary to the predictions of the Kuznets Curve from economics (Galbraith 2007), which states that as a country's agricultural sector develops, market forces can initially increase both inefficiencies and inequalities, and then decrease them after national agricultural income has attained the necessary levels. One can imagine that the three separate sets of data shown in Figure 5 might represent different time-slices of the same inverted and broad parabola proposed by Simon Kuznets (Galbraith 2007).

Discussion

Defining metrics that inform and improve human welfare is difficult. Effective use of metrics requires understanding the connections and relationships across ecological, economic, and social systems. This process requires optimization within context; there is no simple or single metric that defines good for all circumstances. However, using the eco-efficiency index proposed in this manuscript integrated with crop yield provides a reasonably robust measure of the relationship between agricultural productivity and ecosystem services' impacts. Overall, our results show that intensification of agricultural production improves eco-efficiencies, with large opportunities for additional improvements in the developing world. Cumulative resource savings during this period through intensification have been significant. For instance, in the case of irrigated maize, if the high- and medium-intensification production countries had only achieved the same irrigation water-use efficiency as in the low-intensification countries, then approximately 4 quadrillion (4×10^{15}) more litres of irrigation water would have been consumed during the period 2000–2010.

Another key finding of our work is the difficulty associated with collecting the data necessary to calculate relevant eco-efficiency metrics, especially on a global basis. For instance, we had originally intended to derive a metric based on the loss of top-soil per unit of production, but we could find such data for only one production country (the USA). There is an urgent need for greater investment in the collection and reporting of such information, especially in the major crop production countries of the world.

Intensification of agricultural systems in medium- and low-intensification countries would include greater adoption of the following practices, many of which help improve eco-efficiency:

- Tillage systems: Increased adoption of conservation tillage has direct impacts on energy consumption and GHG emission. These practices also help to reduce evaporative losses and to promote deeper penetration of moisture into the soil profile, making it available to the crop later in the season – thereby improving efficiency of water utilization.
- Better equipment: Crop yield can be improved through the use of improved equipment for soil-bed preparation, planting, harvesting, and application of crop chemicals, including the more widespread use of Global Positioning System (GPS) technology. Adoption of these equipment advances will generally improve all of the eco-efficiency metrics by boosting the denominator: crop yield (kg/m^2).
- Water management: The efficiency of irrigation water utilization is directly increased by better management of water, including advanced drainage systems and installation of efficient irrigation systems in those regions where ground or surface water may be sustainably utilized in this manner.
- Planting changes: Higher crop yields can also be obtained by shifting to earlier planting dates and higher plant populations, both of which result in the collection of more solar energy and, therefore, higher amounts of desirable crop biomass per unit of other (non-solar inputs). This directly contributes to enhanced eco-efficiency of the overall production system
- Crop protection products: Crop yield can be lost to pests, and especially under climate change scenarios favouring greater pest and disease incidence. The use of more effective crop protection chemicals and improved application methods (such as seed treatments) can help preserve yield in the face of increased weed, pest, and disease pressure. According to our analysis, such products represent a relatively minor component with respect to both energy inputs and GHG emissions, so their net impact is a strong increase in eco-efficiency.
- Breeding advances: There have been major advances in crop breeding, especially based on modern hybrids, the use of marker-assisted breeding, and other advances. Greater adoption of these varieties would result in both higher yields and greater eco-efficiencies, as has been realized in high-intensification countries.
- Biotechnology: Traits for herbicide tolerance and insect protection have contributed to greater preservation of underlying yield potential, especially under high environmental stress. Many of these traits have already demonstrated these benefits in the hands of farmers (including small-holder farmers) within those countries that are still considered to be at medium or low overall levels of intensification. It is, therefore, clear that these traits have the potential to boost eco-efficiencies in all countries where they are adopted.

For certain of these countries, improving eco-efficiencies would also require significant investments in basic infrastructure (roads, storage, shipping facilities, etc.), in addition to changes in on-farm practices.

The economic literature on adoption and diffusion (Feder *et al.* 1985) suggests that intensification involves expansion of utilization of modern inputs (fertilizer, pesticides, etc.) as well as

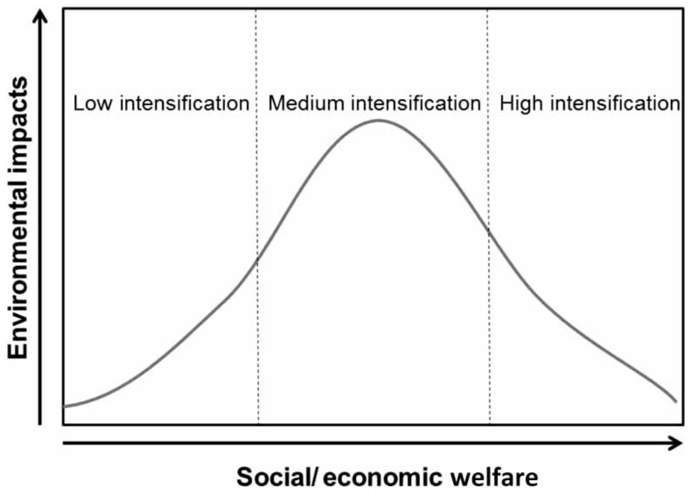

Figure 6. The EKC across three levels of agricultural intensification.

adoption of advanced technologies. The Environmental Kuznets Curve (EKC) hypothesis predicts a parabolic relationship (Figure 6) between environmental indices and some measure of advancing social or economic welfare. While the EKC has been critiqued as an overly simplistic representation of the efficiency of conversion of ecosystem services to human welfare, the relationships between these performance indicators are persistent and robust (Galeotti *et al.* 2009). Eco-efficiency is the inverse integral of a Kuznets relationship, where the degree of environmental impact is represented with respect to the economic welfare metric (yield) (Figure 7, *Y*-axis 1). Higher input use intensity results in yield gains that have an initial segment of increasing returns to scale before leveling off, resulting in an S-shaped productivity function of input use intensity (Figure 7, *Y*-axis 2). The principle of diminishing returns as we approach the limits of agricultural production system efficiency points to the need to expand those limits, and suggests that if higher yields become possible then even higher eco-efficiency

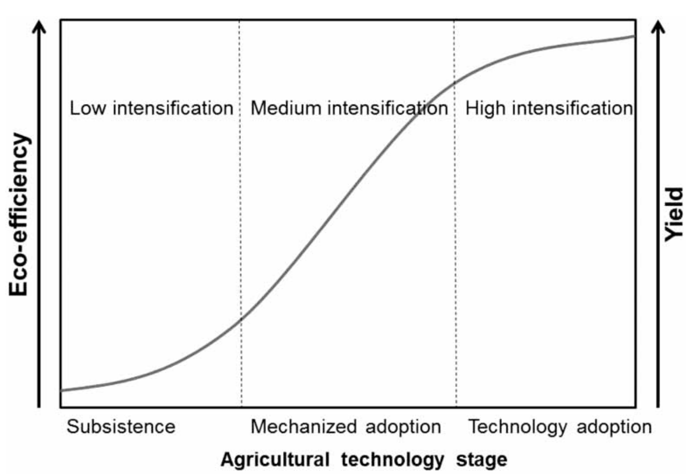

Figure 7. Theoretical relationships between productivity, eco-efficiency, and yield.

returns are also possible. While presenting the EKC within this discussion as method of interpretation, we fully acknowledge our inability to properly evaluate the hypotheses underlying the development of the EKC itself. Nevertheless, we find this to be a very useful and relevant way to think about the changes in eco-efficiency over time as intensification proceeds.

Adoption of conservation technologies such as precision farming or drip irrigation tend to increase input use efficiency, which will reduce residues (for example, chemicals that have not been consumed by the crop), which are a major source of pollution (Khanna and Zilberman 1997). Medium degrees of intensification rely primarily on the use of variable inputs and tend to increase pollution compared with lower levels of intensification. High degrees of intensification tend to combine variable inputs and advanced technologies, and tend to increase output but reduce pollution compared with lower levels of intensification where pollution may peak. When high degrees of intensification are associated with higher income, more advanced agricultural systems, it implies that pollution per unit of output increases with development and then declines, which is akin to the Kuznets Curve that suggests a similar relationship between pollution and income (Dinda 2004). Conceptual alignment of the relationship between eco-efficiency and yield provides a heuristic approach for understanding the challenges and opportunities for agricultural development with respect to current and potential technological advancement.

As we close this discussion, we acknowledge that productivity and eco-efficiency advances alone will not be sufficient to address the long-term need for improving the overall sustainability of global food production systems. In some cases, advances in productivity may even produce undesirable rebound effects, whereby excess short-term local supply can depress prices below the cost of production, thereby harming small holders or inducing unhelpful long-term public policies. We also acknowledge that other important metrics (e.g. for soil health and biodiversity) must be developed and tracked in order to more broadly characterize the consequences of agricultural intensification. Finally, this study examined a relatively short time period (2000–2010), and we recommend that further work be done in order to better understand and quantify the long-term impacts of highly intensified cropping systems.

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