Importing food damages domestic environment: Evidence from global soybean trade

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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).

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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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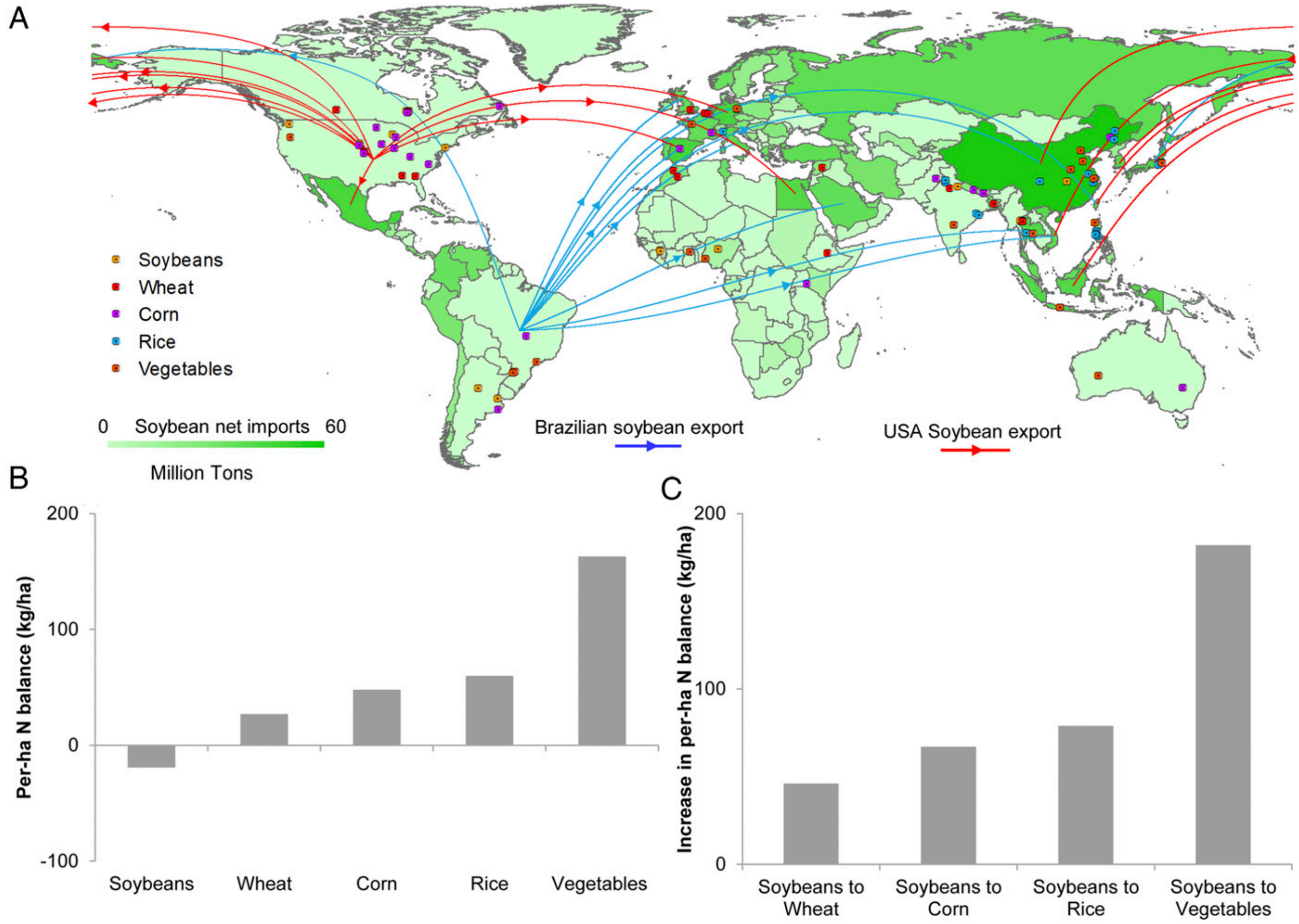

Fig. 1. International soybean trade and metaanalysis on per hectare N balance of soybeans and four major crops (wheat, corn, rice, and vegetables) converted from soybeans. (*A*) The spatial distribution of our metaanalysis data on soybeans, wheat, corn, rice, and vegetables, where the top 10 destinations 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

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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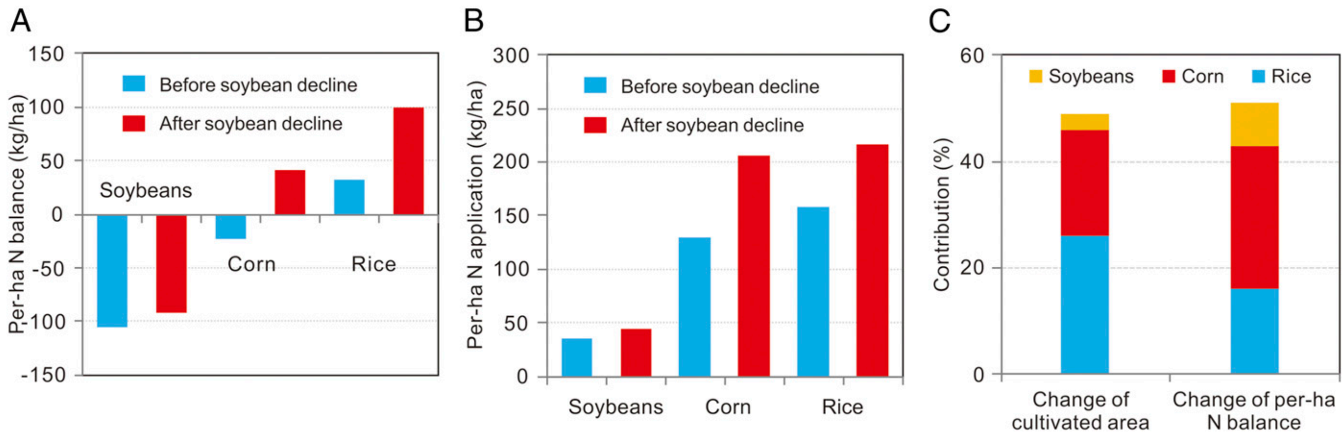

Fig. 2. Per hectare N balance (*A*) and N application (*B*) for soybeans, corn, and rice cultivation before and after soybean decline, and percent contribution of Heilongjiang provincial N balance increase from the change of cultivated area and change of per hectare N balance (*C*). The *Left* bar in *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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Supporting Information

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Supporting Detailed Methods for the Analysis at the Regional Level

Calculation of Provincial N Balance. N balance at the regional level (*PB*, Eq. **S1**, below) equals the sum of per hectare N balance of soybeans (*SB*), corn (*CB*), and rice (*RB*) multiplied by provincial area of soybeans (*SA*), corn (*CA*), and rice (*RA*), respectively (34). The per hectare N balance provides important information for diagnosing nutrient budget and managing fertilizer application. It is the difference between per hectare N input and per hectare N output (33). Per hectare N input in soybeans, corn, and rice was estimated from N application we surveyed, because there was limited manure application in Heilongjiang during the study period. We used the empirical value 60 kg/ha as an approximation for the N fixed by soybeans (32). N output is approximately equal to the sum of N in grain and stover (40–42). Per hectare N outputs of the three crops were calculated with equations derived from empirically statistical relationships (i.e., using grain weight to measure stover weight, and then calculating the N in grain and stover by respective N%) (44). The statistical relationships (soybeans: Eq. **S1**, corn: Eq. **S2**, rice: Eq. **S3**) between N% in grain and stover (Table S3) were estimated from long-term multisite experiments across Heilongjiang and provided by the Institute of Soil Fertilizer and Environmental Resources, Heilongjiang Academy of Agricultural Sciences (33, 45–48).

$$y = 1.0811x + 269.6 \qquad \textbf{[S1]}$$

where x is grain weight of soybeans, y is stover weight of soybeans, $R^2 = 0.537$, and $P < 0.01$;

$$y = 0.8509x + 3274.1 \qquad \textbf{[S2]}$$

where x is grain weight of corn, y is stover weight of corn, $R^2 = 0.582$, and $P < 0.01$;

$$y = 0.939x + 213.56 \qquad \textbf{[S3]}$$

where x is grain weight of rice, y is stover weight of rice, corn, $R^2 = 0.564$, and $P < 0.01$.

For each crop, change in its provincial N balance is determined by changes in per hectare N balance and cultivated area:

$$PB = SB \times SA + CB \times CA + RB \times RA \qquad \textbf{[S4]}$$

Control Group. Crop conversion and change in per hectare N application are two factors influencing provincial N balance. A control group ($PB_{control}$) was established to understand the provincial N balance if there was no significant crop conversion after 2009: that is, respective area proportions of the three crops remained unchanged (no significant crop conversion before soybean decline; i.e., before 2009, confirmed by *t* test). The total areas of the three crops (total areas increased) and per hectare N application used were empirical data after soybean decline in the control group (only proportion of each crop on total area was controlled: that is, the proportion of each crop before and after 2009 remained the same). Thus, $PB_{control}$ is calculated as follows:

$$PB_{\text{control}} = SB_{\text{after}} \times (SP_{\text{before}} \times A_{\text{after}}) + CB_{\text{after}} \times (CP_{\text{before}} \times A_{\text{after}}) + RB_{\text{after}} \times (RP_{\text{before}} \times A_{\text{after}}) \qquad \textbf{[S5]}$$

where SP_{before}, CP_{before}, and RP_{before} are the respective area proportion of soybeans, corn, and rice before soybean decline and A_{after} is the total area of the three crops after soybean decline.

Contribution of Two Factors. 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). Specifically, we calculated the percent contribution of the change of cultivated area (c) to the change of provincial N balance (NB_{cp}) as

$$NB_{cp} = (NB_2 - NB_1 - NB_p)/(NB_2 - NB_1) \times 100\% \qquad \textbf{[S6]}$$

where NB_1 and NB_2 are the provincial N balance at time 1 (before soybean decline) and time 2 (after soybean decline). NB_p is the change of the provincial N balance due to the change of per-ha N balance ($p_2 - p_1$): $NB_p = (p_2 - p_1) \times c_1$. Cultivated area at time 1 (c_1) was used (when NB_p was computed) to see how much the provincial N balance would change at time 2 if the cultivated area remained constant.

The percent contribution of change in per-ha N balance p to the change of provincial N balance (NB_{pp}) is the total contribution minus the contribution due to the change of cultivated area:

$$NB_{pp} = 100\% - NB_{cp} \qquad \textbf{[S7]}$$

Statistical Analysis: Factors Affecting Crop Conversion. To understand crop conversion, we asked household heads about their planted areas of soybeans, corn, and rice in the survey. Because increased crop area may hide the actual change of its importance (e.g., planted area may increase, but proportion of each crop area out of the total planted area at the household level may decrease), we calculated the area proportion of soybeans among the three crops to indicate the importance. Crop conversion is represented by the difference of soybean area proportion before and after soybean decline. Then, we asked for reasons that could influence crop conversion, including sociodemographic factors (Table S4), and main input and output factors of agricultural practice (Table S5) before and after soybean decline. We performed a multivariate regression to identify the significant factors influencing crop conversion, where variance inflation factor (VIF) (VIF > 10) was used to manage collinearity (49).

Household heads' attitudes toward soybean imports were the most significant factor behind the crop conversion (see Table S4 for results of multivariate analysis). Specifically, negative attitudes toward soybean imports ($P < 0.01$) led households to abandon soybeans and grow corn and rice (Table S6) because the imported soybeans had lower prices than domestic soybeans. Meanwhile, male-dominated families ($P < 0.01$) also tended to grow more corn and rice, crops that are more labor-intensive, but also more profitable than soybeans (Table S6).

Calculation of N Pollution if a Higher Fertilizer Efficiency Is Adopted. N fertilizer efficiency can affect N pollution. N fertilizer efficiency varies among countries. For example, corn's N fertilizer efficiency is 57% in the United States (50), 29.1% in China as a whole (16), and 43.6% in Heilongjiang Province of China (51). N fertilizer application to cornfield in China was 274 kg/ha (2005–2015) (16), and 207 kg/ha in Heilongjiang (from our survey for the period 2010–2013). Thus, if the N fertilizer efficiency in the United States is achieved in Heilongjiang, farmers in Heilongjiang would need to apply 49 kg less fertilizer per hectare and cause less pollution (68 instead of 117 kg N/ha) but still have the same amount of N for corn. The steps of calculation are as follows:

i) N currently used (N fertilizer application × N fertilizer efficiency): 207 × 43.6% = 90 kg N/ha;
ii) N currently not used (wasted or polluted from N fertilizer input) (N fertilizer application – N currently used): 207–90 = 117 kg N/ha;
iii) N needed if the N fertilizer efficiency in the United States is achieved (N currently used divided by the N fertilizer efficiency in the USA): 90 ÷ 57% = 158 kg N/ha;
iv) Less N fertilizer application if farmers in Heilongjiang can reach the N fetilizer efficiency in the United States (Current N fertilization application – N needed if the N fertilizer efficiency in the United States is achieved): 207–158 = 49 less kg N/ha;
v) N not used (wasted or pollution from N fertilizer input) if the N fertilizer efficiency in the United States is adopted (N needed according to the N fertilizer efficiency in the USA – N currently used): 158–90 = 68 kg N/ha.

This suggests that N pollution is still significant (68 kg N/ha), even if the N fertilizer efficiency in the United States is adopted in Heilongjiang. To calculate the new per hectare N balance if the N fertilizer efficiency in the United States is adopted in Heilongjiang, however, new coefficients or indices (e.g., yield and N in different parts of the crop can be different) (Fig. S1) are needed. Despite the lack of such information, the N balance is still positive although it can be reduced.

Rotation, the Need for N Fertilizer, and N Balance. Rotation between soybeans and other crops may affect the need for N fertilizer and thus N balance. Soybeans have "priming effect" on soil organic matter. Thus, in the United States Corn Belt, N fertilizer recommendations for corn following soybean are substantially less than for corn following corn. This occurs despite the fact that soil organic matter is "mined" (also called N mineralization from soil organic matter) because the carbon balance of a soybean crop is decidedly negative (18). So, when the N mining from soil organic matter is considered, which is an N input in the N balance equation, the N balance for soybeans will not be so negative, and thus the increase in N surplus when converting from soybean to grain crops will not be as large.

In our study region, however, crop rotation is rather limited. Farmers in Heilongjiang plant corn continuously, where they gradually increase N application annually to maintain/increase yield, rather than rotate with soybeans (according to our surveys 2013 and 2016). Most residuals are burnt after harvest (in October). Heilongjiang is the northernmost province in China with low temperature in winter and strong wind in spring, so N mineralization from soil organic matter is limited and can be ignored. If we do not consider the N mining, the N balance in soybean land was −105 kg N/ha (1998–2009) and −92 kg N/ha (2010–2013), respectively. If we subtract 60 kg N/ha, the N balance in soybean land would be −45 kg N/ha (1998–2009) and −32 kg N/ha (2010–2013) (52). Although the value would change, the N balance for soybeans is still negative even with mining soil organic matter.

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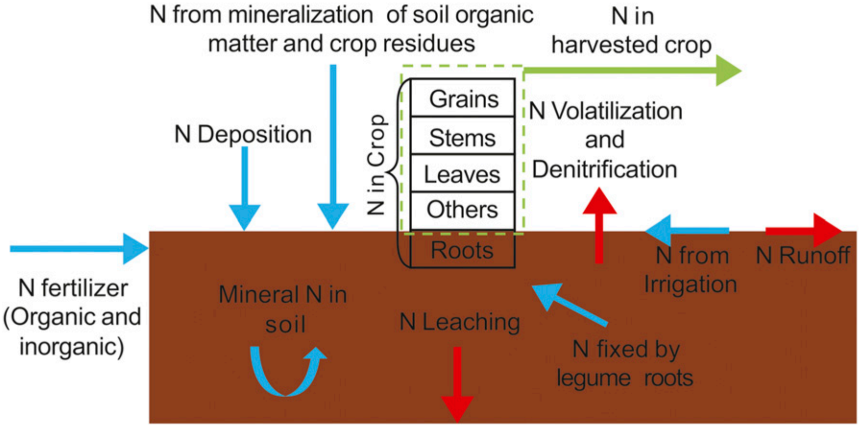

Fig. S1. Illustration showing N dynamics in an agricultural system (38). Blue arrows refer to N input, red arrows indicate N loss, green arrow refers to N output, and green dashed rectangle indicates N in harvested crop parts. N Balance = ΣN inputs − ΣN outputs. Application of N fertilizer is the main N input, including organic (e.g., manure) and inorganic N. N fixed by legume roots is also considered as N input. Other minor N inputs include N deposition, N from mineralization of soil organic matter and crop residues, mineral N in soil, and N from irrigation, which were not included in our calculation. N in crop (soybeans, corn, and rice here) after harvest is the main N output, where most N concentrates in grains, stems, and leaves (40–42). N in roots and others (like ear, stubble, cob in corn) is rare. Roots are left on the sites after harvest and plowed in the next year.

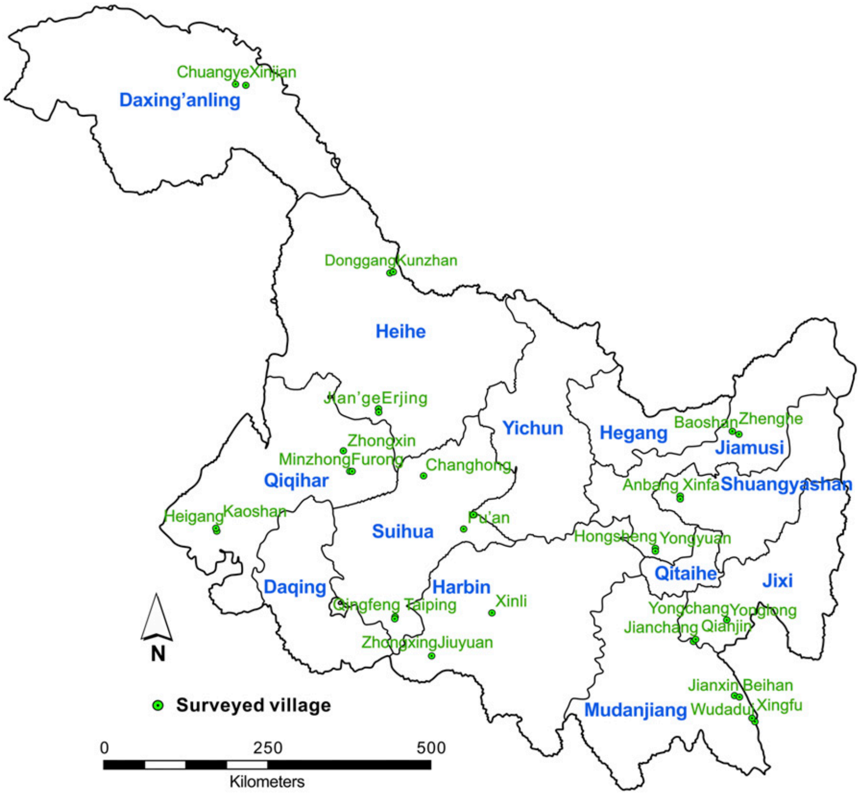

Fig. S2. Map of Heilongjiang Province showing its 13 prefectures (large font in blue), where names and locations of 33 surveyed villages were marked (small font in green). We allocated the number of survey villages according to the change rate of soybean lands among 13 prefectures. Four prefectures (Hegang, Qitaihe, Daqing, and Yichun) were not included in the survey because they are not major agricultural prefectures, and the sum of their soybean areas only accounts for about 6% of the provincial total (34).

Table S1. Top 10 destinations (importers) of the exported soybeans from Brazil and the United States, where their soybean land dynamics from 2010 to 2014, crop conversion due to soybean imports, and supporting references are provided

Exporter	Top 10 importers	Soybean land dynamics (2010–2014)	Crop conversion	References
Brazil	China	Decrease	Soybeans to corn and rice	(53)
	Japan	Decrease	Soybeans to wheat	(54)
	Thailand	Decrease	Soybeans to corn and rice	(55)
	Vietnam	Decrease	Soybeans to corn	(56)
	Italy	Increase*	Corn to soybeans	(57)
	Netherlands	Limited area (<1,000 ha)		
	Saudi Arabia	Limited area (<1,000 ha)		
	Spain	Limited area (<1,000 ha)		
	Taiwan	Limited area (<1,000 ha)		
	United Kingdom	Limited area (<1,000 ha)		
United States	China	Decrease	Soybeans to corn and rice	(53)
	Egypt	Decrease	Soybeans to vegetables	(58)
	Indonesia	Decrease	Soybeans to corn and rice	(31)
	Japan	Decrease	Soybeans to wheat	(54)
	Vietnam	Decrease	Soybeans to corn	(56)
	Korea	Increase*	Rice to soybeans	(59)
	Mexico	Increase*	Corn to soybeans	(22, 60)
	Germany	Limited area (<1,000 ha)		
	Spain	Limited area (<1,000 ha)		
	Taiwan	Limited area (<1,000 ha)		

Data sources are from Food and Agriculture Organization (13).
*Soybean increase in Mexico came from the replacement of corn because Mexico has legally approved the genetically modified soybeans, which is more profitable (22, 29, 60). Soybean increase in Korea came from the replacement of rice paddy, because of the implementation of new policy to control rice overproduction (59). Soybean increase in Italy came from the replacement of corn, mainly because of enormous demands within European Union (61, 62).

Table S2. Sampling stratification by categories of soybean change rate: first (0, −25%), second (−25%, −50%) and third (−50%, −75%) in 13 prefectures of Heilongjiang, where soybean planted area in 2009 and 2012 (unit: 10,000 ha), and change rates are listed

Category	Region	2009	2012	Change rate (%)
First	Daxing'anling	11.1	11.0	−1.5
	Yichun	16.4	12.7	−22.4
	Mudanjiang	24.2	18.7	−22.9
Second	Daqing	4.7	3.3	−30.6
	Qiqihar	85.7	55.9	−34.8
	Heihe	86.2	53.6	−37.8
	Harbin	40.4	20.5	−49.3
Third	Qitaihe	7.0	3.3	−52.1
	Jixi	19.3	7.2	−62.4
	Jiamusi	66.5	22.2	−66.6
	Suihua	36.7	11.9	−67.6
	Shuangyashan	15.7	4.7	−70.2
	Hegang	6.8	1.7	−74.6

First category is slight decrease category, second category is moderate decrease category, and third category is dramatic decrease category (34).

Table S3. N% of crop grain and stover used in the calculation, Heilongjiang

	N%		
Grain or stover	Soybeans	Corn	Rice
Grain	6.597	1.096	0.965
Stover	0.701	0.726	0.662

Data were estimated from long-term multisite experiments across Heilongjiang, provided by the Institute of Soil Fertilizer and Environmental Resources, Heilongjiang Academy of Agricultural Sciences.

Table S4. Statistical summary of sociodemographic factors in survey data at the local level, including factor names, their description, mean, and SD

Factor	Description	Mean	SD
Household member	No. of family members	3.78	1.28
Household farmer member	No. of family's farmer members	2.67	0.85
Household gender ratio	Male = 0; female = 1	0.47	0.15
Household farmer gender ratio	Male = 0; female = 1	0.48	0.16
Household age	Year	40.12	10.76
Household farmer age	Year	45.51	8.58
Household head age	Year	47.45	9.73
Household education	Year	8.26	1.90
Household farmer education	Year	8.16	1.66
Household head education	Year	8.14	2.15
Occupation	Farmer = 0; nonfarmer = 1	0.29	0.23
Household head's perception toward soybean imports	Very negative = 1; negative = 2; neutral = 3; positive = 4; very positive = 5	2.50	0.73

Nonfarmer members (e.g., migrant workers and students) do not participate in the cultivation decision, so only the information of family's farmer member was included in the final model. Family's farmer members above 60 y old were also treated as nonfarmer members.

Table S5. Statistical summary of inputs/outputs factors in survey data at the local level, including factor names, their description, mean, and SD

		After soybean decline		Before soybean decline	
Factor	Description	Mean	SD	Mean	SD
Soybean gross income	Yuan/ha	7,414	1,707	5,344	1,934
Corn gross income	Yuan/ha	13,278	2,914	7,440	2,706
Rice gross income	Yuan/ha	20,747	4,950	17,602	5,633
Soybean N cost	Yuan/ha	98	43	73	30
Soybean P cost	Yuan/ha	446	194	314	134
Soybean K cost	Yuan/ha	242	101	104	41
Corn N cost	Yuan/ha	802	368	507	197
Corn P cost	Yuan/ha	397	134	198	66
Corn K cost	Yuan/ha	406	135	132	43
Rice N cost	Yuan/ha	891	399	630	298
Rice P cost	Yuan/ha	316	151	207	103
Rice K cost	Yuan/ha	419	142	189	59
Soybean pesticide & herbicide cost	Yuan/ha	308	162	151	103
Corn pesticide & herbicide cost	Yuan/ha	265	176	103	110
Rice pesticide & herbicide cost	Yuan/ha	476	268	295	186
Gross family income	10,000 Yuan	6.94	7.86	3.81	4.20
Soybean machinery cost	Yuan/ha	1,400	530	540	135
Corn machinery cost	Yuan/ha	2,650	897	975	324
Rice machinery cost	Yuan/ha	3,750	2,181	1,940	354
Rent area of rainfed land	Ha	3.81	4.51		
Rent area of paddy land	Ha	2.02	3.82		
Rent of rainfed land	Yuan/ha	5,220	2,057		
Rent of paddy land	Yuan/ha	9,082	1,823		

Proportions of soybeans, corn, and rice here are calculated by using the area of soybeans, corn, and rice to divide the area sum of three crops, respectively. During the survey we found that a number of farmers had moved out of villages in Heilongjiang and become residents in cities, driven by urbanization. Most of them had rented their lands to the nearby villagers in recent years (actively since the end of 2000s in Heilongjiang), so we included information of farmland rent (rent area and rent fee) 2010–2013 in the survey. Currency exchange rate in 2013: 1 USD = 6.196 RMB.

Table S6. Results of multivariate regression analysis at the local level, including factor names, VIF, coefficient, and *P* value

Factor	VIF	Coefficient	*P* value
Household farmer number	1.04	0.52	0.32
Household farmer gender ratio	1.05	0.51	0.00***
Household farmer age	2.67	0.01	0.52
Household head age	2.41	0.26	0.05*
Household farmer education	2.78	0.00	0.38
Household head education	2.60	0.00	0.54
Household head's perception toward soybean imports	1.10	−0.01	0.00***
Gross agricultural income$_{(after\ -\ before)}$	1.25	0.00	0.15
Fertilizer cost$_{(after\ -\ before)}$	1.90	0.14	0.33
Farm machinery cost$_{(after\ -\ before)}$	2.30	−0.00	0.00***
Gross family income$_{(after\ -\ before)}$	2.14	0.00	0.19
Pesticide and herbicide cost$_{(after\ -\ before)}$	1.07	0.00	0.00***
Farmland rent area	1.52	0.00	0.77
Farmland rent	2.08	0.00	0.63

R^2 = 0.52 and adjusted R^2 = 0.51. Coefficient and *P* value (****P* ≤ 0.001 and **P* ≤ 0.1) indicated that Household farmer gender ratio and Household head's perception toward soybean imports are two significant factors exhibiting strong influences. Coefficients of farm machinery cost$_{(after\ -\ before)}$ and pesticide and herbicide cost$_{(after\ -\ before)}$ are too small to be influential, verified by standardized coefficients [farm machinery cost$_{(after\ -\ before)}$: −0.07, pesticide and herbicide cost$_{(after\ -\ before)}$: 0.08, Household farmer gender ratio: 0.49, and household head's perception toward soybean imports: 0.67]. We excluded interaction terms, because they did not improve model interpretation.

Table S7. Provincial water requirements of three crops before and after soybean decline and control group in Heilongjiang Province

Crop	Before soybean decline	After soybean decline	Control group
Soybeans	124.6	109.8	171.7
Corn	117.9	212.5	162.4
Rice	83.9	139.8	115.6
Total	326.4	462.0	449.7

Unit: 10^8 m^3. We acquired data on annual water requirements of soybeans (370.7 mm/y), corn (433.8 mm/y), and rice (467.4 mm/y) from long-term experiments conducted in northeast China (63), and calculated the total water requirements by multiplying annual water requirements and respective cultivated areas (34). We built the control group by following the same procedure described in the supporting detailed methods for the analysis at the regional level (*SI Materials and Methods*). The results indicated that crop conversion consumed more water (12.3×10^8 m^3).