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Importing food damages domestic environment: Evidence from global soybean trade

Jing Sun[a,b], Harold Mooney[c,1], Wenbin Wu[a], Huajun Tang[a], Yuxin Tong[d], Zhenci Xu[b], Baorong Huang[e], Yeqing Cheng[f], Xinjun Yang[g], Dan Wei[d], Fusuo Zhang[h], and Jianguo Liu[b,1]

[a]Key Laboratory of Agricultural Remote Sensing, Ministry of Agriculture/Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, 100081 Beijing, China; [b]Center for Systems Integration and Sustainability, Michigan State University, East Lansing, MI 48823; [c]Department of Biology, Stanford University, Stanford, CA 94305; [d]Institute of Soil Fertilizer and Environment Resources, Heilongjiang Academy of Agricultural Sciences, 150086 Harbin, China; [e]Institutes of Science and Development, Chinese Academy of Sciences, 100190 Beijing, China; [f]College of Geography and Environmental Sciences, Hainan Normal University, 571158 Haikou, China; [g]College of Urban and Environmental Sciences, Northwest University, 710127 Xi'an, China; and [h]College of Resources and Environmental Sciences, China Agricultural University, 100193 Beijing, China

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Protecting the environment and enhancing food security are among the world's Sustainable Development Goals and greatest challenges. International food trade is an important mechanism to enhance food security worldwide. Nonetheless, it is widely concluded that in international food trade importing countries gain environmental benefits, while exporting countries suffer environmental problems by using land and other resources to produce food for exports. Our study shows that international food trade can also lead to environmental pollution in importing countries. At the global level, our metaanalysis indicates that there was increased nitrogen (N) pollution after much farmland for domestically cultivated N-fixing soybeans in importing countries was converted to grow high N-demanding crops (wheat, corn, rice, and vegetables). The findings were further verified by an intensive study at the regional level in China, the largest soybean-importing country, where the conversion of soybean lands to corn fields and rice paddies has also led to N pollution. Our study provides a sharp contrast to the conventional wisdom that only exports contribute substantially to environmental woes. Our results suggest the need to evaluate environmental consequences of international trade of all other major goods and products in all importing countries, which have significant implications for fundamental rethinking in global policy-making and debates on environmental responsibilities among consumers, producers, and traders across the world.

agriculture | environment | nitrogen | Sustainable Development Goals | telecoupling

International food trade plays a critical role in global food security and economic development, but has also caused many environmental problems, such as water pollution and biodiversity loss in exporting countries (1–3). For example, due to increasing oversea demands, unprecedented deforestation in the Brazilian Amazon and *cerrado* caused by soybean and grazing land expansion has drawn global concern (4–6).

Much research has concluded that international trade inherently displaces environmental burdens from importing countries to exporting countries, and thus importing countries benefit from the displacement environmentally (7–10). Based on the new integrated framework of telecoupling (socioeconomic and environmental interactions over distances) (11, 12), we hypothesize that importing countries could also suffer from environmental problems.

To test this hypothesis, we analyzed environmental effects of soybean trade at the global level by performing a metaanalysis of 168 studies across six continents on per-hectare nitrogen (N) balance (N applied to the growing field minus the N appearing in the crop) (Fig. S1), where the crops include soybeans and four major crops (wheat, corn, rice, and vegetables) converted from soybeans (Fig. 1*A*). We estimated the N balance change associated with the crop conversion (soybeans to four major crops) affected by soybean imports in the top 10 destinations of exported soybeans from the world's top two soybean producers and exporters (Brazil and the United States) (Fig. 1*A* and Table S1) (13).

To verify the findings at the global level, we conducted an intensive study in the most important soybean production region of the world's largest soybean importer (China) that has gone through extensive crop conversion due to the soybean import. China imported 61% of global exported soybeans (71.4 million tons) in 2013, for example, with Brazil and the United States being the top two suppliers that provide cheaper soybeans to China (14, 15). Soybean lands in China are experiencing a clear decreasing trend because more than 80% of soybeans used by its domestic food industry are now imported (11).

Results

Globally, crop conversion from soybeans to wheat, corn, rice, and vegetables in importing countries caused N pollution (excess over growth requirement that ended up as runoff, leaching, and losses to the atmosphere). Results calculated from the metaanalysis indicate that the global average of per hectare N balance varied substantially among different crops: per hectare N balance of soybeans was negative, while the per hectare N balance of wheat, corn, rice, and vegetables was positive (Fig. 1 *B*) and increased after

Significance

Achieving global environmental sustainability and food security is among the world's biggest challenges. International food trade plays an important role in global food security. It is widely believed that importing countries benefit environmentally from international food trade at the environmental cost of exporting countries. Contrary to the conventional wisdom, our study reveals a major environmental problem in importing countries. The unexpected findings suggest the need to reevaluate environmental consequences of international trade in all importing countries through discussions regarding environmental responsibilities among consumers and producers. There is an urgent need for innovative solutions for reducing environmental pollution and enhancing food security to offset the negative impacts of international trade globally.

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[1]To whom correspondence may be addressed. Email: haroldmooney@gmail.com or liuji@msu.edu.

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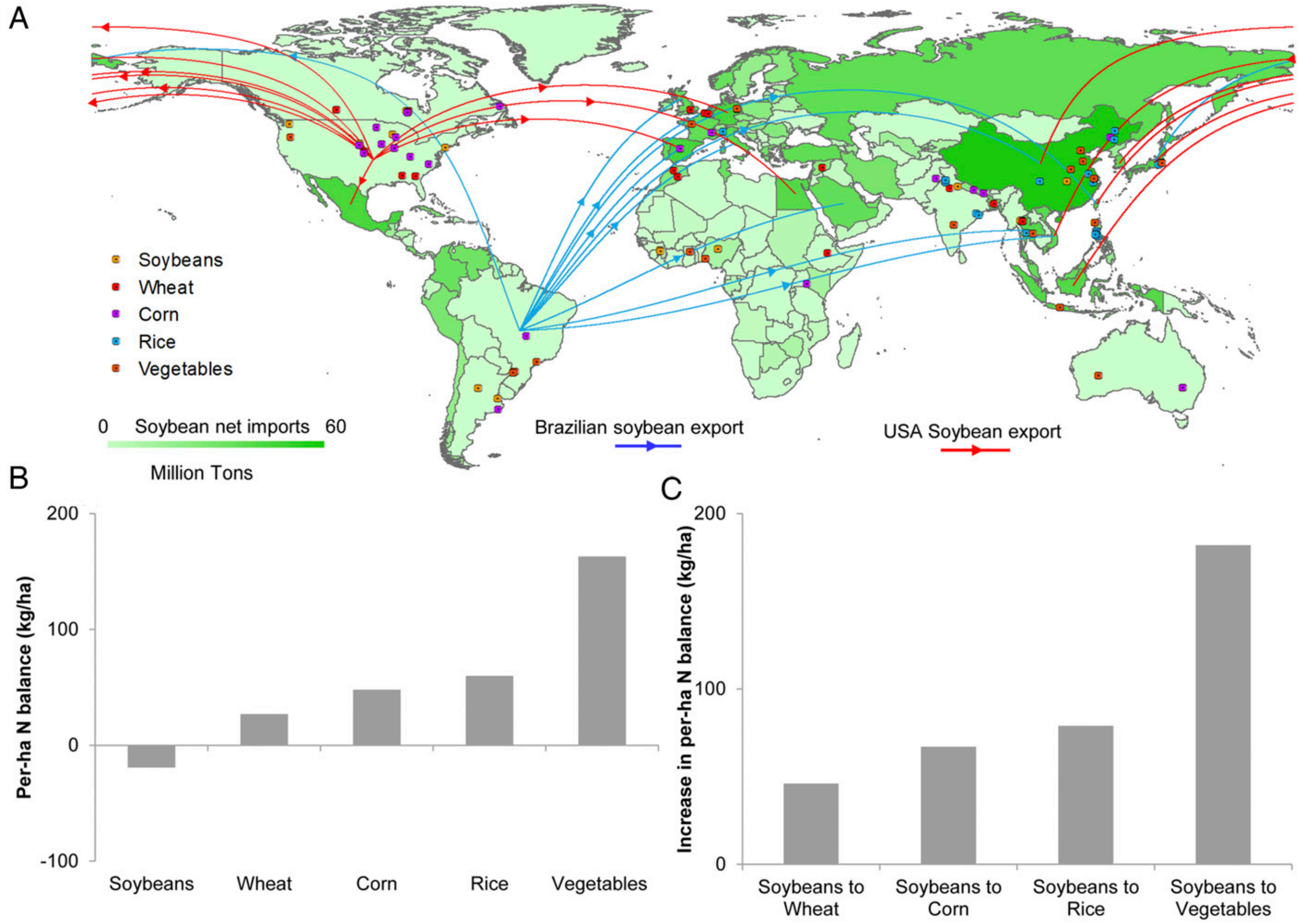

Fig. 1. International soybean trade and metaanalysis on per hectare N balance of soybeans and four major crops (wheat, corn, rice, and vegetables) converted from soybeans. (*A*) The spatial distribution of our metaanalysis data on soybeans, wheat, corn, rice, and vegetables, where the top 10 destinations of Brazil's and the United States' exported soybeans are indicated by blue arrows and red arrows, respectively. (*B*) Comparisons of per hectare N balance among soybeans, wheat, corn, rice, and vegetables [mean of per hectare N balance for soybeans (−19 kg/ha) was significantly smaller than wheat (27 kg/ha, $P < 0.01$), wheat was significantly smaller than corn (48 kg/ha, $P < 0.01$), corn was not significantly smaller than rice (60 kg/ha), and rice was significantly smaller than vegetables (163 kg/ha, $P < 0.01$)]. (*C*) The increase of per hectare N balance after conversion from soybeans to wheat, corn, rice, and vegetables.

conversion from soybeans to other crops (Fig. 1*C*). Among the top 10 destinations of exported soybeans from Brazil and the United States, 5 appeared on both lists, so 15 countries were included in the analysis (Table 1). From 2010 to 2014, soybean areas in six countries decreased after conversion to other crops. Data show that N balance on the converted soybean land had all turned from negative to positive: for example, from −32,595 to 91,925 tons in China and from −1,039 to 3,221 tons in Thailand (Table 1). Because of various domestic regulations (Table S1), three countries increased their soybean areas from 2010 to 2014, where the N balance on the expanded soybean land turned from positive to negative (Table 1): for example, from 2,503 to −990 tons in Mexico (from corn to soybeans) and from 194 to −61 tons in Korea (from rice to soybeans). Together, the N balance in these nine soybean importing countries turned from −30,131 to 100,427 tons, leading to enormous N pollution (Table 1). The six remaining countries, such as Saudi Arabia, had limited soybean areas (<1,000 ha) and thus had minimal impacts on the N balance.

The change in N pollution due to land conversion at the global level is verified by our intensive study in China. Specifically, the N balance in the study area also increased or turned from negative to positive after soybeans were converted to other crops (Table 2). The per hectare N balance in the three main types of croplands all increased (Fig. 2*A*). The increase was the largest in rice fields (from 32 to 100 kg/ha) and smallest in soybean lands where the per hectare N balance was still negative after the soybean decline (from −105 to −92 kg/ha). Per hectare N balance in corn fields had turned from negative to positive (from −23 to 42 kg/ha). The elevated per hectare N balance was due to increases in N application (to increase yield), with the highest increased amount (68 kg/ha) in rice fields, followed by corn (65 kg/ha), and with the lowest increased amount (13 kg/ha) in soybean lands (Fig. 2*B*). Although the net change of per hectare N applied to corn was larger than rice (Fig. 2*B*), the net change of per hectare N balance of corn was smaller than that of rice, because N use efficiency in corn was significantly higher than that in rice (i.e., absorbing more N) (16). Our results also indicated that almost half of the contribution (49%) to the increased N balance came from cropland conversion, and the increased per hectare N application contributed 51% (Fig. 2*C*). The role of cropland conversion was further confirmed by the results from our control group (no crop conversion but increased per hectare N application), which still showed a negative provincial N balance after soybean decline (Table 2).

Discussion

Our analysis, counterintuitively, showed that importing food has led to domestic environmental problems. The N pollution due to land conversion as a result of soybean imports is because soybeans

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Table 1. Results of N balance change due to crop conversion in top soybean destinations exported from Brazil and the United States

Importing countries	Crop conversion	Soybean area change (2010–2014) (ha)	Former N balance on lands before conversion (tons)	New N balance on converted lands (tons)	Net N balance change (tons)
China	Soybeans to corn and rice	−1,715,547	−32,595	91,925	124,520
Thailand	Soybeans to corn and rice	−54,693	−1,039	3,221	4,260
Vietnam	Soybeans to corn	−88,449	−1,680	4,246	5,926
Indonesia	Soybeans to corn and rice	−45,138	−858	2,584	3,442
Egypt	Soybeans to vegetable	−3,254	−62	530	592
Japan	Soybeans to wheat	−6,100	−116	366	482
Korea	Rice to soybeans	3,230	194	−61	−255
Mexico	Corn to soybeans	52,156	2,503	−990	−3,493
Italy	Corn to soybeans	73,367	3,522	−1,394	−4,916
Total		−1,784,428	−30,131	100,472	130,558

The values of per hectare N balance for crops in the calculation are from Fig. 1*B*. The respective converted area to corn and rice in Indonesia, China, and Thailand is based on the area change of corn and rice from 2010 to 2014.

can fix N and thus require substantially less N fertilizer and growing soybeans overused less N than growing other major crops (17, 18). In our study, we treated overused N as an overall environmental pollution indicator and did not trace specific pollution in the atmosphere and water bodies due to the lack of relevant specific data. In addition to N, we also analyzed the change of water requirement in our intensive study, which shows more water was required after the conversion from soybeans to corn and rice (*Supporting Information* and Table S7) and thus added more resource burden. We hope that this study offers a basis for more detailed research in the future.

Our results suggest the need to study environmental impacts of international trade of all other types of goods and products besides soybeans in all importing countries. This is because environmental impacts of imports may differ with types of goods and products. International food trade has led to substantial conversion of other domestically cultivated crops to different crops as a result of the cheaper imported counterparts (19–21). For example, many corn lands in Mexico and South American countries like Chile have been converted to vegetables with more N pollution, due to the cheap imported corn from the United States (22, 23). Besides changes in nitrogen dynamics, other factors, such as water use, may also change, as illustrated in our paper. If the original agricultural land is converted for other uses (e.g., forests and residential land), environmental consequences may differ. Additionally, it would be interesting to factor in the environmental financial costs associated with traded goods and products in both the importing and exporting countries. It is our hope that this study provides a good foundation for relevant future research by stimulating the collection and analyses of socioeconomic and environmental data related to trade worldwide.

Our study also indicates the value of information about trade-induced environmental problems in importing countries for policy-making and international negotiation. Information from previous studies has led countries of exporting industrial goods, like Finland and China, to demand that the importers be responsible for environmental problems (e.g., the greenhouse gas emissions) produced in the exporting countries (24, 25). For the case of N pollution in food-importing countries, we think the responsibility lies in both importing and exporting countries. Because the environmental problem caused by soybean import is an international issue, international organizations, such as the Food and Agriculture Organization of the United Nations and relevant nongovernment organizations, could help farmers in China and elsewhere (e.g., through technical and financial support) to improve cultivation of soybeans and other crops for high yield and low pollution. One effective method is the integrated farming system, which can increase crop yields with lower environmental costs through enhancing N fertilizer efficiency (26, 27). For example, our estimation indicates that the N pollution during the conversion from soybeans to corn can be reduced but would still remain substantially significant even if farmers in Heilongjiang adopt the N fertilizer efficiency achieved by the United States farmers and reduce N fertilizer application (*Supporting Information*). The findings from our study indicate the hidden environmental problem in importing countries and the need for systematic analyses of international trade to ensure global food security and environmental sustainability in the metacoupled world (28).

Methods

Indicator of Trade Impacts on the Environment. Soybeans are an important and widely traded food (Fig. 1*A*) (13, 29, 30). Imported soybeans can affect crop composition in soybean-importing countries, leading to conversion of soybeans to N-demanding grains (wheat, corn, and rice) (18, 20, 31). High fertilizer demands of grains cause environmental pollution after crop conversion from soybeans (32, 33) (see Fig. S1 for an illustration of N dynamics in an agricultural system). To evaluate the altered nutrient balance, we measured nutrient input from fertilizer minus nutrient output absorbed by crops to represent environmental change (33). We studied N balance because N is the most important nutrient for crop growth, but it can pollute soil, water, and air if used in excess (33). Positive N balance—that is, N in excess of crop growth requirement—is detrimental to the environment, while negative N balance may lower crop yield but have limited environmental impacts (33).

Metaanalysis of N Balance at the Global Level. To collect N balance information at the global level, we conducted a metaanalysis by using keywords to search topics and titles of publications in Web of Science and China National Knowledge Infrastructure (CNKI, the largest academic searching engine in China). We used CNKI because China is a major food-importing country, many relevant studies were published in Chinese, and our intensive study was in China. The keywords included "nutrient," "nitrogen balance," "soybeans," "wheat," "corn," "rice," and "vegetables." We used English and Chinese as searching languages and focused on the data published in peer-reviewed papers. We found 168 studies met our criteria that recorded the N balance, including 34 soybeans, 31 wheat, 33 corn, 33 rice, and 37 vegetables (see the suggested readings in *Supporting Information*). We examined the per hectare N balance of soybeans, wheat, corn, rice, and vegetables.

Table 2. Provincial N balance of three crops before and after soybean decline and control group

Crop	Before soybean decline	After soybean decline	Control group
Soybeans	−353	−289	−423
Corn	−62	198	156
Rice	57	293	246
Total	−358	202	−21

Unit: 1,000 metric ton.

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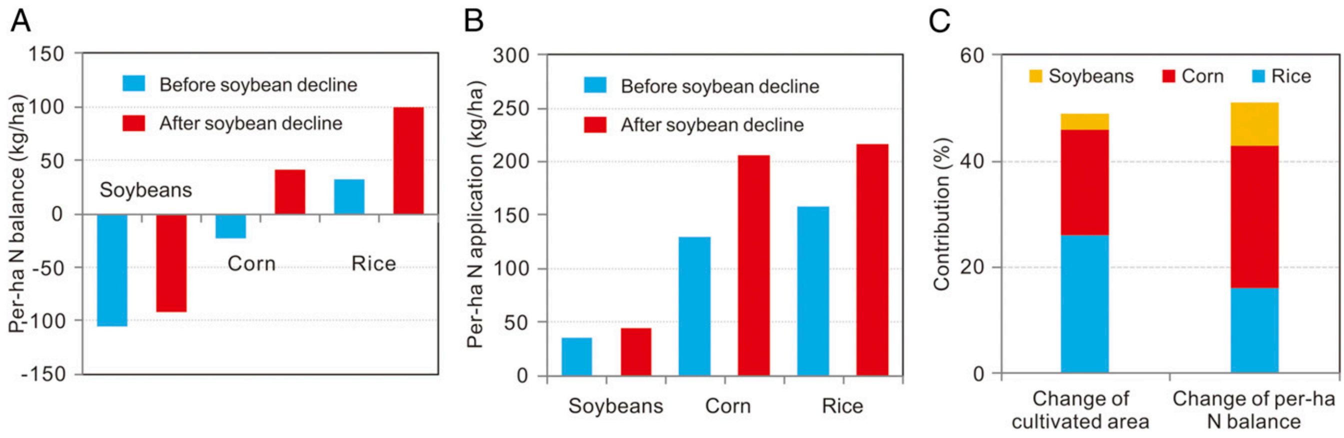

Fig. 2. Per hectare N balance (*A*) and N application (*B*) for soybeans, corn, and rice cultivation before and after soybean decline, and percent contribution of Heilongjiang provincial N balance increase from the change of cultivated area and change of per hectare N balance (*C*). The *Left* bar in *C* is the percent contribution from the change of cultivated area (49% in sum, of which 3% from soybeans, 20% from corn, and 26% from rice); the *Right* bar is the percent contribution from the change of per hectare N balance (51% in sum, of which 8% from soybeans, 27% from corn, and 16% from rice).

Intensive Study at the Regional Level.

Study region. China's traditional "granary," Heilongjiang Province, is an ideal region for an intensive study on regional N balance affected by imports. Its soybean production accounts for one-quarter to one-third of the national total and can reflect the national trend (34). As the largest soybean importer, China imported 61% of global exported soybeans (71.4 million tons) in 2013, mainly from Brazil and the United States, that provide cheaper soybeans than those produced inside China (14, 15). Soybean lands in China are experiencing a clear decreasing trend because more than 80% of soybeans used by its domestic food industry are imported (11). Because of soybean imports, soybean lands in Heilongjiang decreased from 4.0 million ha in 2009 to 2.4 million ha in 2013, leading to 35% reduction in soybean production (34, 35). Most of the lost soybean lands have been converted to corn and some to rice (20).

Household survey. To estimate N balance at the regional level, we conducted a household survey in the major soybean production region in China (Heilongjiang Province) in 2013. Farming in Heilongjiang is dominated by households, so the household survey is the main method to collect relevant nitrogen information, such as fertilizer application across the province. The survey was conducted through face-to-face interviews with the heads of 836 households (see Fig. S2 for survey sites and Table S2 for the design of survey route). Most surveyed villages experienced farmland reallocation according to household size in 1998, and soybean farming started to decrease in 2009 in Heilongjiang. Thus, the survey questions and relevant analyses span two periods: that is, before soybean decline (1998–2009) and after soybean decline (2010–2013).

Per hectare N balance. The information from the household survey and literature provides the foundation for calculating the N balance (Fig. S1). Per hectare N input of soybeans, corn, and rice was estimated from N application, while per hectare N output of the three crops was calculated with empirical equations (*Supporting Information*). In Heilongjiang, there was little N from water irrigation or organic fertilizer as there was little irrigation and little manure application (Fig. S1). N deposition in Heilongjiang was very minor (less than 3 kg/ha) (36). N input from mineralization of soil organic matter was limited (37), thus was not included in the analysis. According to our survey in Heilongjiang, N input through mineralization of crop residues was also limited, as stovers (stover refers to stem and leaves here) of soybeans and rice were used for household fuel (for both cooking and heating) and corn stover was burned on site with ashes blown away in a windy autumn and spring. There is no stover plow in Heilongjiang, because stover is not decayed by the next spring and plow adds extra cost. We also assumed that mineral N in the soil at harvest is equal to initial mineral N present in soil before planting, although the latter is slightly smaller than the former (38). Without considering N deposition, N mineralization, and mineral N in the soil, we had conservative estimates of N loss to the environment. In other words, we underestimated the N pollution on the environment. We used the widely used empirical value of 60 kg/ha as an approximation for the rate of N fixed by soybeans (32). N loss includes N volatilization, denitification, leaching, and runoff, which pollute water, soil, and air (39). N in crops (soybeans, corn, and rice) after harvest is the main N output, where most N concentrates in grains, stems, and leaves (40–42), with extremely rare N in roots and other crop parts (like ear, stubble, cob in corn). Roots are left on the sites after harvest and plowed in the next year.

Provincial N balance. For each crop, N balance of Heilongjiang (N balance at the provincial level) is the multiplication of per hectare N balance and cultivated area across the entire province. The Statistic Yearbook of Heilongjiang provided information about the provincial areas of soybeans, corn, and rice (34). Because change in per hectare N application (increase N application to increase yield) and crop conversion (from soybeans to more N-demanding crops: corn and rice here) are two factors influencing provincial N balance, we built a control group to understand the provincial N balance if there was no significant crop conversion after the year 2009. In other words, the area proportions of the three crops remained unchanged in the control group (no significant crop conversion before soybean decline in 2009, confirmed by *t* test). To estimate the percent contribution of crop conversion and change in per hectare N application to the change of provincial N balance, we adopted a decomposition method (43).

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