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Global virtual-land flow and saving through international cereal trade

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Abstract: With intense urbanization and sustained population growth, securing food production with limited land sources has increasingly become a pressing issue. Based on an analysis of international cereal (i.e., barley, buckwheat, maize, oats, rice, rye, sorghum, soybean, and wheat) trade and differences in yields of the cereal between export and import countries over the period of 2007 to 2011, we explore the great potential of land saving through the international cereal trade. By 'land saving', we refer to the reduced global total of lands required to produce a necessary amount of cereal when cereal is exported from a country with relatively large yield of the cereal to a country with relatively small yield of the cereal. Our scenario analysis suggests that international cereal trade would help mitigate the shortage of domestic arable land for many island countries (e.g., Japan) and countries in the arid Middle East and North Africa (e.g., Syria and Morocco). Furthermore, international cereal trade has the potential to generate 'land saving' of 50,092,284 ha of land per year, which is roughly the size of Spain. Drawing upon the definition of a similar concept – virtual water (Hoekstra and Hung 2002), we define virtual land as the area of land resources used for the production of goods. Through introducing the concept of virtual land, we believe land resources that are traditionally considered as stationary resources can flow with anthropogenic socioeconomic activities. The largest virtual-land flows (> 3,000,000 ha/year) exist between the United States (US) to China, Brazil to China, the US to Japan, the US to Mexico, and Argentina to China. However, not all virtual-land flows necessarily result in land saving. Thus, more endeavors are needed to plan the virtual-land flows for a larger land saving at the global scale.

Keywords: virtual land; land saving; land flow; international cereal trade

1 Introduction

Tackling the problem of supporting a rapidly growing population with increasingly limited natural resources is of vital importance for humankind. With intensified global connections and socioeconomic integration, scholars have begun to realize the potential of international

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trade as a venue for saving natural resources (Chapagain *et al*., 2006; Hoekstra and Chapagain, 2008; Fader *et al*., 2011). As a case in point, Hoekstra and colleagues (Hoekstra and Hung, 2002; Chapagain and Hoekstra, 2004; Chapagain *et al*., 2006; Hoekstra and Chapagain, 2007) have developed water footprint theory and proposed the concept of virtual water: the amount of freshwater that is consumed to produce goods (Hoekstra and Chapagain, 2007). Water saving can occur when a commodity is shipped from a site with relatively high to another site with relatively low water productivity (Chapagain *et al*., 2006). Following the definition of virtual water, we define virtual land as the area of land resources used throughout the production processes of the goods. In a sense when a country is importing/exporting goods, it is essentially importing/exporting the land used to produce these goods. In other words, land resources can 'flow' when commodities are traded from one country/region to another. Moreover, as countries' productivity varies, producing the same commodities would require different amounts of land resources in different countries. These differences in required virtual land to produce certain goods allow for the possibility of land savings through trade at the global scale: we may produce more commodities with the existing amount of land resources or we may sustain the current level of production with less land resources. Such land savings would take place when commodities are traded from a country with more efficient land uses to a country with less efficient land uses. For example, producing 1 ton of wheat needs 0.35 ha of land per year in India but only 0.15 ha of land per year in France (FAO, 2014). If India imports 1 ton of wheat from France, at the national level India saves 0.35 ha of land while at the global scale 0.20 ha land resources are saved.

Cereal commodities are land-intensive and in high-demand. With existing land resources and cereal production capacity, a serious shortage of cereal supply will emerge in 2050 when global population is projected to be 50% larger than at present (Tilman *et al*., 2002). Since land resources are limited on earth, saving more land resources means additional cereal or other foods can be produced. Therefore, in addition to endeavors to improve the yield of grains, it is necessary to exploit the potential of land saving through international cereal trade. Many previous studies have shown that a certain volume of water resources can be saved by agricultural trade (Fraiture *et al*., 2004; Chapagain *et al*., 2006; Fader *et al*., 2011; Dalin *et al*., 2012), but very limited studies were performed on land saving through international trade. Würtenberger *et al*. (2006) and Qiang *et al*. (2013) have discussed country-specific land saving through agricultural trade for Switzerland and China respectively. Meanwhile, Fader *et al*. (2011) analyzed global land saving through agricultural trade during 1998 to 2002 however their analysis focused more on water footprints and water resources saving. Thus there exists a large lacuna in research on land saving/loss through international cereal trade at the global and the national levels.

The main objectives of this study are to investigate global virtual-land flows related to international cereal trade over recent five years (2007–2011) and explore land saving/loss generated by the cereal trade. To fulfill these objectives, we first select nine major cereals (i.e. barley, buckwheat, maize, oats, rice, rye, sorghum, soybean, and wheat). Then, we calculate and illustrate specific areas of land saving/loss led by trade of the nine cereals at the national and the global levels. Next, we discuss each country/region's dependency on external virtual land. Finally we analyze major virtual-land flows related to cereal trade between large virtual-land-export and virtual-land-import countries and land saving/loss derived from

the major virtual-land flows at the global scale.

2 Data and method

Our analysis focuses on nine major cereals (i.e., barley, buckwheat, maize, oats, rice, rye, sorghum, soybean, and wheat). A comprehensive dataset of production and trade of the nine kinds of cereals was obtained from the FAOSTAT that is established by the Food and Agriculture Organization of the United Nations (FAO) (2014). The dataset had the following variables for each country during 2007 to 2011: yield, harvested area, import quantity, and export quantity.

A country's import/export quantity of cereals may vary greatly in different years. For example, China (here and hereafter referring to mainland China) exported 2,336,620 tons of wheat in 2007 but only 12 tons in 2010. Pakistan imported 1925 tons of rice in 2010 but in 2011 the imported quantity of rice by Pakistan rocketed to 21,052 tons. To obtain stable patterns of virtual-land flow and land saving/loss through international cereal trade of a country or the globe, we averaged data of cereal production and trade for the five-year study period (i.e. 2007 to 2011). At the national level virtual land can be saved or lost by importing or exporting cereals and so in this study imported virtual land (IVL_c) and exported virtual land (EVL_c) were calculated by equations 1 and 2 respectively:

$$IVL_C = \frac{\sum_{y=1}^{5}\sum_{i=1}^{9}\frac{I_{c,i,y}}{Ye_{c,i,y}}}{5} \tag{1}$$

$$EVL_C = \frac{\sum_{y=1}^{5}\sum_{i=1}^{9}\frac{E_{c,i,y}}{Ye_{c,i,y}}}{5} \tag{2}$$

where $I_{c,i,y}$ and $E_{c,i,y}$ represent import and export quantities of cereal i of country c in the year y respectively, and $Ye_{c,i,y}$ represent yield of cereal i of country c in the year y. A county's net land saving through cereal trade (NLS_c) is calculated by equation 3:

$$NLS_c = IVL_c - EVL_c \tag{3}$$

If NLS_c is larger than 0, it indicates the country c saved land resources through cereal trade. If NLS_c is smaller than 0, it indicates the country c lost land resources through cereal trade.

At the global level virtual land can be saved through cereal trade when cereals are shipped from countries with more efficient land uses to countries with less efficient land uses. Consequently, global total virtual-land saving (*GNLS*) was computed by equation 4:

$$GNLS = \sum_{i=1}^{9} GNLS_i = \sum_{i=1}^{9}\left(\frac{\sum_{y=1}^{5}\left(\sum_{c=1}^{n}\frac{I_{c,i,y}}{Ye_{c,i,y}}\sum_{c=1}^{n}\frac{E_{c,i,y}}{Ye_{c,i,y}}\right)}{5}\right) \tag{4}$$

where $GNLS_i$ is saved virtual land through international trade of cereal i and n represents the number of countries involved in the international cereal trade during 2007 to 2011. If *GNLS* is smaller than 0, it implies that in most international trades cereals were shipped from less-efficient-land-use countries to more-efficient-land-use countries and consequently virtual-land loss rather than virtual-land saving occurred through international cereal trade. A

few countries imported or exported cereals during 2007 to 2011 but lack corresponding data of yields. We assumed that yields of the cereals in such countries are global average yields of the cereals. The countries lacking yield data nearly all have very small import/export quantity of cereals, so our assumption did not generate substantial impacts on *GNLS*.

To further analyze impacts of international cereal trade on demand of a country, we calculated each country's external land dependency (ELD_c) by equation 5:

$$ELD_c = \frac{\sum_{y=1}^{5}\left(\frac{\sum_{i=1}^{9}\frac{l_{c,y,i}}{Ye_{c,y,i}}}{\sum_{i=1}^{9}HA_{c,y,i}}\right)}{5} \tag{5}$$

where $HA_{c,y,i}$ represents harvested area of cereal i of the country c in the year y. Hence, the larger an external land dependency (ELD) of a country, the more dependent the country is on international cereal trade and other countries' land resources.

To map major virtual-land flows, we calculated the area of virtual land flowing between each two trading partners of cereal by equation 6:

$$VI_{ec-ic} = \frac{\sum_{y=1}^{5}\sum_{i=1}^{9}\frac{E_{ec-ic,i,y}}{Ye_{ec,i,y}}}{5} \tag{6}$$

where $VL_{ec\text{-}ic}$ denotes the area of virtual land exported from the country of *ec* to the country of *ic*, $E_{ec\text{-}ic,i,y}$ denotes export quantities of cereal i from the country e*c* to the country *ic* in the year y, and $Ye_{ec,i,y}$ represents yield of cereal i of the export country *ec* in the year y. We also calculated net land saving generated by the individual land flow between each two trading partners ($NLS_{ec\text{-}ic}$) by equation 7:

$$NLS_{ec-ic} = \frac{\sum_{y=1}^{5}\sum_{i=1}^{9}\left(\frac{E_{ec-ic,i,y}}{Ye_{ic,i,y}} - \frac{E_{ec-ic,i,y}}{Ye_{ec,i,y}}\right)}{5} \tag{7}$$

A positive value of $NLS_{ec\text{-}ic}$ indicates that land resources are saved by the cereal trade between the two countries. Otherwise, land resources are lost by the trade at the global scale.

3 Results

3.1 Virtual-land flow and saving/loss at the national level

During 1997 to 2011, 201 countries (or regions) were involved in international cereal trade when 167 countries (or regions) saved land resources while 34 countries (or regions) lost land resources through the international cereal trade (Table 1 in appendix). China, Japan, Mexico, Morocco, Algeria, Venezuela, Germany, Spain, the Republic of Korea, and the Netherlands are the largest virtual-land-import countries. Imports of soybean, maize and/or wheat greatly shape the imported virtual land of the ten countries (Figure 1). Eight of the ten countries (i.e., China, Japan, Mexico, Morocco, Algeria, Venezuela, Republic of Korea, and Spain) have the largest net land-saving values and consequently saved the largest areas of land resources through cereal trade. Although they imported very large amounts of virtual

land, Germany and the Netherlands also exported large areas of virtual land (1,527,475 ha and 895,418 ha, respectively). Indonesia and Nigeria replace Germany and the Netherlands and become the ninth and the tenth largest land-saving country respectively through cereal trade (Table 1).

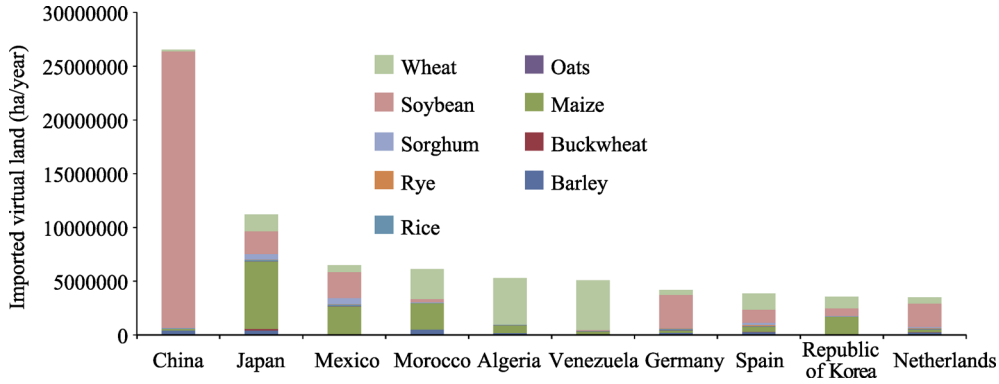

Figure 1 Imported virtual lands for the ten largest virtual-land-import countries

Table 1 Net land saving for ten countries with the largest land saving through international cereal trade (ha/year)

Country	Barley	Buck-wheat	Maize	Oats	Rice	Rye	Sorghum	Soybean	Wheat	Sum
China, mainland	428978	–81671	–88827	12896	–63483	0	–21012	25557987	36922	25781790
Japan	431432	128429	6279733	33427	105190	38876	493419	2134916	1556441	11201864
Mexico	37174	0	2552578	67634	121105	59	574826	2422318	474403	6250096
Morocco	508002	1	2480014	611	1271	0	70869	282336	2794927	6138032
Algeria	177007	0	738516	3328	53429	0	109	51	4311183	5283623
Venezuela	22	0	362312	259	30788	1	275	64168	4631608	5089433
Republic of Korea	15523	2524	1688240	1622	45090	3508	3693	722724	1064366	3547290
Spain	204313	134	469809	24364	–13070	72180	224056	1211139	1342817	3535743
Indonesia	12.47045	1	261584	217	218708	1778	332	1281372	1561662	3325665
Nigeria	161	346	–1068	9	869775	0	7923	–14962	2144898	3007082

During 2007 to 2011, 116,390,949 ha/year virtual land was exported and 81.21% of the exported virtual land was derived from ten countries (i.e., the United States, Brazil, Australia, Argentina, Canada, Russia, Ukraine, Kazakhstan, France, and Thailand). Exports of soybean, maize, wheat, or barley massively shape exported virtual land of the ten countries except Thailand (Figure 2). Exported virtual land of Thailand is mostly derived from exports of rice. Due to the very large exported virtual land, nine of the ten largest virtual-land-export countries (i.e., the United States, Australia, Brazil, Argentina, Canada, Russia, Ukraine, Kazakhstan, and France) experienced the largest net land loss in the world. India is the other top 10 net-land-loss country because of its very large net virtual-land loss in exports of maize and rice (Table 2).

3.2 Virtual-land flow and saving at the global level

During 1997 to 2011 global total harvested area per year of the nine kinds of cereals is

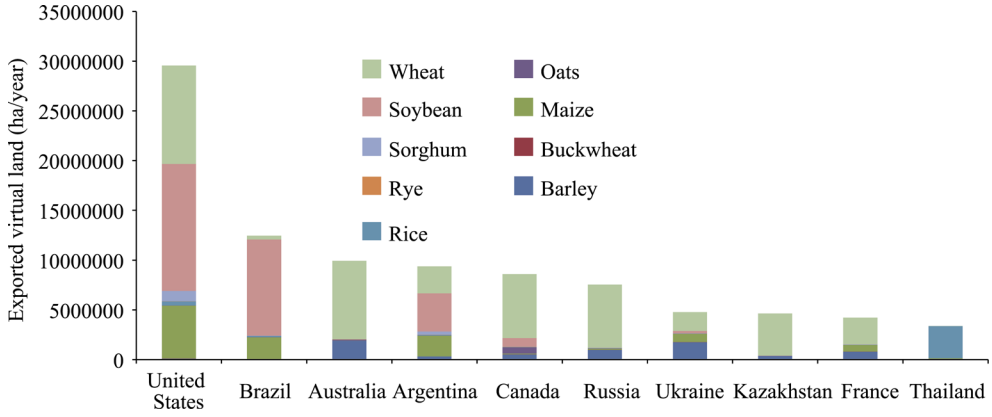

Figure 2 Exported virtual lands for the ten largest virtual-land-export countries

Table 2 Net land saving for ten countries with the largest land loss through international cereal trade (ha/year)

Country	Barley	Buck-wheat	Maize	Oats	Rice	Rye	Sorghum	Soybean	Wheat	Sum
US	17653	–15496	–5260252	777382	–332477	72504	–1048653	–12613184	–9089213	–27491736
Australia	–1909820	232	–2971	–112716	6837	–830	–17183	–212	–7885973	–9922634
Brazil	108130	–186	–2048760	–3014	9416	26	–19919	–9648151	2106069	–9496388
Argentina	–314566	0	–2120317	–887	–79277	6	–301830	–3414157	–2697611	–8928639
Canada	–512797	–1443	145415	–634845	95259	–66811	1658	–741034	–6400894	–8115493
Russia	–905298	–2556	–104323	–1536	32739	–26595	–507	591841	–6275804	–6692039
Ukraine	–1767875	–715	–819118	–4835	13319	–15713	–25763	–240754	–1897307	–4758761
Kazakhstan	–329121	–1269	–521	–3831	–3027	–497	1	4171	–4221700	–4555794
France	–811921	3145	–600686	–10832	73780	–4268	6414	196389	–2618306	–3766286
India	–61129	371	–1276268	2859	–1088450	–473	–82869	–21869	188562	–2339266

755,549,880 ha, 15.4% of which (i.e., 116,390,949 ha) was exported as virtual land and consequently led to 50,092,284 ha/year virtual-land saving at the global scale. In other words, without the international cereal trade, an additional 50,092,284 ha of land, almost equal to the area of Spain, was needed to meet the demand for cereal in one year. Figure 3 shows that trade of soybean, maize and wheat have the largest contributions to global land saving. International trade of soybean, maize and wheat led to exports of 30,904,124 ha/year, 16,262,145 ha/year, and 48,994,862 ha/year virtual land, and consequent land saving of 18,353,082 ha/year, 13,838,961 ha/year, and 10,724,783 ha/year respectively. Trade of rice, barley, and sorghum also considerably contribute to land saving. With international trade of rice, barley, and sorghum 8,144,730 ha/year, 8,721,120 ha/year, and 1,761,535

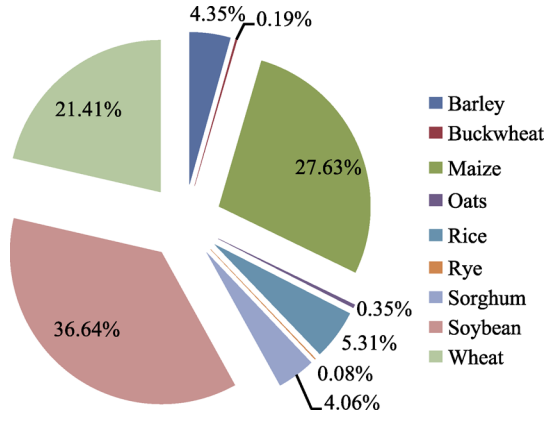

Figure 3 Contributions of different cereals to global land saving

ha/year virtual land was exported from 143 countries to 202 countries respectively which resulted in land saving of 2,658,103 ha/year, 2,177,040 ha/year, and 2,032,291 ha/year respectively. Relatively small virtual land was exported with international trade of oats, buckwheat, and rye and consequently relatively small areas of land resources of 2,658,103 ha/year, 92,752 ha/year, and 40,242 ha/year were saved from the trade of the three kinds of cereal respectively (Table 3).

Table 3 Virtual-land saving and land-saving efficiency for different cereals (ha/year for harvested area, imported virtual land, exported virtual land, and saved virtual land)

	Barley	Buck-wheat	Maize	Oats	Rice	Rye	Sorghum	Soybean	Wheat	Sum
Harvested area	52244089	2277652	163321757	10442451	159725031	5991368	42842243	98516364	220188925	755549880
Imported virtual land	10898160	235887	30101106	1226827	10802834	447742	3793826	49257205	59719646	166483233
Exported virtual land	8721120	143135	16262145	1051797	8144730	407500	1761535	30904124	48994862	116390949
Saved virtual land	2177040	92752	13838961	175030	2658103	40242	2032291	18353082	10724783	50092284
Land-saving efficiency	0.25	0.65	0.85	0.17	0.33	0.10	1.15	0.59	0.22	0.43

Note: Land-saving efficiency=Saved virtual land/exported virtual land

Although the largest virtual-land export derived from wheat trade (Table 3), trade of soybean and maize led to the largest virtual-land savings (Figure 3). That is because land-saving efficiency varies greatly for different cereals. In other words, when the same area of virtual land involved in different cereals is exported, the area of land saving is different. It can be seen (Table 3) that sorghum has the largest land-saving efficiency. During 2007 to 2011, 1,761,535 ha/year virtual land was exported with sorghum trade resulting in 2,032,291 ha/year land saving with land-saving-efficiency of 1.15. Compared to sorghum, oats and rye have very small land-saving efficiencies that are only 0.17 and 0.10 respectively (Table 3). Rice, barley, and wheat have medium land-saving efficiencies that are 0.33, 0.25, and 0.22 respectively. Although sorghum has a very large land-saving efficiency, its demand (i.e., an export quantity of 6,483,235 ton/year) is not very large. Soybean and maize both have relatively large land-saving efficiencies (0.59 and 0.85 respectively) and very large demands (export quantities of 84,521,025 ton/year and 106,061,257 ton/year respectively), so international trade of soybean and maize contributed to the largest virtual-land savings in the trade of the nine kinds of cereals.

4 Discussion

4.1 External land dependency

Globally there are 167 net virtual-land import countries with positive net-land-saving values through cereal trades, 62 of which exported virtual land larger than their domestic land producing cereals in area. Countries greatly dependent on international cereal trade (i.e. having very large ELD) are mostly located in West Asia (e.g. United Arab Emirates with ELD of 392, Qatar with ELD of 219, and Kuwait with ELD of 159) or North Africa (e.g., Djibouti with ELD of 12680), or are island nations (e.g., Mauritius with ELD of 969, Maldives with ELD of 89, and Papua New Guinea with ELD of 44) (Table 2 in appendix). These countries

have to import a large area of virtual land to meet domestic demand on land resources due to their scarce lands suitable for cultivation or limited territories. Additionally, 24 countries/regions imported virtual land from international cereal trade but did not have any domestic land planting cereals. The 24 countries/regions (e.g. Bahrain, Hong Kong, Iceland, and Singapore) are nearly all island nations/regions (Table 2 in appendix).

It should be noted that as the largest population country China's ELD is only 0.2688. As the second largest population country India's ELD is –0.0238, which implies that India nearly need not import virtual land to meet domestic demand on cereal and even can export virtual land for other countries. As the third largest population country, the United States is the largest virtual-land export (and net virtual-land export) country. Even though having the largest populations, India, China, and the United States also have the largest domestic arable lands (98,280,538 ha, 95,926,026 ha, and 88,441,963 ha respectively) in the world. Thus, compared to population, domestic arable land may have greater impacts on virtual-land flow. In 2007 and 2008 China could export a considerably large amount of maize and wheat to the Democratic People's Republic of Korea, Japan, and the Republic of Korea. These exports from China partly contribute to the adequate supply of cereal in global markets. However, with exceptional economic growth China's demand on virtual land has increased remarkably. Since 2009 China has become a wheat net-import country and in 2010 China's imported amount of maize began to be larger than its exported amount of maize. Moreover, the amount of soybean that China imported from the global markets increased massively during the period of 2007–2011. The changes in the balance of China's cereal import and export resulted in an apparent increase in net imported virtual land in China (Table 4). Therefore, affluence is likely to be another dynamic of virtual-land flow.

Table 4 Changes of net imported virtual land in China from 2007 to 2011 (ha)

	2007	2008	2009	2010	2011
Barley	220342	298505	465964	607120	552957
Buckwheat	–94986	–71850	–77311	–95506	–68703
Maize	–944805	–36605	–8739	264705	281310
Oats	1730	9410	14739	19229	19373
Rice	129463	99606	65213	35975	–12840
Rye	0	0	0	0	0
Sorghum	–60852	–28967	–7329	8834	–16744
Soybean	20885180	21711957	25891107	30847583	28454109
Wheat	–489017	–19756	186814	256646	249923
Sum	19647056	21962301	26530458	31944586	29459385

4.2 Major virtual-land flows and their contribution to global land saving

The largest two virtual-land flows generated by cereal trade exist between the United States to China and Brazil to China. At the national level the United States and Brazil lost 6,925,492 ha/year and 5,385,085 ha/year land resources respectively due to the cereal export to China. However, 11,574,575 ha and 9,136,082 ha lands are needed per year to produce the same amount of imported cereal if the cereals were produced in China. Hence, at the global scale 4,649,083 ha/year and 3,750,997 ha/year land resources were saved through cereal trade from the United States and Brazil to China. Table 5 shows that the United States and

Table 5 The 11 largest virtual-land flows (>1,000,000 ha/year) and land saving generated by the 11 individual virtual-land flows (ha/year)

		Barley	Buck-wheat	Maize	Oats	Rice	Rye	Sor-ghum	Soybean	Wheat	Sum
From the US to China	Produced in the US	0	9	94321	0	300	169	449	6755511	74733	6925492
	Produced in China	0	10	157551	0	350	106	488	11369400	46670	11574575
	Land saving	0	1	63230	0	50	–63	39	4613889	–28063	4649083
From Brazil to China	Produced in Brazil	0	0	8061	0	0	0	0	5375671	1353	5385085
	Produced in China	0	0	3225	0	0	0	0	9132113	744	9136082
	Land saving	0	0	–4836	0	0	0	0	3756442	–609	3750997
From the US to Japan	Produced in the US	49492	19803	1530255	794	42203	1165	114437	920101	1143114	3821364
	Produced in Japan	45194	43084	5742507	1054	60659	720	172295	1581127	951354	8597995
	Land saving	–4298	23281	4212253	260	18456	–445	57858	661026	–191760	4776631
The US to Mex-ico	Produced in the US	13512	4	856712	4268	76305	86	506261	1221127	880524	3558799
	Produced in Mexico	20641	4	2597371	6802	126503	113	568953	2362737	498360	6181482
	Land saving	7129	0	1740659	2533	50198	26	62691	1141610	–382164	2622683
From Argentina to China	Produced in Argentina	12669	0	231	0	0	0	1764	3062232	0	3076896
	Produced in China	14429	0	268	0	0	0	2240	4962496	0	4979433
	Land saving	1760	0	37	0	0	0	476	1900264	0	1902537
From Canada to the US	Produced in Canada	131772	1588	33764	613713	0	45820	0	109596	820789	1757042
	Produced in the US	116720	1773	31810	774724	0	64403	0	103019	756988	1849437
	Land saving	–15052	185	–1954	161011	0	18583	0		–63801	92395
From Argentina to Brazil	Produced in Argentina	91391	0	3895	0	36100	24	11	315	1546233	1677969
	Produced in Brazil	100754	0	6380	0	55288	30	20	311	1747153	1909937
	Land saving	9363	0	2485	0	19188	5	9	–4	200921	231968
From the US to Republic of Korea	Produced in the US	263	44	654768	475	11600	4422	365	193281	449706	1314923
	Produced in Republic of Korea	418	38	1292935	449	12703	2806	946	333690	373658	2017643
	Land saving	155	–5	638167	–26	1103	–1616	581	140409	–76048	702720
From Brazil to Spain	Produced in Brazil	0	0	271063	54	1635	0	7787	793475	7	1074021
	Produced in Spain	0	0	105264	50	1045	0	4621	896714	5	1007699
	Land saving	0	0	–165799	–4	–590	0	–3166	103239	2	–66322
From the US to Nigeria	Produced in the US	0	0	87	0	3058	0	0	1123	1032562	1036830
	Produced in Nigeria	0	0	435	0	12575	0	0	3091	618377	634478
	Land saving	0	0	348	0	9517	0	0	1968	–414185	–402352
From Australia to Japan	Produced in Australia	347358	0	388	16860	0	0	4918	104	658657	1028285
	Produced in Japan	191863	0	855	14456	0	0	5293	135	290267	502869
	Land saving	–155495	0	466	–2404	0	0	376	31	–368390	–525416

Brazil exporting soybean to China massively contributes to the land saving. Additionally, exports of maize and wheat from the United States to China also contribute to land saving, but exporting maize from Brazil to China generates land loss at the global scale.

Table 6 exhibits virtual-land flows from the ten largest virtual-land-export countries to the ten largest virtual-land-import countries in which virtual-land flows from the United States to China, from Brazil to China, from the United States to Japan, from the United States to Mexico, from Argentina to China, from the United States to the Republic of Korea, from Brazil to Spain, and from Australia to Japan are larger than 1,000,000 ha/year. As the twelfth largest virtual-land-import country, Nigeria imported 1,036,830 ha/year virtual land from the United States during 1997 to 2011. Additionally, besides being the largest virtual-land-export countries the United States and Brazil import a large area of virtual land every year through international cereal trade. Virtual-land flows from Canada to the United States and from Argentina to Brazil are also larger than 1,000,000 ha/year (Table 5).

Table 6 A matrix of virtual-land flows from the ten largest virtual-land-export countries to the ten largest virtual-land-import countries (ha/year)

to from	Algeria	China	Germany	Japan	Mexico	Morocco	Netherland	Republic of Korea	Spain	Venezuela
Argentina	297011	3064227	12339	145593	207	157409	38059	19286	138130	51075
Australia	9000	583643	2564	1028285	0	5406	0	632115	21626	780
Brazil	128302	5385085	285728	256728	7102	155818	902309	278143	1074021	18196
Canada	194716	200730	48790	662470	302889	191865	166028	188006	80430	287538
France	600470	31545	280919	598	840	289953	563972	0	397441	0
Kazakhstan	2324	0	66539	699	0	8490	824	0	6124	0
Russian	6368	2108	8307	18074	0	39979	7298	12785	55256	0
Thailand	11746	112486	9465	82935	42	14	27118	20010	12629	41
Ukraine	47181	1626	14787	46115	0	30327	256155	179143	347056	0
US	130927	6925492	402548	3821364	3558799	245622	205316	1314923	437362	364466

Note: The areas of virtual land are calculated by yields of export countries.

Figure 4 shows the 11 most major virtual-land-flow routes (i.e. >1,000,000 ha/year). These virtual-land-flow routes are nearly the same with the virtual-water-flow routes explored by Hoekstra and Mekonnen (2012) even though besides agricultural products, industrial products were also included in Hoekstra and Mekonnen's (2012) virtual-water-flow study. A combined consideration of Table 5 and Figure 4 can explore that the United States and Northeast Asia (i.e. China, Japan, and the Republic of Korea) are global centers of virtual-land export and virtual-land import, respectively. Compared to Fader *et al*.'s (2011) virtual-land-saving study that was conducted for the period of 1998–2002, this study shows that the status of the United States as the global virtual-land export center is not changed while the status of Northeast Asia as the global virtual-land import center becomes more apparent. During 2007 to 2011, 24.81% of virtual land was absorbed by the three Northeast Asian countries. However, not all cereal trade originating from the United States necessarily generated land saving at the global scale. For example, the cereal trade between the United States and Nigeria generated net land loss at the global scale (Table 6). It can be found (Table 7) that the yield of maize is rather large but that of wheat is relatively small in the United

States. Consequently, when a large amount of maize is exported from the United States, a land saving at the global scale is very likely to be generated. Yet when a large amount of wheat is exported from the US, the cereal trade is likely to result in land loss at the global scale. Similarly, land loss may occur as well when China, Japan, and the Republic of Korea import cereal. Yields of the eight kinds of cereal are not very small in China, Japan, and the Republic of Korea, and some yields of China, Japan, and the Republic of Korea are even much larger than global averages (Table 7). A major reason for Japan and the Republic of Korea importing large amounts of cereal every year is that their limited territory cannot provide sufficiently large areas of farming land to produce cereal to meet their domestic demands. Despite the small ELD, China's huge population inevitably produces a considerable

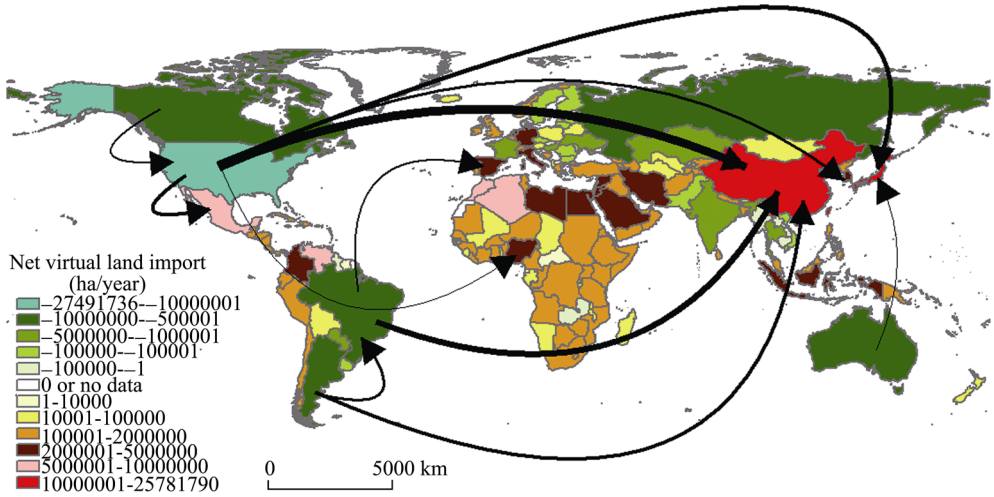

Figure 4 Net imported virtual land per country and directions of virtual-land flow related to international cereal trade over the period of 2007–2011
Note: Only the largest virtual-land flows (>1,000,000 ha/year) are shown.

Table 7 Average yields of cereal of the countries that are involved in the 11 largest virtual-land flows over the period of 2007–2011 (hg/ha)

	Barley	Buckwheat	Maize	Oats	Rice	Rye	Sorghum	Soybean	Wheat
Argentina	33608	N/A	67713	18440	65654	15281	45124	26307	28715
Australia	17580	N/A	55434	13785	88503	5985	31559	20552	15803
Brazil	29383	11606	40314	20205	42969	12822	23577	28670	24678
Canada	31679	11500	89157	28296	N/A	23860	N/A	26644	27436
China	35883	8320	54375	27444	65637	30805	38360	16788	47390
Japan	32215	5176	25799	17232	60659	N/A	N/A	16432	36174
Mexico	23418	N/A	31832	15298	47504	15000	36698	15423	51922
Nigeria	N/A	N/A	18472	N/A	17188	N/A	12694	9075	16697
Republic of Korea	28139	10135	48869	N/A	71266	N/A	16006	16760	36098
Spain	30518	N/A	103826	21333	73755	21217	41459	25335	32050
US	36507	8785	96569	22432	78329	17153	41927	28357	29541
Average of the world	28101	10841	43758	24022	37524	28398	28674	16297	30796

dynamic demand on cereal and draws global virtual land to its territory. Therefore, a positive yield difference between export and import countries may not be a major dynamic of a virtual-land flow related to an international cereal trade and international cereal trade does not always result in land saving at the global scale.

5 Conclusions

This study highlights that international cereal trade does not only greatly mitigate shortages of domestic arable land resources of individual countries/regions but also saves a considerably large area of land at the global scale.

(1) During 2007 to 2011 international cereal trade generated 50,092,284 ha/year land saving, roughly the size of Spain.

(2) Different cereals contribute to global land saving through international trade differently. Sorghum has the largest land-saving efficiency, but soybean trade saved the largest area of land resources amongst the selected nine cereals. That is due to the fact that soybean enjoys a relatively high land-saving efficiency and accounts for a very substantive portion of international cereal trade during 2007 to 2011.

(3) Although international cereal trade has led to a very large land saving, not all individual cereal trade between two countries save land resource at the global scale. For example, cereal trades from the United States to Nigeria and those from Australia to Japan led to land loss at the global scale. Thus, purely considered from an aspect of saving global land resources, more endeavor is still needed to plan cereal trade among individual countries.

(4) Additionally, we find that countries with very large population (e.g. China and India) are not necessarily dependent on virtual-land import. Domestic arable land area and economic level are also very likely to impact virtual-land flow.

Hence, in the future we will pay special attention to dynamics of virtual-land flow given that this study has shown that population pressure and positive differences on yields between export and import countries may not be crucial dynamics of virtual-land flow. The concept of telecoupling points out that with continued globalization, interactions between distant social and environmental systems is becoming increasingly intense (Liu *et al*., 2013). The concept of virtual land provides a framework to study the linkage between natural resources in physical spheres and anthropogenic activities in social systems. Thus, this study does not only explore great potential of land saving through international cereal trade but also addresses deeper thinking. In the era of globalization stationary natural resources can be re-allocated spatially through international trades. Future management of natural resources should be planned and executed in combined natural-social systems and not only in physical spheres.

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Appendix

Table 1 in appendix Net land saving through cereal trade for 201 countries/regions

Country	Net land saving (ha/year)	Country	Net land saving (ha/year)
China, mainland	25781790	Chad	89898
Japan	11201864	Madagascar	88253
Mexico	6250096	Mauritius	76395
Morocco	6138032	Belarus	74177
Algeria	5283623	Mali	74023
Venezuela	5089433	New Zealand	73689
Republic of Korea	3547290	Mongolia	73688
Spain	3535743	Bolivia	72615
Indonesia	3325665	Turkmenistan	67181
Nigeria	3007082	Rwanda	66663
Syrian Arab Republic	2709493	Brunei Darussalam	59237

Country	Net land saving (ha/year)	Country	Net land saving (ha/year)
Iran	2708283	Uzbekistan	57307
Germany	2656802	Gabon	53846
Netherlands	2599105	Togo	53398
Egypt	2517040	Slovenia	50966
Italy	2511334	Fiji	50372
China, Taiwan	2370107	Burundi	45856
Libya	2288057	Namibia	43297
Colombia	2272798	Bahrain	42036
Jordan	2175838	Poland	40525
Saudi Arabia	2031040	Barbados	37782
Iraq	1898973	Malawi	37283
Yemen	1855308	New Caledonia	33984
Peru	1845530	Macedonia	33389
Portugal	1838485	Austria	33355
Turkey	1682336	Comoros	32637
Israel	1649835	Guinea-Bissau	28843
Tunisia	1516452	Malta	25056
Malaysia	1515052	Iceland	21120
Bangladesh	1464979	Bhutan	19551
Philippines	1334338	Solomon Islands	15646
Sudan (former)	1317915	Montenegro	11827
Zimbabwe	1243656	Grenada	9070
Belgium	1059951	Saint Vincent and the Grenadines	8614
Tanzania	908146	Timor-Leste	8285
Ecuador	873227	China, Macao	7430
Cuba	869336	Maldives	6366
Ethiopia	864130	Belize	5246
Dominican Republic	858426	Luxembourg	4693
Kenya	846853	French Polynesia	4131
Mozambique	831303	Seychelles	4054
Somalia	768800	Samoa	4001
Cyprus	667163	Central African Republic	3926
Cameroon	655903	Faroe Islands	3308
Honduras	632844	Vanuatu	3092
Côte d'Ivoire	617596	Bahamas	3085
United Kingdom	612499	Equatorial Guinea	2061
Guatemala	577794	Kiribati	1818
South Africa	570190	Sao Tome and Principe	1562
Azerbaijan	563093	Netherlands Antilles	1540

Country	Net land saving (ha/year)	Country	Net land saving (ha/year)
Costa Rica	552873	Guam	1367
United Arab Emirates	529476	Aruba	1236
Angola	512591	Saint Kitts and Nevis	919
Chile	499125	Saint Lucia	683
Lesotho	495154	Suriname	566
Greece	467651	Antigua and Barbuda	400
Senegal	463390	Dominica	373
Georgia	420378	Cayman Islands	134
Congo, DR	398694	Bermuda	89
Sri Lanka	388194	British Virgin Islands	78
Norway	385292	Tonga	47
Botswana	337530	Cook Islands	27
Ghana	310273	Tuvalu	14
Lebanon	307742	Nauru	12
Panama	295734	Saint Pierre and Miquelon	5
Kuwait	292829	Niue	4
Afghanistan	292335	Guyana	–8251
Eritrea	273103	Laos	–23863
El Salvador	257957	Myanmar	–31085
Jamaica	247537	Denmark	–47363
Haiti	240268	Cambodia	–51372
Uganda	227905	Estonia	–58421
Mauritania	205813	Croatia	–61967
Niger	181457	Zambia	–64596
Korea, DPR	175929	Slovakia	–69767
Armenia	175220	Sweden	–121542
Liberia	171749	Viet Nam	–123817
Kyrgyzstan	171738	Republic of Moldova	–133933
Congo	171554	Finland	–163867
Bosnia and Herzegovina	162307	Latvia	–174263
Papua New Guinea	159575	Czech Republic	–296855
Tajikistan	154086	Lithuania	–297548
Occupied Palestinian Territory	151591	Serbia	–300503
Ireland	150592	Bulgaria	–622897
Guinea	149275	Romania	–709695
Benin	148063	Pakistan	–763843
Swaziland	143101	Uruguay	–900625
Singapore	141955	Thailand	–1216772
Oman	140984	Hungary	–1218750

Country	Net land saving (ha/year)	Country	Net land saving (ha/year)
Switzerland	138553	Paraguay	–2298939
Nicaragua	137253	India	–2339266
Cabo Verde	132540	France	–3766286
Burkina Faso	117850	Kazakhstan	–4555794
Gambia	115396	Ukraine	–4758761
Qatar	114497	Russia	–6692039
China, Hong Kong	113223	Canada	–8115493
Nepal	106546	Argentina	–8928639
Djibouti	101444	Brazil	–9496388
Sierra Leone	95590	Australia	–9922634
Albania	92221	US	–27491736
Trinidad and Tobago	90963		

Table 2 in appendix External land dependency for 207 countries/regions

Country	Domestic harvested area (ha/year)	Net virtual-land import ha/year)	External land dependency
Bahrain	0	42036	N/A
Bermuda	0	89	N/A
Aruba	0	1236	N/A
Cayman Islands	0	134	N/A
Cook Islands	0	27	N/A
Equatorial Guinea	0	2061	N/A
Faroe Islands	0	3308	N/A
French Polynesia	0	4131	N/A
Kiribati	0	1818	N/A
China, Hong Kong	0	113223	N/A
Iceland	0	21120	N/A
China, Macao	0	7430	N/A
Nauru	0	12	N/A
Netherlands Antilles	0	1540	N/A
Niue	0	4	N/A
Saint Kitts and Nevis	0	919	N/A
Saint Lucia	0	683	N/A
Saint Pierre and Miquelon	0	5	N/A
Seychelles	0	4054	N/A
Singapore	0	141955	N/A
Tonga	0	47	N/A
Tuvalu	0	14	N/A
British Virgin Islands	0	78	N/A

Country	Domestic harvested area (ha/year)	Net virtual-land import ha/year)	External land dependency
Samoa	0	4001	N/A
Djibouti	8	101444	12680.45
Mauritius	79	76395	969.4771
United Arab Emirates	1348	529476	392.7864
Barbados	102	37782	371.8745
Qatar	524	114497	218.5054
Saint Vincent and the Grenadines	41	8614	209.0683
Kuwait	1838	292829	159.2845
Jamaica	1812	247537	136.6398
Maldives	71	6366	89.41679
Guam	17	1367	82.36963
Oman	3179	140984	44.34845
Papua New Guinea	3649	159575	43.73127
Brunei Darussalam	1614	59237	36.69754
Jordan	61135	2175838	35.59059
New Caledonia	1069	33984	31.7904
Trinidad and Tobago	3441	90963	26.43648
Grenada	345	9070	26.30414
Bahamas	149	3085	20.67528
Israel	84125	1649835	19.61176
Cyprus	37032	667163	18.01575
Solomon Islands	1104	15646	14.17457
Netherlands	214211	2599105	12.13338
Congo	15033	171554	11.4115
Fiji	4416	50372	11.4068
Antigua and Barbuda	42	400	9.512762
China, Taiwan	274056	2370107	8.648252
Costa Rica	71569	552873	7.725073
Malta	3418	25056	7.33072
Libya	344875	2288057	6.634461
Portugal	302005	1838485	6.087596
Occupied Palestinian Territory	25614	151591	5.918301
Lebanon	56866	307742	5.411732
Japan	2082021	11201864	5.380283
Saudi Arabia	378857	2031040	5.36097
Dominican Republic	194428	858426	4.415143
Venezuela	1156968	5089433	4.398942
Cabo Verde	31517	132540	4.205284
Republic of Korea	1056738	3547290	3.356831

Country	Domestic harvested area (ha/year)	Net virtual-land import ha/year)	External land dependency
Belgium	323792	1059951	3.273554
Botswana	116100	337530	2.907228
Lesotho	176601	495154	2.803802
Dominica	134	373	2.776378
Yemen	716132	1855308	2.590733
Cuba	347296	869336	2.503153
Montenegro	4776	11827	2.47617
Swaziland	57835	143101	2.47432
Malaysia	681726	1515052	2.222379
Georgia	193377	420378	2.173876
Vanuatu	1436	3092	2.153605
Algeria	2595359	5283623	2.035796
Colombia	1117125	2272798	2.034507
Gabon	27552	53846	1.954316
Panama	159076	295734	1.859073
Comoros	19923	32637	1.638174
Peru	1180361	1845530	1.56353
Tunisia	1064240	1516452	1.424915
Somalia	547519	768800	1.404153
Honduras	453727	632844	1.39477
Norway	305381	385292	1.261676
Sao Tome and Principe	1280	1562	1.220426
Morocco	5202344	6138032	1.179859
Armenia	158815	175220	1.103296
Ecuador	836617	873227	1.043759
Senegal	471980	463390	0.981798
Gambia	118933	115396	0.970265
Switzerland	143224	138553	0.967389
Chile	525426	499125	0.949942
Mauritania	225367	205813	0.913233
Syrian Arab Republic	2978814	2709493	0.909588
Namibia	49214	43297	0.87977
Iraq	2194160	1898973	0.865467
Egypt	3071090	2517040	0.819592
Côte d'Ivoire	757427	617596	0.815387
Eritrea	348968	273103	0.782603
Liberia	227792	171749	0.753975
El Salvador	357343	257957	0.721875
Guatemala	812813	577794	0.710857

Country	Domestic harvested area (ha/year)	Net virtual-land import ha/year)	External land dependency
Italy	3795662	2511334	0.661633
Zimbabwe	1897122	1243656	0.655549
Albania	144483	92221	0.638282
Mexico	9807793	6250096	0.637258
Azerbaijan	926739	563093	0.607607
Spain	6101613	3535743	0.579477
Bosnia and Herzegovina	300516	162307	0.540096
New Zealand	136832	73689	0.53854
Slovenia	95287	50966	0.534869
Ireland	292372	150592	0.515071
Greece	1075372	467651	0.434874
Haiti	558282	240268	0.43037
Germany	6308509	2656802	0.421146
Cameroon	1572667	655903	0.417064
Kenya	2225932	846853	0.380449
Sri Lanka	1044338	388194	0.371713
Angola	1389877	512591	0.368803
Tajikistan	419941	154086	0.366924
Mongolia	216505	73688	0.340354
Mozambique	2524021	831303	0.329357
Bhutan	64497	19551	0.303131
Iran	8977052	2708283	0.30169
Nicaragua	465976	137253	0.29455
Kyrgyzstan	587278	171738	0.29243
China, mainland	95926026	25781790	0.268767
Guinea-Bissau	122888	28843	0.234711
Ghana	1327241	310273	0.233773
Nigeria	13199408	3007082	0.227819
Burundi	222385	45856	0.206202
Congo, DR	1972782	398694	0.202097
United Kingdom	3042437	612499	0.201318
Macedonia	170815	33389	0.19547
Sudan (former)	6850399	1317915	0.192385
Indonesia	17327619	3325665	0.191929
Philippines	7039240	1334338	0.189557
Belize	28034	5246	0.187119
Luxembourg	25402	4693	0.184755
Tanzania	4930370	908146	0.184194
Sierra Leone	570478	95590	0.167561

Country	Domestic harvested area (ha/year)	Net virtual-land import ha/year)	External land dependency
Rwanda	427070	66663	0.156093
South Africa	3663430	570190	0.155644
Uganda	1551600	227905	0.146884
Benin	1036465	148063	0.142854
Ethiopia	6143549	864130	0.140656
Turkey	12070141	1682336	0.13938
Bangladesh	11938752	1464979	0.122708
Guinea	1300539	149275	0.114779
Korea, DPR	1556132	175929	0.113055
Afghanistan	2933000	292335	0.099671
Timor-Leste	101481	8285	0.081642
Chad	1191948	89898	0.075421
Turkmenistan	909898	67181	0.073834
Togo	769537	53398	0.06939
Niger	2959222	181457	0.061319
Madagascar	1729575	88253	0.051026
Burkina Faso	2507613	117850	0.046997
Austria	773020	33355	0.04315
Bolivia	1896329	72615	0.038292
Belarus	1968230	74177	0.037687
Uzbekistan	1546120	57307	0.037065
Nepal	3155971	106546	0.03376
Mali	2399517	74023	0.030849
Malawi	1780026	37283	0.020945
Central African Republic	211306	3926	0.018582
Suriname	50169	566	0.011272
Poland	5598390	40525	0.007239
French Guiana	2937	0	0
Montserrat	16	0	0
Micronesia	145	0	0
Puerto Rico	313	0	0
Réunion	1847	0	0
Western Sahara	3210	0	0
Myanmar	8791644	–31085	–0.00354
Viet Nam	8793695	–123817	–0.01408
Cambodia	3010111	–51372	–0.01707
Laos	1013995	–23863	–0.02353
India	98280538	–2339266	–0.0238
Denmark	1445560	–47363	–0.03276

Country	Domestic harvested area (ha/year)	Net virtual-land import ha/year)	External land dependency
Pakistan	12853408	–763843	–0.05943
Guyana	126099	–8251	–0.06543
Zambia	972373	–64596	–0.06643
Slovakia	756406	–69767	–0.09224
Thailand	12551109	–1216772	–0.09695
Croatia	596105	–61967	–0.10395
Sweden	941866	–121542	–0.12904
Romania	5116961	–709695	–0.13869
Moldova	942070	–133933	–0.14217
Serbia	2038082	–300503	–0.14744
Finland	1075940	–163867	–0.1523
Russia	40285302	–6692039	–0.16612
Czech Republic	1470762	–296855	–0.20184
Estonia	289268	–58421	–0.20196
Brazil	41761186	–9496388	–0.2274
Kazakhstan	15545136	–4555794	–0.29307
US	88441963	–27491736	–0.31084
Ukraine	15163800	–4758761	–0.31382
Lithuania	917500	–297548	–0.3243
Argentina	26511894	–8928639	–0.33678
Latvia	507980	–174263	–0.34305
Bulgaria	1712390	–622897	–0.36376
France	9102805	–3766286	–0.41375
Hungary	2664717	–1218750	–0.45737
Australia	19594911	–9922634	–0.50639
Canada	15971880	–8115493	–0.50811
Paraguay	3948183	–2298939	–0.58228
Uruguay	1506166	–900625	–0.59796