

## Trade in the US and Mexico helps reduce environmental costs of agriculture

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## LETTER

## Trade in the US and Mexico helps reduce environmental costs of agriculture

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## Abstract

Increasing international crop trade has enlarged global shares of cropland, water and fertilizers used to grow crops for export. Crop trade can reduce the environmental burden on importing countries, which benefit from embedded environmental resources in imported crops, and from avoided environmental impacts of production in their territory. International trade can also reduce the universal environmental impact of food production if crops are grown where they are produced in the most environmentally efficient way. We compared production efficiencies for the same crops in the US and Mexico to determine whether current crop trade between these two countries provides an overall benefit to the environment. Our economic and environmental accounting for the key traded crops from 2010 to 2014 shows that exports to Mexico are just 3% (~16 thousand Gg) of the total production of these crops in the US, and exports to US represent roughly 0.13% (~46 Gg) of Mexican total production of the same crops. Yields were higher in US than Mexico for all crops except wheat. Use of nitrogen fertilizer was higher in US than in Mexico for all crops except corn. Current trade reduces some, but not all, environmental costs of agriculture. A counterfactual trade scenario showed that an overall annual reduction in cultivated land (~371 thousand ha), water use (~923 million m<sup>3</sup>), fertilizer use (~122 Gg; ~68 Gg nitrogen) and pollution (~681 tonnes of N<sub>2</sub>O emissions to the atmosphere and ~511 tonnes of leached nitrogen) can be achieved by changing the composition of food products traded. In this case, corn, soybeans and rice should be grown in the US, while wheat, sorghum and barley should be grown in Mexico. Assigning greater economic weight to the environmental costs of agriculture might improve the balance of trade to be more universally beneficial, environmentally.

## 1. Introduction

Global food supply has increased over the past 50 years, primarily due not to increasing national self sufficiency, but to increasing international food trade [1]. Currently, approximately 23% of the food produced for human consumption is traded internationally [2], using nearly 20% of global cropland [3, 4]. Globalization of food trade increases the disconnect between food consumption and production [2, 5, 6] as well as the disconnect between food consumption and the environmental impact of production [7]. Because food imports embody land [3, 8] and water [9, 10], international food trade indicates that importing countries are dependent on natural endowments elsewhere [6, 11–13].

In an increasingly globalized world, trade patterns can change the environmental costs of agriculture, as well as who bears these costs [14]. In international crop trade, the benefits received by the importing country include locally avoided environmental costs of production in addition to the actual crops traded. Pursuing sustainable global food production [15–17] suggests that we must monitor farming practices [18], including water management [2, 9], and fertilizer usage [7] taking into account the possible environmental trade-offs [19]. International trade implies that this monitoring take into account the ways that trade between nations changes the overall environmental price of agricultural production in addition to the costs incurred in each trading country.

While international food trade is clearly part of the solution to meeting increased food demand, especially given the environmental and climatic challenges to food production faced by many regions [20, 21], it remains unclear whether this trade will ultimately increase or decrease the environmental impact of agriculture, globally or in any particular location. Displacements of environmental pressures through trade may carry environmental benefits: trade can lead to environmental optimization by benefiting from comparative advantages in terms of production technologies or natural endowments [22]. International agricultural trade can be environmentally beneficial when countries import from places where production is more efficient, such as from higher yielding countries [3], or from countries where water [23] and fertilizer [24] are used more efficiently. However, this global environmental benefit can come at the expense of local environments [24, 25]. For instance, one quarter of all agricultural phosphorus (P) fertilizer is used in US to produce crops for export, which both depletes phosphate rock reserves in the country [26] and pollutes its waterways [27, 28]. Similarly, approximately 13% of agricultural atmospheric emissions of ammonia ( $\text{NH}_3$ ) in the US comes from crops grown for export, leading to considerable negative impacts on human health and ecosystems [29].

Before free trade was formalized in North America in 1994, scientists predicted that Mexico would increase its crop production and wondered whether the local environment there would be compromised [30]. But the actual results for international trade and the environment remain unclear. Some show that trade can benefit the environment in some ways [31, 32], while others show that trade harms the environment in other ways [33].

Here, we use bilateral trade between US and Mexico as a case study to investigate the local and global benefits and costs of agricultural trade. The US, a net exporting country, produces 60% of world corn exports and about 25% of world wheat exports [34]. In the case of US—Mexico trade, corn, wheat, soybeans, sorghum, rice and barley account for 70% of all crops exported from US to Mexico (by US\$) [35], even though Mexico also produces these same crops locally [36]. We ask: (1) is crop trade between US and Mexico environmentally efficient? That is, does it use less water and fertilizer, and produce less pollution, to export these six crops between the US and Mexico under the current dynamic? And (2) are there alternative scenarios to the current trade dynamic that have less environmental impact and more economic benefits? We use trade between the US and Mexico as a model system to more broadly understand the implications of trade on the environment.

## 2. Methods

Our analysis is based on the United Nations System of Economic and Environmental Accounting Framework, SEEA [37] and its satellite version developed by FAO for Agriculture, SEEA-Agri [38]. The SEEA framework is comparable to the System of National Accountings but its scope is broader because it includes environmental variables measured in physical units—not only economic variables measured in monetary values. The SEEA-Agri is a flexible input–output model that allows building-up tables considering the inputs from the environment in the economy as well as the effects of the agricultural sector on the environment, which ultimately facilitates the evaluation of the policies affecting sustainability of agriculture. Following the SEEA-Agri approach, we combined economic variables (such as producer and export prices) with environmental variables reported in different physical units ( $\text{m}^3$  of water, ha of land, tons of crops, kg of fertilizers and pollutant emissions) to gather, report and compare data on how much of the land, water and fertilizers are needed to grow crops for exports, and estimate some of the environmental negative impacts.

Our analysis comprised three main steps. First, we completed an environmental and economic accounting of the production of selected crops exported from the US to Mexico. Second, we compared the efficiency of production of one tonne of each selected crop in each country. Finally, we developed counterfactual trade scenarios to identify the combination of exports and locally grown crops that would bring the least global environmental costs. All analyses were completed using average values from 2010 to 2014 for the main crops exported from US to Mexico such as corn, wheat, soybeans, sorghum, rice and barley [35]. These six crops are produced in both countries and exported to one another; therefore we included analyses for exports from US to Mexico as well as exports from Mexico to the US. Because we used international aggregate databases, some details about quality and uses of selected crops were not able to be included; thus we considered crops generically, and assumed that import substitution was broadly feasible in terms of crops uses and consumption. Regarding production, we assumed that if crops were reported as grown in the same area or territory the production substitution to grow other crops was feasible. For instance, cultivated land used to grow corn in Mexico was considered suitable to grow wheat, assuming soil suitability and farmers knowledge to change crop production.

### 2.1. Economic and environmental accounting

We gathered economic and environmental data related to exports of selected crops of US and Mexico (table 1). The values from this accounting were the base for the trade-scenarios.

**Table 1.** Summary of the description, data sources and formulae for estimation of concepts comprising the economic and environmental accounting. The right column includes the economic and environmental or physical units used to report the values in the accounting tables 2 and 3.

Description, data source, and formulae	Units
<b>Export quantity</b> of each crop from UN Comtrade [36]	kg
<b>Export value</b> of each crop from UN Comtrade [36]	US\$
<b>Export share from total production</b> estimated using export quantity from UN Comtrade [36] and total production from FAO-STAT [39], $\text{Kg of export} / \text{total Kg produced}$	%
<b>Mexico's domestic consumption of imports from US</b> estimated using Mexico's national production from FAOSTAT [39], imports from US and total exports from UN Comtrade [36], $\text{imports} / \text{domestic consumption}$ ; where $\text{domestic consumption} = \text{national production} + \text{imports} - \text{exports}$	%
<b>Land</b> estimated converting kg to tonnes of export quantity from UN Comtrade [36] and using yield rates (tonne/ha) per crop per country from FAPRI [40] for corn, wheat, soybeans, sorghum and barley; from FAOSTAT [39] for rice (average estimated with available data 2006–2010), $\text{Tonnes exported} / (\text{tonne/ha})$	ha
<b>Water use</b> estimated using hectares and water consumption per crop per country—available data (2002) used constant for all series of years from Hoekstra and Hung [41], $\text{Ha} \times (\text{m}^3 \text{ ha}^{-1})$	$\text{m}^3$
<b>Fertilizers</b> estimated use of nitrogen, phosphate and potash, using land (as estimated above) and application rates per crop per country from FAPRI [40], $\text{land (ha)} \times (\text{kg ha}^{-1})$	Kg
<b>Pollution from nitrogen fertilizer</b> estimated with total applied nitrogen (N) fertilizer (kg) and using the IPCC [42] formulae for (I) volatilized nitrous oxide ( $\text{N}_2\text{O}$ , $\text{Kg applied N} \times 1\%$ ) and (II) N lost by leaching or runoff ( $\text{Kg applied N} \times 0.75\%$ )	Kg

## 2.2. Production efficiencies comparisons

Because the US and Mexico produce, export, and import the same crops, we can compare the relative production efficiencies in each country to assess the least environmentally damaging country in which to grow each crop. We estimated the resources needed in the US and in Mexico to produce one tonne of each crop. We considered as economic resource the average producer price (US\$/tonne)—described by FAO as prices received by farmers, available from FAO [39]—as a way of knowing where is cheaper to produce crops independently to the export value. We compared environmental resources use linked to crop production such as land (ha) needed in each country based on typical yields reported by FAPRI [40], and water consumption ( $\text{m}^3$ ) using data from Hoekstra and Hung on national level water consumption per crop [41]. In addition, we compared use of fertilizers (kg) using application rates ( $\text{kg ha}^{-1}$ ) for nitrogen, phosphate and potash for each crop using data available from FAPRI [40].

## 2.3. Trade scenarios

We estimated the economic costs—using producer prices and export value of crops—, as well as the amount of land, water, and fertilizers required, along with pollution from nitrogen fertilizer, in three scenarios to understand which trade combinations might lead to the least negative environmental effects of agricultural production in each country, and across both countries combined. The full-trade scenario comprised actual quantities of crop exports. The no-trade scenario assumed that all crops required were grown locally in what would currently be the importing country. The partial-trade scenario showed that, with a combination of imports and locally-grown crops, some environmental costs could be avoided. In this scenario, we assumed that each crop was grown in whichever had

the lowest environmental cost, while those with greater environmental costs of local production were imported. We based the composition of trade on the results from production efficiency. We separately estimated a set of scenarios for US exports and for Mexico exports. Trade scenarios for US exports to Mexico considered the annual average quantity of crop exports reported in the economic and environmental accounting—which in this case was 16 108 Gg of crops. For the case of trade scenarios for Mexico exports to the US the annual average exported quantity of crops was 46 Gg.

## 3. Results

### 3.1. Current state of trade between the US and Mexico and its implications

On average, each year, the US exported 16 108 Gg of corn, wheat, soybeans, sorghum, rice, and barley to Mexico, obtaining ~US\$ 5.2 billion as export revenue (table 2). Just over 8 338 Gg (52%) of this was corn. This accounts for only 3% of the total production of these crops in the US. To produce these crops, the US harvested approximately 3.1 million hectares, consuming ~11.1 billion  $\text{m}^3$  of water, and applying ~525 000 tonnes of fertilizers. Half of this fertilizer was nitrogen, causing around 2200 tonnes of leached nitrogen and 2900 tonnes  $\text{N}_2\text{O}$  emissions to the atmosphere. This represents ~32% of Mexico's consumption of these crops, indicating a level of dependence on imports from the US.

Mexico exported to US an annual average of ~46 Gg of the same crops (67% of which was corn), obtaining ~US\$ 22.9 million as export income (table 3). This is roughly 0.13% of Mexico's total production of these crops. To produce these crops, Mexico harvested around 12 000 hectares and consumed ~45 million  $\text{m}^3$  of water. Approximately 1400 tonnes

**Table 2.** The economic and environmental accounting comprises average values from 2010 to 2014, for exports from US to Mexico. This table represents the actual state of the export trade of crops, in economic terms (US\$) and in environmental units (land and water), as well as the use of fertilizers with the consequent impact on the environment. The percentage of exports to Mexico from total US production shows the market share of each crop and total. The percentage of imports from total consumption in Mexico shows the dependence on crops from US to complete crops supply in that country.

Economic accounting				
	Quantity (Gg)	Dollars (Million US\$)	% of exports to MX from total US production	% of imports from US from MX total consumption
Corn	8338	2210	2%	27%
Wheat	2642	806	5%	46%
Soybeans	2908	1515	3%	96%
Sorghum	1352	354	14%	16%
Rice	823	343	8%	76%
Barley	45	16	1%	6%
TOTAL	16 108	5244	3%	32%

Environmental accounting				
Fertilizers (Tonnes)				
	Nitrogen	Phosphate	Potash	TOTAL
Corn	146 468	49 093	58 585	254 146
Wheat	78 661	31 031	12 143	121 835
Soybeans	5317	20 101	31 072	56 490
Sorghum	41 235	9628	6057	56 920
Rice	25 866	4414	4505	34 786
Barley	1047	252	62	1361
TOTAL	298 595	114 519	112 424	525 538

	Land (thousand ha)	Water (million m <sup>3</sup> )	N leaching (Tonnes)	N <sub>2</sub> O emissions from N fertilizer (Tonnes)
Corn	824	2610	1099	1465
Wheat	901	3372	590	787
Soybeans	979	3328	40	53
Sorghum	325	837	309	412
Rice	106	916	194	259
Barley	12	43	8	10
TOTAL	3146	11 105	2239	2986

of fertilizers were applied to grow these crops, of which ~75% was nitrogen. Our models estimated that this caused ~9.6 tonnes of leached nitrogen and ~12.7 tonnes of N<sub>2</sub>O emissions to the atmosphere.

### 3.2. Why trade is mostly from the US to Mexico

In the international crop trade, the US is a net exporter. From the total production, the US exports to the world 12% of corn, 51% of wheat, 46% of soybeans, 41% of sorghum, and 36% of rice (average values from 2010 to 2013, [39]). On the other hand, the US imports from the global market only the equivalent to 0.5% of corn, 4% of wheat, 0.7% of soybeans and sorghum, 7% of rice and 8% of barley (average values from 2010 to 2013, [39]) of its total consumption.

Under the North American Free Trade Agreement (NAFTA), Mexico and the US have eliminated all trade tariffs and quantitative restrictions on importing and exporting agricultural goods [43]. Even though free trade is granted in both directions, the US has both an economic and environmental advantage in growing

the crops in our analysis, which lead it to be a stronger exporter than Mexico.

One important economic advantage for the US over Mexico is its capacity to provide agricultural subsidies that allow the US to export agricultural products at prices below the cost of production (defined by World Trade Organization as *dumping*). The *dumping margins* (the percentage of export prices below production cost) between the US and Mexico were 19% for corn, 12% for soybeans, 34% for wheat, and 16% for rice [44]. From 2010 to 2014 the cumulative reported agricultural support in the US was approximately US\$ 327 311 million, and only US\$ 31 325 million in Mexico [45]. This is equivalent to ~US\$ 400 per hectare of agricultural land per year in the US and ~US\$ 225 per hectare in Mexico per year.

Some important environmental advantages for the US over Mexico are the amount of available agricultural land and the quantity of freshwater available for agriculture relative to Mexico. The US reports 155.1 million hectares of arable land, while Mexico reports just 23.1 million hectares [46]. From 2005 to



**Table 3.** The economic and environmental accounting comprises average values from 2010 to 2014, for exports from Mexico to US. This table represents the current trade state regarding to the export of crops, in economic terms (US\$) and in environmental units (land and water), as well as the use of fertilizers with the consequent impact on the environment. The percentage of exports to Mexico from total production shows the market share of each crop and total.

Economic accounting				
	Quantity (Gg)	Dollars (Million US\$)	% of exportsto US from total MX production	
Corn	31	17	0.13%	
Wheat	12	5	0.31%	
Soybeans	0.04	0.05	0.04%	
Sorghum	1	0.3	0.02%	
Rice	1	1	0.52%	
Barley	0.2	0.1	0.03%	
TOTAL	46	23	0.13%	
Environmental accounting				
Fertilizers (Tonnes)				
	Nitrogen	Phosphate	Potash	TOTAL
Corn	1016	75	19	1110
Wheat	225	14	7	245
Soybeans	—	0.8	0.7	1.4
Sorghum	4	0.2	—	5
Rice	29	6	7	42
Barley	0.7	0.03	34	34
TOTAL	1275	96	67	1438
	Land (thousand ha)	Water (million m <sup>3</sup> )	N leaching (Tonnes)	N <sub>2</sub> O emissions from N fertilizer (Tonnes)
Corn	9	32	8	10
Wheat	2	9	2	2
Soybeans	0.03	0.1	—	—
Sorghum	0.4	1.3	0.03	0.04
Rice	0.3	2.1	0.2	0.3
Barley	0.1	0.3	0.01	0.01
TOTAL	12	45	10	13

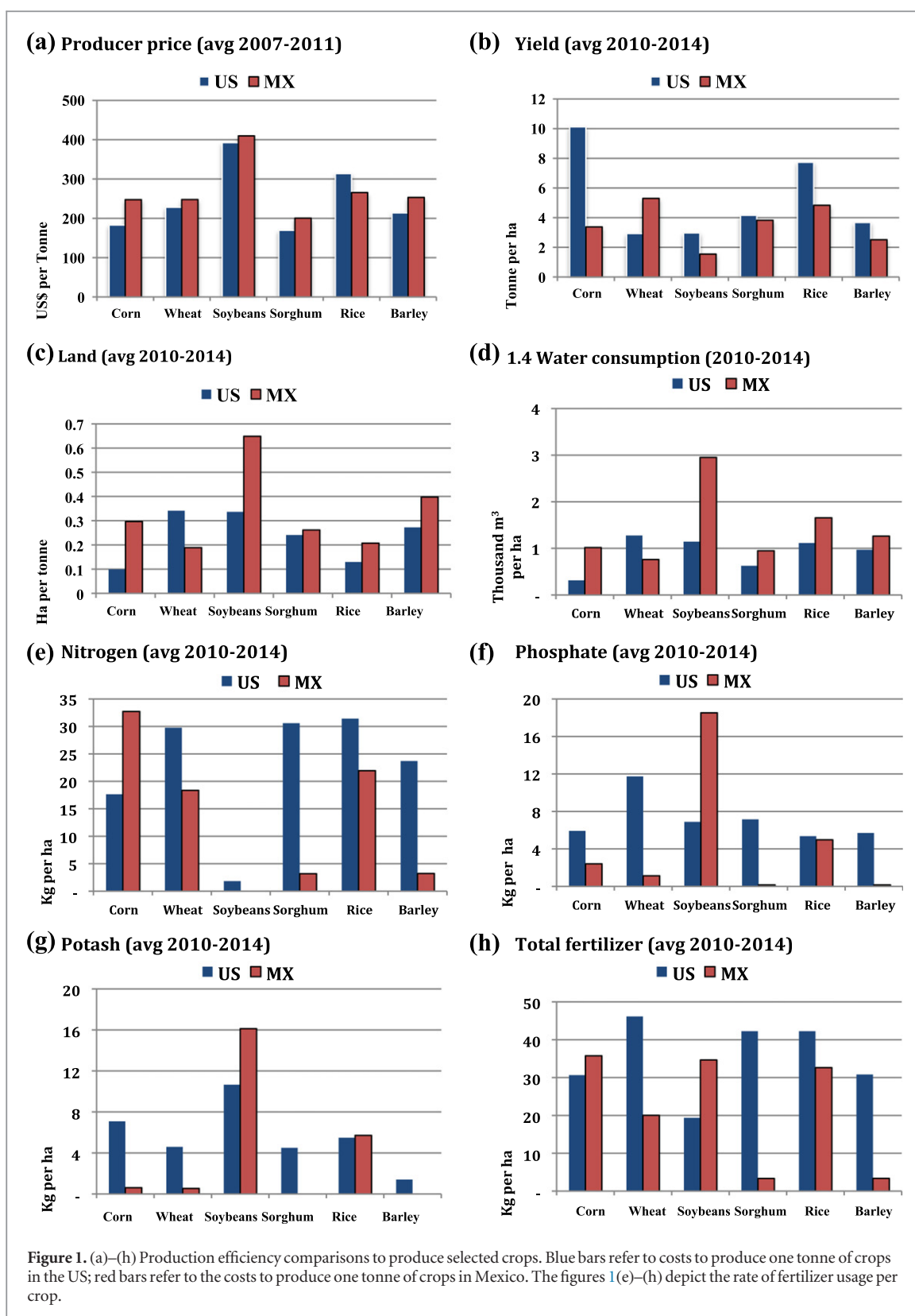
2014, Mexico had  $\sim 3300 \text{ m}^3$  of renewable freshwater flows per capita, while US had more than double that amount, nearly  $8900 \text{ m}^3$  per capita [47]. These natural endowments give considerable advantage to US for growing and exporting water- and land-intensive crops.

### 3.3. Comparing production efficiencies between US and Mexico

Producer prices were lower in US than in Mexico for all selected crops except rice (figure 1(a)). Yields were higher in the US for all crops except for wheat (figure 1(b)). The largest difference in yields between the countries was that of corn. Aligned with yields, the amount of land required to produce one tonne of each crop was higher in Mexico (except for wheat). Soybean, the crop with the lowest yield in Mexico, required almost double the land needed to grow soybean in the US (figure 1(c)). The consumed water was higher in Mexico for all crops except for wheat. In both countries, soybeans consumed the most water (figure 1(d)). Quantities of nitrogen used were higher in US for all crops except for corn (figure 1(e)). The amount of phosphate application

was also higher in US for all crops, except for soybeans (figure 1(f)). Quantities of potash fertilizer were also higher for all crops in US, except for soybeans, which received more fertilizer in Mexico (figure 1(g)). Finally, all crops received more fertilizer in US than in Mexico, with the exception of corn and soybeans (figure 1(h)).

Production efficiency comparisons highlight the least environmentally damaging country in which to grow each crop (table 4). To produce one tonne of corn in Mexico required 200% more land, 225% more water, and 86% more nitrogen than in the US; to produce one tonne of soybeans in Mexico required 93% more land, 158% more water, 169% more phosphate, and 51% more potash than in the US; and, to produce one tonne of rice in Mexico required 60% more land, 49% more water and 4% more potash than in the US. Thus, because Mexico required more resources (land, water, and fertilizers) to produce corn, soybeans, and rice, the environmentally least damaging option is to grow these crops in the US and export them to Mexico. On the other hand, wheat, sorghum, and barley were produced with fewer inputs in Mexico. To produce one tonne of wheat in the US required 45% more land, 40% more



water, 38% more nitrogen, 90% more phosphate, 88% more potash than in Mexico; to produce one tonne of sorghum in US required 90% more nitrogen, 98% more phosphate, and 100% more potash than in Mexico; and, to produce one tonne of barley in the US required 86% more nitrogen, 97% more phosphate, and 100% more potash than in Mexico.

### 3.4. Trade scenarios

The first set of trade scenarios considered exports from the US to Mexico (table 6). The full-trade scenario showed the state of trade as it exists today—the actual quantities of crops traded, amount received in return as export income, and use of resources as is in the economic and environmental accounting. The no-

**Table 4.** This table shows in numbers the differences in production requirements for each input and each crop in the US and Mexico to produce one tonne of each crop. In this table the values for the US are subtracted from the values for Mexico to identify the economic and environmental benefits or costs. The third line for each crop contains positive and negative results. The positive results show when the US has higher producer prices and yields; or has higher environmental inputs requirements (land and water), as well as higher use of fertilizers. The negative results show when the economic and environmental costs are higher in Mexico.

DIFFERENCE US—MX (to produce ONE TONNE of each crop, avg 2010–2014)									
		Prod. Price <sup>a</sup>	Yield	Land	Water	Nitrogen	Phosphate	Potash	Total fertilizer
		US\$	Tonne ha <sup>-1</sup>	Ha	m <sup>3</sup>	Kg	Kg	Kg	Kg
Corn	US	183	10.1	0.1	313	18	6	7	31
	MX	247	3.4	0.3	1017	33	2	1	36
		(65)	6.8	(0.2)	(704)	(15)	4	6	(5)
Wheat	US	228	2.9	0.3	1276	30	12	5	46
	MX	248	5.3	0.2	761	18	1	1	20
		(20)	(2.4)	0.2	515	11	11	4	26
Soybeans	US	393	3.0	0.3	1144	2	7	11	19
	MX	410	1.5	0.6	2952	0 <sup>b</sup>	19	16	35
		(17)	1.4	(0.3)	(1807)	2	(12)	(5)	(15)
Sorghum	US	169	4.2	0.2	626	31	7	5	42
	MX	200	3.8	0.3	947	3	0.2	0 <sup>b</sup>	3
		(31)	0.3	(0.0)	(321)	27	7	5	39
Rice	US	314	7.7	0.1	1113	31	5	5	42
	MX	265	4.8	0.2	1654	22	5	6	33
		48	2.9	(0.1)	(542)	9	0.4	(0.2)	10
Barley	US	214	3.7	0.3	970	24	6	1	31
	MX	253	2.5	0.4	1261	3	0.2	0 <sup>b</sup>	3
		(39)	1.2	(0.1)	(291)	20	6	1	27
TOTAL	US	1501	31.6	1	5441	135	43	34	211
	MX	1624	21.4	2	8592	79	27	23	130
		(123)	10.2	(1)	(3151)	56	16	11	82

<sup>a</sup> Producer prices are average 2007–2011 from FAOSTATS [39].

<sup>b</sup> Mexico does not apply nitrogen to soybeans production nor potash to sorghum and barley production, according to data source FAPRI [40].

trade scenario, in which no crops are traded, showed that Mexico would spend US\$ 4.4 billion to produce in-country those crops that are normally imported, rather than US\$ 5.2 billion to purchase them from the US, (a difference of US\$ 835 million per year) (table 5). To do this, Mexico would need 5.4 million ha of new cultivated land, which is 2.2 million ha more than the land currently used in the US, to grow these crops. Mexico would also require an additional 21.8 billion m<sup>3</sup> of water—10.7 billion m<sup>3</sup> more water than is required to grow these same crops in the US. In comparison to the US, Mexico would need less phosphate (32 229 tonnes); but more nitrogen, (340 723 tonnes in total—42 129 tonnes more than the US) to grow these crops and this would result in greater N<sub>2</sub>O emissions to the atmosphere (3407 tonnes in total—421 tonnes more than in the US). Additionally, more nitrogen leaching would occur (2555 tonnes in total—316 tonnes more than in the US). The partial-trade scenario, in which Mexico produced wheat, sorghum and barley locally and imported all other crops, offered the most environmental advantages. This would benefit the region overall (figure 2) by requiring the least total amount of land (365 thousand ha less than in full-trade scenario) and having the lowest water consumption (~900 million

m<sup>3</sup> less than full-trade scenario). It also avoided application of ~122 thousand tonnes of fertilizers (~67.6 thousand tonnes of nitrogen) and ~677 tonnes of avoided N<sub>2</sub>O emissions to the atmosphere along with ~508 tonnes of avoided nitrogen leaching.

The second set of trade scenarios referred to exports from Mexico to the US (table 7). As previously, the full-trade scenario showed the actual current trade situation. The no-trade scenario showed that to produce the 46 Gg crops currently imported from Mexico, the US would spend US\$ 9.16 million, rather than US\$ 22.9 million to purchase them (a difference of US \$ 14 million yr<sup>-1</sup>) (table 5). The US would need less land (around 7600 ha in total—4600 ha less than Mexico) and less water (27.3 million m<sup>3</sup> in total—17.3 million m<sup>3</sup> less than Mexico). In comparison to Mexico, to produce the same crops the US would need more fertilizers (1643 tonnes in total, 239 tonnes more Mexico)—including 344 tonnes of phosphate (249 tonnes more than Mexico) and 296.4 tonnes of potash (263 tonnes more than Mexico). The partial-trade scenario (US produced locally all corn, soybeans and rice needed, and Mexico exported to US only wheat, sorghum and barley) showed some environmental benefits. This hypothetical scenario would benefit the region by using ~22 million m<sup>3</sup> less water and avoiding the



**Table 5.** Economic trade-scenario comparisons for exports between US and Mexico (annual average values from 2010 to 2014). In the full-trade scenario column, the data represent the total value of crop exports at export price at the exporting country; the no-trade scenario column reports data of the imported quantities value of crops at producer prices in the importing country; the partial-trade scenario column includes data of a combination of both previous trade-scenarios. The green columns on the right include data on the economic benefits from partial-trade scenario, which are benefits for the importing countries but an economic loss for the exporting country.

	Scenarios			Benefits from no-trade scenario	Benefits from partial-trade scenario
	Full-trade	No-trade	Partial-trade		
Exports from U.S. to Mexico	5244	4409	5005	-835	-239
Exports from Mexico to U.S.	23	9	11	-14	-12
Exports from both U.S. and Mexico	5267	4418	5016	-849	-251

**Table 6.** Trade-scenario comparisons for selected crops exported from US to Mexico (annual average values from 2010 to 2014) relative to environmental variables. The two columns on the right in green show the counterfactual savings in resource use and environmental costs.

	Environmental Variables					Benefits from no-trade scenario	Benefits from partial-trade scenario
	Scenarios						
	Full-trade	No-trade	US	MX	Total		
Quantity (Gg)	16 108	16 108	12 069	4038	16 108		
Land (1000ha)	3146	5421	1909	872	2781	2275	-365
Water (Million m <sup>3</sup> )	11 109	21 853	6853	3355	10 208	10 744	-901
Nitrogen (Tonnes)	298 594	340 723	177 651	53 266	230 918	42 129	-67 676
Phosphate (Tonnes)	114 519	82 290	73 608	3235	76 843	-32 229	-37 676
Potash (Tonnes)	112 423	59 077	94 162	1446	95 608	-53 346	-16 815
Total Fertilizer (Tonnes)	525 537	482 099	345 422	57 947	403 368	-43 438	-122 169
N <sub>2</sub> O Emissions (Tonnes)	2986	3407	1777	533	2309	421	-677
N Leaching (Tonnes)	2239	2555	1332	399	1732	316	-508

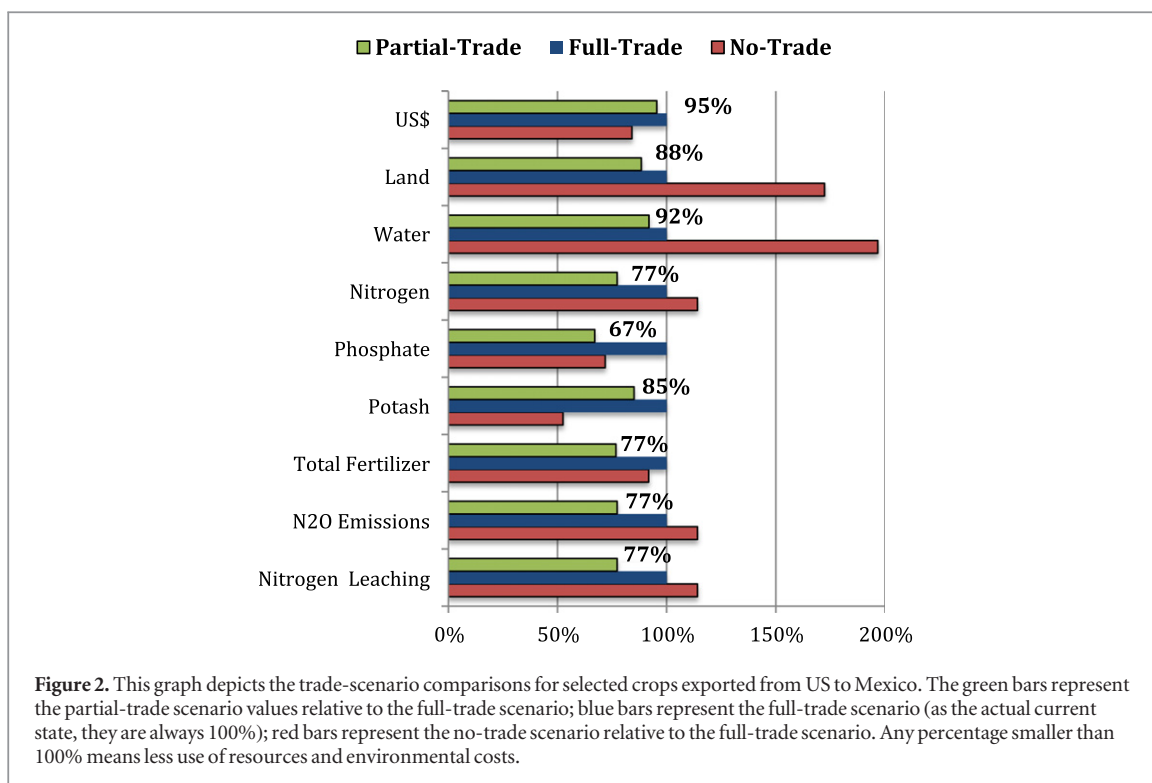
application of ~426 tonnes of nitrogen (with the consequent ~4.2 tonnes of avoided N<sub>2</sub>O emissions to the atmosphere and ~3.2 tonnes of avoided nitrogen leached per year). In figure 3, 100% of nitrogen equals 1275 tonnes, while 100% of phosphate equals 95.5 tonnes and 100% of potash equals 33.6 tonnes, therefore in the partial-trade scenario 426 tonnes of nitrogen are avoided, even though 330 tonnes of phosphate and potash are increased (the trade-off brought 96 tonnes of avoided nitrogen).

With a partial-trade scenario in both countries, there would be an annual global environmental saving of land (~371 thousand ha), water (~923 million m<sup>3</sup>), and fertilizers (~122 thousand tonnes)—of which ~68 thousand tonnes would be nitrogen, ~37.5 thousand tonnes would be phosphate and ~16.6 Gg would be potash, along with ~681 tonnes of N<sub>2</sub>O emissions to the atmosphere and ~511 tonnes of leached nitrogen. To achieve this, corn, soybeans and rice should be produced in the US and wheat, sorghum and barley in Mexico. While most of the environmental impacts

would occur in the US, some would also occur in Mexico (table 8). Approximately 70% of the total land and water used to grow these crops would be used in the US, along with ~86% of total fertilizers.

#### 4. Discussion

We aimed to determine whether international trade between US and Mexico between 2010 and 2014 was environmentally efficient. That is, did trade reduce the overall environmental cost of food production? Our results showed that trade reduces environmental costs relative to the situation in which both countries consume only food grown in-country. If Mexico produced all the crops it currently imports from US, more land, more water, and more fertilizers would be required. If US produced locally all crops currently imported from Mexico, more nitrogen fertilizer would be required. Additionally, our results showed that there are alternative trade models that would carry



**Table 7.** Trade-scenario comparisons for selected crops exported from Mexico to US (annual average values from 2010 to 2014) relative to environmental variables. The two columns on the right in green show the counterfactual savings in resource use and environmental costs.

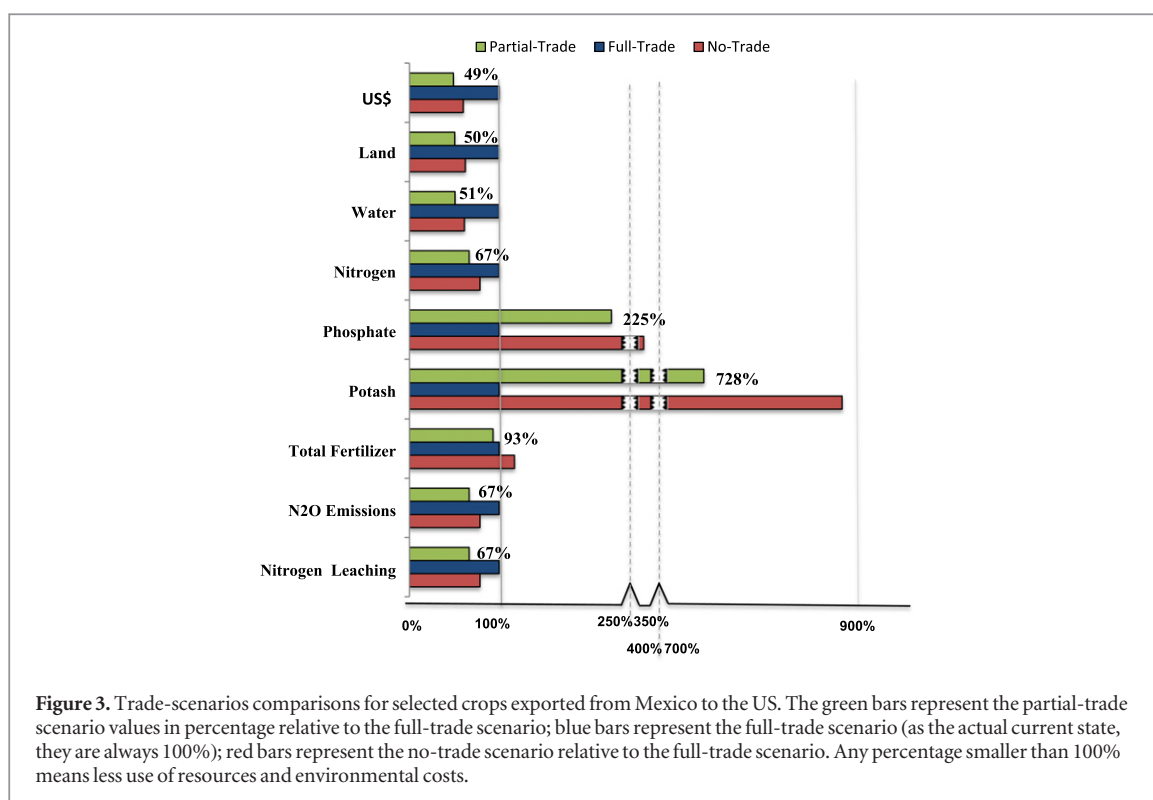
Environmental Variables	Scenarios						Benefits from no-trade scenario	Benefits from partial-trade scenario
	Full-trade	No-trade	Partial-trade					
			US	MX	Total			
Quantity (Gg)	46	46	32	14	46			
Land (1000ha)	12	8	3	3	6	-5	-6	
Water (Million m <sup>3</sup> )	45	27	12	11	23	-17	-22	
Nitrogen (Tonnes)	1275	1002	618	230	848	-273	-427	
Phosphate (Tonnes)	96	345	201	14	215	249	119	
Potash (Tonnes)	34	296	238	7	245	263	211	
Total Fertilizer (Tonnes)	1404	1643	1057	250	1307	239	-96	
N <sub>2</sub> O Emissions (Tonnes)	13	10	6	2	9	-2.73	-4	
N Leaching (Tonnes)	10	8	5	2	6	-2	-3	

even lower regional environmental costs. If the US and Mexico continued trading, but each country specialized in those crops it can produce most efficiently, we would expect to use less land, less water, and less fertilizers mainly nitrogen and the consequent reduction of N<sub>2</sub>O emissions nitrogen leaching.

The downside of the alternative trade composition—presented here as the partial-trade scenario—is that countries would decrease their export activity and increase their local production; therefore, both countries would diminish their revenue from exports. This result quantifies, and supports, earlier suggestions that there are existing trade-offs between

economic and environmental benefits of agricultural production [48].

Our results supported the idea that food trade can contribute to global water savings [23]. The US has much greater water availability per capita than Mexico [47], and it is more efficient user of water per hectare of irrigated land [49] as well. It thus has a considerable advantage as a net exporter [4] of water-intensive crops. Our results for corn also supported earlier results showing that countries often import from countries with higher yields [3], or higher efficiency in fertilizer usage [24]. Nevertheless, wheat showed the opposite results. Despite enjoying considerably

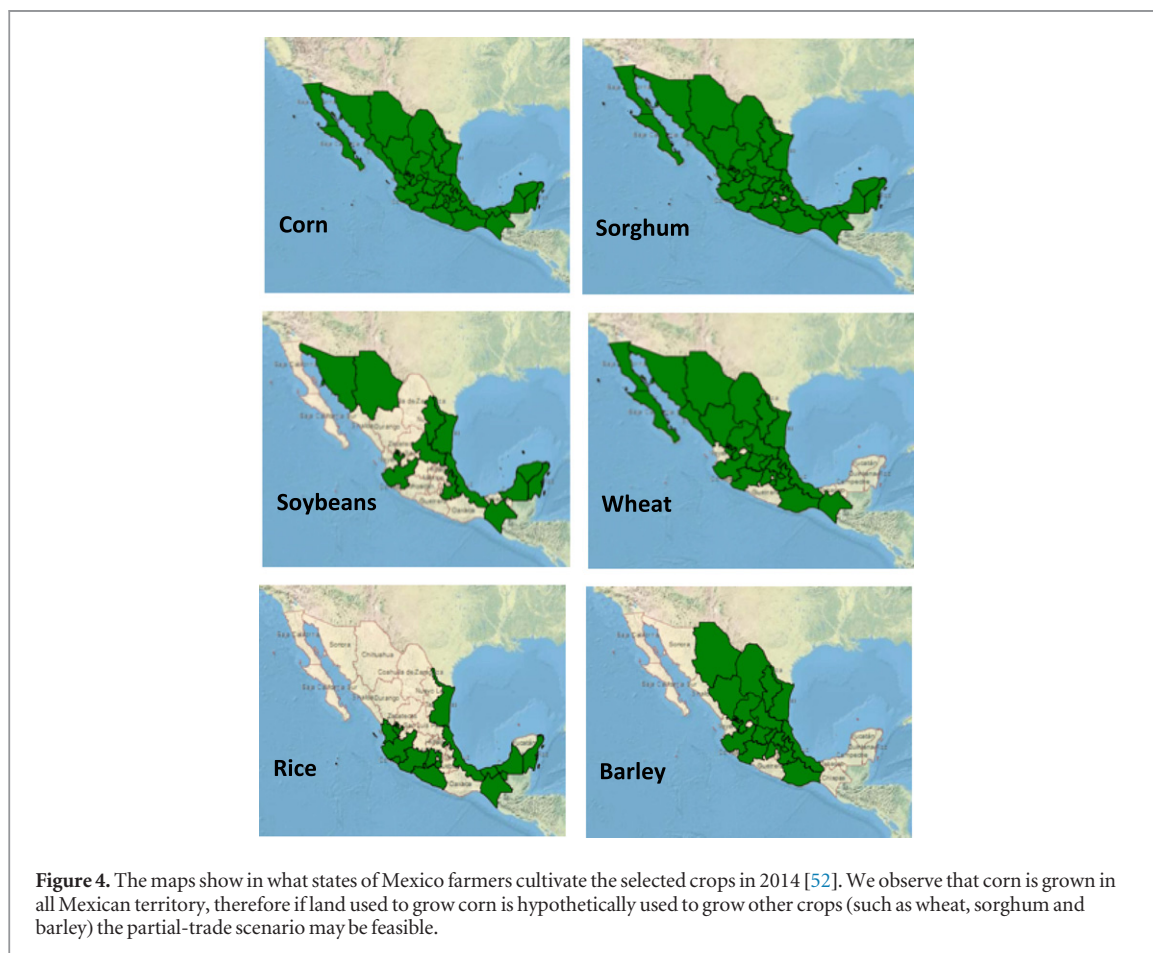


**Table 8.** Trade-scenario comparisons for selected crops exported from US to Mexico plus exported crops from Mexico to US (annual average from 2010 to 2014) relative to environmental variables. The two columns on the right in green show the counterfactual savings in resource use and environmental costs.

	Environmental Variables					Benefits from no-trade scenario	Benefits from partial-trade scenario
	Scenarios						
	Full-trade	No-trade	Partial-trade				
		US	MX	Total			
Quantity (Gg)	16 154	16 154		12 101	4052		
Land (1000ha)	3158	5429	1912	875	2787	2270	−371
Water (Million m <sup>3</sup> )	11 154	21 880	6865	3366	10 231	10 727	−923
Nitrogen (Tonnes)	299 869	341 725	178 270	53 496	231 766	41 856	−68 103
Phosphate (Tonnes)	114 615	82 635	73 809	3249	77 058	−31 980	−37 557
Potash (Tonnes)	112 457	59 373	94 400	1452	95 852	−53 083	−16 604
Total Fertilizer (Tonnes)	526 941	483 742	346 479	58 197	404 676	−43 199	−122 265
N <sub>2</sub> O Emissions (Tonnes)	2999	3417	1783	535	2318	419	−681
N Leaching (Tonnes)	2249	2563	1337	401	1738	314	−511

higher yields, and reduced use of water and fertilizers, Mexico still imported from the US a significant quantity of wheat. Most likely, economics is driving this trade pattern: it remains cheaper to produce wheat in the US than in Mexico, despite the need for more inputs. This supports earlier studies that show that that prices of food production can be disconnected from the environmental dimension [4], often because agricultural subsidies decrease production prices while encouraging the intensification of inputs (such as fertilizers) [50].

Incentives for agriculture such as subsidies create trade distortions along with negative externalities to the environment. Trade, rural subsidy regimes and production incentives have promoted land and water environmental stress [51] by increasing the use environmental assets (such as land) and the input use (such as fertilizers) creating environmental imbalances. Economic incentives can sometimes create market failures that promote the overuse of natural resources in places where it does not necessarily make sense to do so. Trade policies that could create an efficient allocation



**Table 9.** Amount and proportion of use of land, water and fertilizers (and environmental pollution from nitrogen use) used in the partial-trade scenario comprising trade of selected crops between US and Mexico.

	Total global partial-trade	US	MX
Quantity (Gg)	16 154	75%	25%
Land (Thousand ha)	2787	69%	31%
Water (Million m <sup>3</sup> )	10 231	67%	33%
Nitrogen (Tonnes)	231 766	77%	23%
Phosphate (Tonnes)	77 058	96%	4%
Potash (Tonnes)	95 852	98%	2%
Total Fertilizer (Tonnes)	404 676	86%	14%
N <sub>2</sub> O Emissions (Tonnes)	2318	77%	23%
N Leaching (Tonnes)	1738	77%	23%

of production would, by necessity, reflect the real economic and environmental cost of production.

Our results for the other crops we studied highlighted trade-offs between cropland efficiency (yield) and fertilizer use efficiency. That is, we observed that US has higher yields for all crops except wheat but requires more fertilizers to achieve this yield. Thus, decisions to prioritize land use efficiency would reduce fertilizer use efficiency and vice versa. There is no overall environmentally better trade pattern for both fertilizer use and land use.

Our results further showed that the best way to minimize the overall environmental cost is to specialize in the production of those crops where they are more efficiently grown, requiring less land, water and/or fertilizers. In the alternative trade scenario with the least environmental costs, the US would need to produce, export and consume locally (instead of importing from Mexico) corn, soybeans and rice. On the other hand, Mexico would need to produce, export and consume locally (instead of importing from US) wheat, sorghum and barley.

In the hypothetical case that the US produces locally the corn, soybeans and rice imported from Mexico (approximately 32 Gg), it would require around 10 thousand hectares of land, which are equivalent to just 0.3% of the more than 3 million hectares dedicated to produce crops for exports to Mexico [46].

In the case of growing wheat, sorghum and barley in Mexico instead of importing these products from the US it would require approximately 850 thousand hectares of land. Data shows that wheat, sorghum and corn are produced in almost all states of Mexico [52], as depicted in figure 4. On the other hand, since 1994 Mexico has significantly decreased the use of agricultural land to grow corn—around 2 million hectares [52, 53], contributing to the increase of abandoned agricultural land in that country [54, 55]. If the land previously used to grow corn is used to cultivate

wheat, sorghum and barley, it would more than account for the additional land needed in this partial trade scenario.

## 5. Conclusion

Our results affirm the potential environmental benefits from crop trade in North America, by reducing overall consumption of natural resources and use of fertilizers (therefore pollution to the atmosphere, water and soil) when importing instead of producing locally (mainly crop flows from US to Mexico). These results are not only relevant for trade dynamics between the US and Mexico, but serve as a model system to understand other bilateral trade activities. Our findings suggest that improved trade composition can bring more environmental benefits than those obtained with the existing trade dynamic, which seems to be dominated by economic considerations. We observed that economic efficiency does not align with environmental efficiency; for instance producer prices in one country can be lower even though more fertilizers are used and more pollution is produced. Ultimately, our alternative trade scenario suggests that for the global environment benefit countries should export only those crops requiring less land and water, and/or fewer fertilizers than the importing country. Quantifications of the economic and environmental benefits and costs such as this one, can help improve managers' decisions by highlighting the facts about trade-offs and synergies between economic and environmental benefits.

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