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Abstract

As with life cycle assessment (LCA) studies in general, agricultural LCAs often rely on static and outdated inventory data, but literature suggests that agricultural systems may be highly dynamic. Here, we applied life cycle impact assessment methods to investigate the trends and underlying drivers of changes in non-global environmental impacts of major crops in the US. The results show that the impact per hectare corn and cotton generated on the ecological health of freshwater systems decreased by about 50% in the last decade. This change is mainly due to the use of genetically modified (GM) crops, which has reduced the application of insecticides and relatively toxic herbicides such as atrazine. However, the freshwater ecotoxicity impact per hectare soybean production increased by 3-fold, mainly because the spread of an invasive species, soybean aphid, has resulted in an increasing use of insecticides. In comparison, other impact categories remained relatively stable. By evaluating the relative ecotoxicity potential of a large number of pesticides, our analysis offers new insight into the benefits associated with GM crops. Our study also implies that because different impact categories show different degrees of changes, it is worthwhile focusing on the rapidly changing categories when updating agricultural LCA databases under time and resource constraints.

1. Introduction

Agriculture is essential for feeding a majority of the global population, but it has also been identified as one of the major drivers behind various global environmental degradations [1–3]. Due to a quintupling of global fertilizer use in the past decades, agriculture has greatly disturbed the global nitrogen and phosphorus cycles [4]. This results in a wide range of environmental issues from release of N_2O, formation of photochemical smog over large regions of earth, to accumulation of excessive nutrients in estuaries and costal oceans [3]. Agriculture dominates pesticide use [5], which contaminates surface and ground water and threatens human and ecological health [6, 7]. So also does agriculture dominate freshwater withdrawal worldwide [8], adding stresses where there are competing needs for water [9]. Despite the severity of existing environmental impacts of agriculture, the challenge of addressing them is compounded by increasing global food demand [10]. Continuous global population growth and spread of economic prosperity [11], mainly in developing countries, will likely drive the global food demand to double by 2050 [12].

Over the past decade, life cycle assessment (LCA) has been increasingly applied to agricultural and food products [13, 14], with a number of agricultural LCA databases developed worldwide recently [15–19]. LCA is a tool that quantifies products' environmental releases and resource use throughout the life cycle and evaluates the potential impacts they generate on human and ecological health [20]. Impact categories evaluated in LCA span a wide range, from global warming, ozone depletion, acidification, eutrophication, to ecotoxicity, human health cancer, and human health non-cancer [21]. Applications of LCA in agriculture include comparing the environmental performance of alternative products or technologies [22], such as organic versus conventional farming [23], and identifying hotspots and improvement opportunities [24]. In particular, LCA has played an active and important role in assessing the environmental benefits of bioenergy [25] and contributed to the making of public climate policies [26].

As with LCA studies in general, agricultural LCAs often rely on static and single-year inventory data with commonly 5–10 years of data age. In the Ecoinvent (version 2.2) database, for example, the data year for *US Corn Farming* is around 2005 and for *Swiss Corn Farming* is around 2000 [27]. Literature suggests, however, that agricultural systems may be highly dynamic due in part to the increasingly changing climate [28] and technological advances such as improved yield and energy efficiency [29]. These factors may bring about significant changes in the use of input materials and the yield of crops, hence significant changes in the environmental impacts. For example, direct energy inputs per ha corn produced in the US declined by about 40% between 1996 and 2005 and in the meantime corn yield increased by about 30% [30].

In this study, we seek to evaluate if ongoing changes in input use and structure of four major crops in the US might have resulted in significant changes in their environmental impacts over the past decade, focusing on regional issues such as eutrophication, acidification, and ecological toxicity. The crops studied are corn, soybean, wheat, and cotton, which together account for around 70% of total harvested area domestically [31]. The main objectives of the study are to understand the extent to which different environmental impacts might have changed and to identify major drivers behind such changes.

2. Materials and methods

2.1. Method

Following previous LCA studies [32–34] we analyzed the cradle-to-gate life cycle environmental impacts of 1 ton and 1 hectare (ha)-year of crop production. The system boundary covers both direct and supply chain environmental releases associated with crop cultivation and harvest. Direct releases, such as nutrient leaching and runoff, result from the use of agricultural inputs. Indirect environmental releases occur along the upstream supply chain, including those from production and transportation of agricultural inputs like synthetic fertilizers. In previous analyses [35, 36], we have identified direct environmental releases as the major source of the overall life-cycle impacts of crops, thus in this study our data collection and analysis efforts were focused on direct releases. For supply chain environmental releases, we used the Ecoinvent database (version 2.2) [27].

We began with collecting data on the use of agricultural inputs in different years, and then estimated associated environmental releases based on environmental statistics and models. The releases data compiled were next aggregated using characterization models from Life Cycle Impact Assessment (LCIA) [37] to quantify their relative magnitudes of environmental impact. Equation (1) summarizes this calculation:

$$E_{i,k} = \sum_j C_{i,j}\left(m_{j,k}^D + m_{j,k}^I\right), \tag{1}$$

where i denotes impact category, k crops, and j environmental releases. m^D and m^I represent direct and indirect environmental releases, respectively. And C represents characterization factors used to aggregate releases j into characterized environmental impact scores E.

A characterization factor in LCA reflects the potency of an environmental exchange relative to that of a reference exchange for a given impact category [38]. Global warming potentials, for example, are commonly used characterization factors in LCA for the impact category of climate change. Characterization factors used in this study are from the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) version 2.0 developed by the US Environmental Protection Agency [39]. As our study targeted non-global impacts, the impact categories selected from TRACI 2.0 are acidification (air), eutrophication (water), smog formation, freshwater ecotoxicity, and human health criteria (air), cancer, and non-cancer (e.g., reproductive, developmental, and neurotoxic effects). Tale S1 in the supporting information (SI) provides a detailed explanation of these impact categories. Categories excluded from TRACI 2.0 are global warming, ozone depletion, and eutrophication (air). We also included irrigation water use as an indicator of the stress crops place on water scarcity. We excluded water use embodied in other inputs than irrigation partly because of a mismatch between the data years for irrigation water and other inputs like fertilizers (see section 2.2) and partly because embodied water in agricultural inputs is generally negligible relative to irrigation water use [36, 40].

2.2. Data on agricultural inputs

Major agricultural inputs include fertilizers, pesticides, irrigation water, and energy [35]. Data on fertilizer and pesticide use are from the US Department of Agriculture (USDA) [41], which surveys farmers in top-producing states annually on a rotating basis (table 1). We selected the years with the largest number of states covered for each crop to best represent US national situations. We found that top-producing states were consistently surveyed in the years selected for each crop, which ensures comparability across years. For example, the same 19 states were covered for corn and they accounted for around 95% of total corn area harvested in each of the years selected. Similarly, the same 9, 19, and 15 states were covered for cotton, soybean, and wheat, and these stated accounted for around 92%, 96%, and 88% of total area harvested, respectively.

Irrigation water use data are from the Farm and Ranch Irrigation surveys conducted also by USDA

Table 1. Number of states surveyed by USDA between 2000 and 2012[a].

	2000	01	02	03	04	05	06	07	08	09	10	11	2012
Corn	18	**19**	7	18		**19**					**19**		
Cotton	**11**	7		**12**		9		**11**			7		
Soybean	18	7	**20**		11	17	**19**						**19**
Wheat													
Durum	**1**		1		**2**		2			**3**			2
Spring	**4**		3		**7**		6			**7**			4
Winter	**16**		10		**14**		14			**16**			13

[a] Values in bold indicate years selected for analysis for each crop.

Table 2. Estimation of direct environmental releases from agricultural inputs.

Sources	Environmental releases	Ref/note
Nitrogen input	NH_3 to air	[50, 51]
	NO_x to air	[52]
	N runoff and leaching	[46]
Phosphate fertilizers	P runoff and leaching	[46]
	Heavy metals to soil	[53, 54]
Pesticides	Emissions to air	[48, 55]
	Runoff and leaching	[48]
	Releases to soil	[48]
Farm equipment	NO_x, SO_x, $PM_{2.5}$, PM_{10}, CO	[45]
	Speciated VOCs	[57]

[42], and the most recent three surveys for 2002, 2007, and 2012 were used for our analysis. State-level energy use data were also compiled from the USDA [43], but the data are somewhat outdated as they reflect crops planted in late 1990s or early 2000s. USDA has unfortunately ceased to update such data for most crops except for corn, which were updated to the year 2005 [30]. On the other hand, farms have become more efficient in response to rise in fuel and fertilizer prices in the last decade [44]. For example, on-farm energy use in corn production reduced by >20% between 2001 and 2005 [30]. To reflect the trend of farm energy efficiency gains, we adopted the estimates from the widely used GREET model [45], which shows an efficiency increase of about 30% for corn and soybean growth over the last decade. Few studies exist on cotton and wheat on-farm energy change, thus we assumed a similar 30% efficiency gain for them over the timescale investigated. Details on all the inputs applied to each crop can be found in tables S2–S6 (SI). Note that we did not consider nitrogen from manure considering that it is generally small relative to other nitrogen sources [46], and we estimated nitrogen input from biological fixation for soybean (see SI).

2.3. Direct environmental releases

Building on our previous studies [35, 36], we estimated a large number of substances (>100) from the use of agricultural inputs based on emission factors from various models and references (see table 2). Most of the substances covered are pesticides and speciated volatile organic compounds (VOCs). Details on all emission factors compiled can be found in tables S7–S12 (SI). In the context of characterization method in LCIA, it is important to clearly define 'release' and 'compartment of initial release', so that appropriate fate, transport, and exposure models are applied to release figures. For pesticide application several approaches have been utilized in LCA literature and databases. The Ecoinvent (v2.2) database, for example, assumes that all pesticides applied are released to agricultural soils [27]. In contrast, the PestLCI model treats agricultural soils as part of the technosphere and views pesticides released from soil as pollution [47]. Berthoud *et al* [48] and others, on the other hand, view that pesticides are released to multiple compartments (i.e., air, soil, and water) at the point of application [35, 48, 49]. We adopted the third approach in this paper. Specifically, we used a pesticide's vapor pressure to approximate its air emissions [48], assumed a generic factor of 0.5% of the total applied for pesticides lost to water systems through runoff and leaching [48], and assumed the remaining fraction, capped at 85% of the total applied, for pesticides emitted to soil [48].

Last, the data we compiled are at the state level, but given our emphasis on the change of environmental impacts of US agriculture on average we aggregated the state-level results to present totals. We also aggregated the three different types of wheat (winter, spring durum, and spring other) into one 'wheat' by adding up their annual agricultural inputs and outputs. In deriving the impacts per ton crop produced, we followed previous studies [30, 58] and used 3-year average yield data to reduce annual variation caused by possible extreme weather such as droughts and floods. For example, 2001 impact per ton for corn was calculated by dividing 2001 impact per ha by the average corn yield of 2000, 2001, and 2002.

3. Results and discussion

3.1. Changes in environmental impacts of US major crops

Figures 1 and 2 present our main results; because irrigation data span a different time frame, irrigation results are presented in a separate figure. Numerical information underlying figure 1 can be found in table S13 (SI). The major finding of our analysis is that

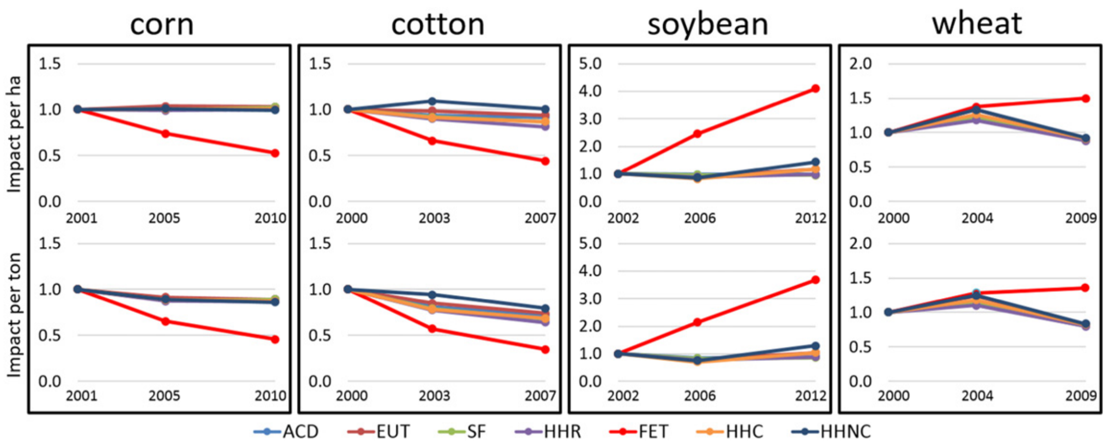

Figure 1. Changes in environmental impacts of US corn, cotton, soybean, and wheat. Impacts for different years were normalized to that for the base-year and expressed on the basis of impact per ha and per ton. ACD = acidification, EUT = eutrophication, SF = smog formation, HHR = human health respiratory, FET = freshwater ecotoxicity, HHC = human health cancer, and HHNC = human health non-cancer.

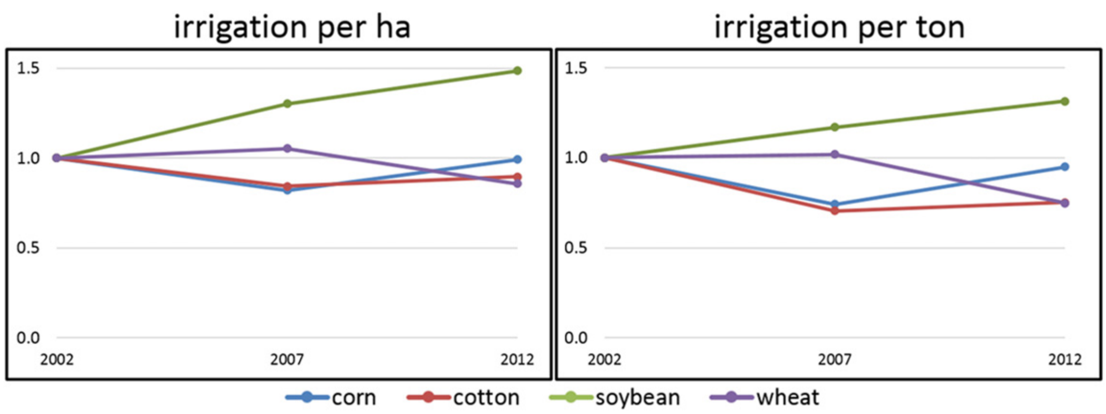

Figure 2. Changes in average on-farm irrigation water use per ha and per ton crop production, with results for different years normalized to that for 2002. Results for irrigation water per ha were derived from (*irrigation intensity for irrigated area × area irrigated*)/*total area harvested*.

freshwater ecotoxicity is the most dynamic of all impact categories, while the change is not unidirectional across the crops studied. We elaborate on this impact category, including its major contributors and probable drivers, in the next section (3.2). Here we focus on other impact categories.

Non-ecotoxicity categories were relatively stable over the past decade. Mostly, they changed 10–20% for each crop within the timescale studied. This is mainly because nutrient inputs—particularly nitrogen—are the major contributor for many of these impact categories. The use of nutrients results in both direct environmental releases (e.g., NH_3, NO_x, and nitrogen and phosphorus runoff) and indirect releases (e.g., such as NO_x) from the production of fertilizers. Also, fertilizers, particularly phosphate, introduce heavy metals into agricultural soils [54]. The total amount of nitrogen and phosphonate inputs remained largely unchanged for all of the crops over the periods investigated, and this is the main reason that most of the non-ecotoxicity impacts do not show a significant change.

For corn, soybean, and wheat, nutrients in general account for >75% of the non-ecotoxicity impacts (i.e., acidification, smog formation, eutrophication, human health cancer, non-cancer, and respiratory impacts). For cotton, energy use was intensive, about two times that of corn. As a result, nutrients account for around 50–80% for the non-ecotoxicity categories, while energy use contributes 25%, 40%, and 50% for acidification, smog formation, and human health respiratory impacts. For all crops, heavy metals introduced by phosphate fertilizers were identified to be the major contributor (60%–90%) to human health non-cancer impact.

As figure 2 reflects, changes in the average irrigation water use from 2002 to 2012 were also moderate for corn, cotton, and wheat, with variations <20% between 2002 and 2007 or between 2002 and 2012. In contrast, a noticeable upward trend can be observed for soybean. Average irrigation water use per ha soybean production increased by around 50%, from 180 m^3 in 2002 to 270 m^3 in 2012. On a per ton basis, the percentage increase is 30%, from 72 to 95 m^3, due to yield increase over the period. Behind this upward trend are several factors, including the slightly increasing irrigation intensity for irrigated area, but the major contributor is the growth in area irrigated (from 2.2 to 3.0 million ha) and its share in the total area harvested (from 7% to 10%). What led to the growth in soybean area irrigated is unclear, however, and further research is needed. Here, we offer a possible explanation. In the past 'ethanol decade', soybean and corn areas significantly expanded into other cropland and also grassland [59, 60]. Because such marginal land as grassland is on average not as fertile as existing corn or soybean fields [36], irrigation might have been applied to boost or maintain yield. Consequently, as total soybean and corn area expanded, so also did the area irrigated. In the case of corn, however, although area irrigated grew from 4.0 to 5.4 million ha between 2002 and 2012, its share in the total area harvested only slightly increased (from 14% to 15%). Additionally, irrigation intensity for area irrigated decreased from 3660 to 3350 $m^3\,ha^{-1}$. As a result, average irrigation use per ha or per ton corn production barely changed from 2002 to 2012.

3.2. Changes in freshwater ecotoxicity impact of US major crops

As reflected in figure 1, freshwater ecotoxicity impact per ha corn production decreased by around 50% from 2001 to 2010. Major contributors include reduced use of herbicides *atrazine* and *acetochlor*, and of insecticides *terbufos*, *dimethenamid*, and, especially, *chlorpyrifos* (figure 3). The downward trend is likely due to the continuous expansion of herbicide resistant (HR) and insect-resistant corn, particularly *glyphosate* tolerant and *Bacillus thuringiensis* (*Bt*) corn. Since its introduction in 1996, HR corn has now expanded to over 70% of cornfields [61], resulting in increasing use of *glyphosate* compounds in place of conventional herbicides like *atrazine* and *acetocholor*. In fact, *glyphosate* and related compounds had gradually surpassed *atrazine* and other herbicides over the past decade to become the most commonly applied pesticide [53]. As *glyphosate* compounds are relatively less toxic to ecosystems compared with the replaced herbicides like *atrazine* and *acetochlor* [62], the overall ecotoxicity impact of corn attributable to herbicides decreased moderately between 2001 and 2010. Meanwhile, *Bt* corn has also dominated US cornfields now [61], offering both economic and environmental benefits by protecting yield and reducing handling and use of insecticides [63]. This likely further contributed to the downward trend of corn's freshwater ecotoxicity impact.

Similar to corn, the freshwater ecotoxicity impact per ha cotton production decreased by 60% from 2000 to 2007, due to the reduced use of *chlorpyrifos*, *lambda-cyhalothrin*, and particularly *cyfluthrin* (figure 3). Application of *cyfluthrin* reduced from 11 g ha^{-1} in 2000 to 4 g ha^{-1} in 2007. Similar to corn, the downward trend in cotton's freshwater ecotoxicity impact was attributable to the expansion of HR and *Bt* varieties, which are now planted on 95% and 75% of US cotton fields respectively [61]. Our result on decreasing freshwater ecotoxicity impact of corn and cotton due to changes in pesticide use and patterns reinforces previous findings [63–65].

Unlike corn and cotton, soybean's freshwater ecotoxicity impact quintupled between 2002 and 2012. HR soybean has also expanded dramatically in the US, now planted on 95% of soybean fields [61]. Along with the expansion, application of *glyphosate* compounds per ha increased by over 60% between 2002 and 2012, and now they account for 80% of total pesticides applied in soybean growth. However, the benefits of HR soybean seem to have been entirely offset by the increasing use of insecticides *lambda-cyhalothrin*, *cyfluthrin*, and *chlorpyrifos* (figure 3). This is due to the invasion of soybean aphid, a species native to eastern Asia and first detected in North America in 2000, and application of insecticides has been the primary means of pest management [66]. Since its first detection, soybean aphid had rapidly spread to 30 states in the US by 2009 and become a major source of economic loss in soybean production [67]. As a result, the total quantity of insecticides applied to soybean quadrupled between 2002 and 2012, resulting in a 3-fold increase in soybean's freshwater ecotoxicity impact.

The freshwater ecotoxicity impact of wheat increased by about 40% from 2000 to 2009, attributable partly to increased use of several insecticides including *chlorpyrifos*, *cyfluthrin*, *beta-cyfluthrin*, and *lambda-cyhalothrin*. Also, pesticide application rate in general increased from 0.45 kg ha^{-1} in 2000 to 0.88 kg ha^{-1} in 2009. Unlike the other major crops, however, there is not a clear explanation for the upward trend. One possible reason may be the growing resistance of pests as a result of increasing pesticide use. Further research is needed in this area.

3.3. Sensitivity analyses

We conducted sensitivity analysis to test the robustness of the changes in freshwater ecotoxicity impact, considering that it is our major finding and that large uncertainty is involved in the estimation of pesticide releases and assessment of their ecotoxicity impact [62, 68, 69]. First, the proportion in which pesticides are emitted to water systems was identified as the major contributor to crops' freshwater ecotoxicity. Literature also shows it may vary greatly, from 5% [56] to 0.1% or even less [49, 68] (0.5% used in this study). We thus built three scenarios to test the sensitivity of the ecotoxicity result to different leaching and runoff rates. Additionally, we tested the sensitivity of the trends to other analytical approaches to pesticide releases (see section 2.3), with one assuming all

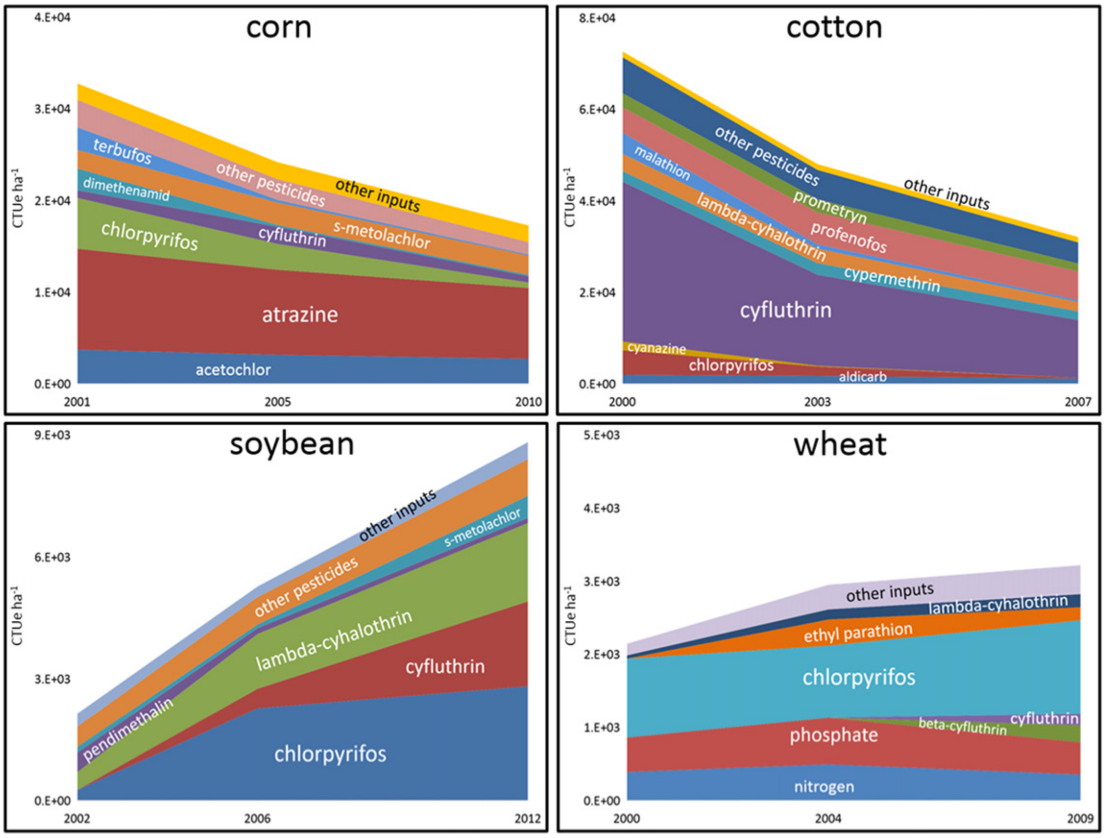

Figure 3. Changes in the composition of the cradle-to-gate life cycle freshwater ecotoxicity impact per ha corn, cotton, soybean, and wheat production over the past decade, expressed in comparative toxic units (CTU), which is a measure of the potentially affected fraction of species integrated over time and volume per unit mass of a chemical emitted.

pesticides to remain in soils and the other excluding the impact of pesticides on agricultural soils. All five scenarios are presented in figure 4, which reinforces the trends identified of freshwater ecotoxicity impact regardless of different runoff and leaching rates or different analytical approaches to pesticide releases.

Second, impact assessment of freshwater ecotoxicity is also highly uncertain, with the uncertainty range for TRACI 2.0 likely being 1–2 orders of magnitude [62]. However, detailed information on the distribution of each characterization factor is not available yet, thus a full uncertainty analysis is not feasible at this stage. To further test the robustness of the ecotoxicity results, we applied two other characterization models (i.e., IMPACT 2002+ and CML 2001) [70, 71] to evaluate the aquatic ecotoxicity impact of pesticide releases. For corn, cotton, and soybean, the other two models confirm the directionality of the changes but generally show a lower magnitude of change (figure 5). This is due in part to differences in the number of pesticides covered by the three models and in part to differences in the relative ecotoxicity potential they assign to each pesticide. Generally, IMPACT 2002+ and CML 2001 cover a smaller number of pesticides than TRACI 2.0, thus they may not capture all the changes in pesticide use and patterns that are captured by TRACI 2.0. For wheat, however, the results from the three characterization models disagree with regard to the directionality as well as the magnitude of changes (see SI). A detailed comparison, together with contribution analysis, is provided in the SI.

4. Conclusions

In this study, we evaluated several non-global environmental impacts of US corn, cotton, soybean, and wheat, and analyzed how they changed in the past decade. Due likely to the increasing adoption of genetically modified (GM) varieties, freshwater ecotoxicity impact per ha corn production declined by around 50% from 2001 to 2010 and per ha cotton production declined by 60% from 2000 to 2007. Due to the invasion of alien species (aphid) and increasing use of insecticides, freshwater ecotoxicity impact per ha soybean production increased by 3-fold from 2002 to 2012. In the meantime, on-farm irrigation water use per ha soybean harvested increased by about 50%. In comparison, other non-global impacts were relatively stable.

The major implication of our study is that identifying the underlying drivers of the dynamical mechanisms in agricultural systems would be essential for making informed agricultural decisions and policies, prioritizing LCA data update needs, and interpreting

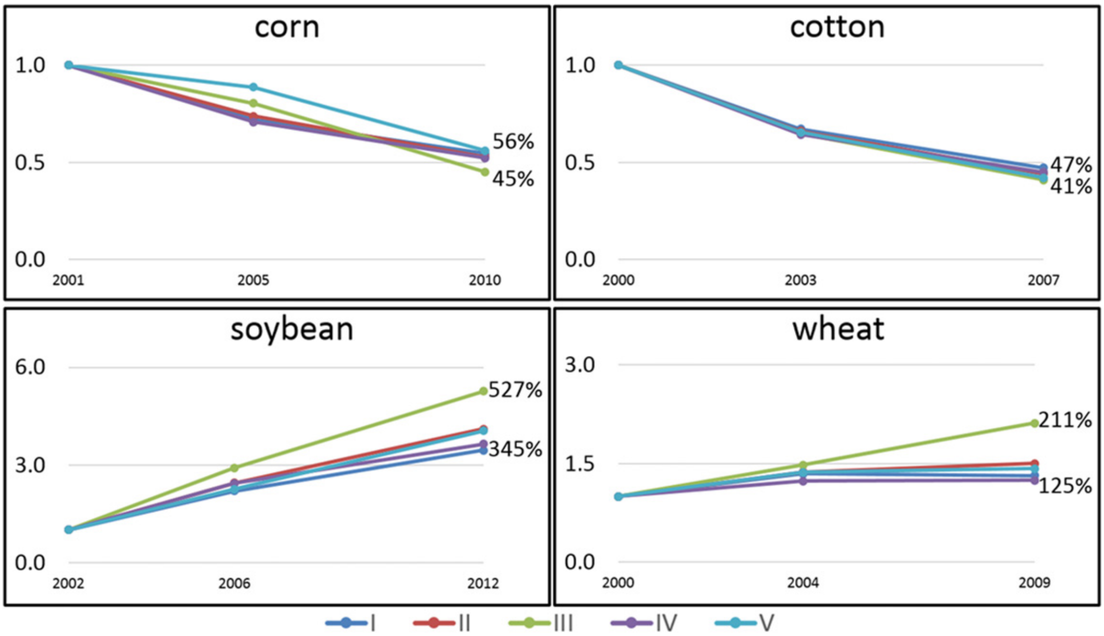

Figure 4. Changes in freshwater ecotoxicity impact per ha crop production based on different scenarios reflecting different pesticide runoff and leaching rates and approaches to pesticide releases. Results for different years were normalized to that for the base-year. Shown in each panel are maximal and minimal ratios, as an indicator of the variation of the scenarios tested. Scenario I = low runoff and leaching rate (0.1%); II = moderate runoff and leaching rate (0.5%, adopted in this study); III = high runoff and leaching rate (5%); IV = pesticides assumed to remain all in soil (100%); V = pesticides to soil considered as part of the technosphere and excluded from the overall ecotoxicity impact (with moderate runoff and leaching rate (0.5%) and estimation of pesticides to air based on their vapor pressure).

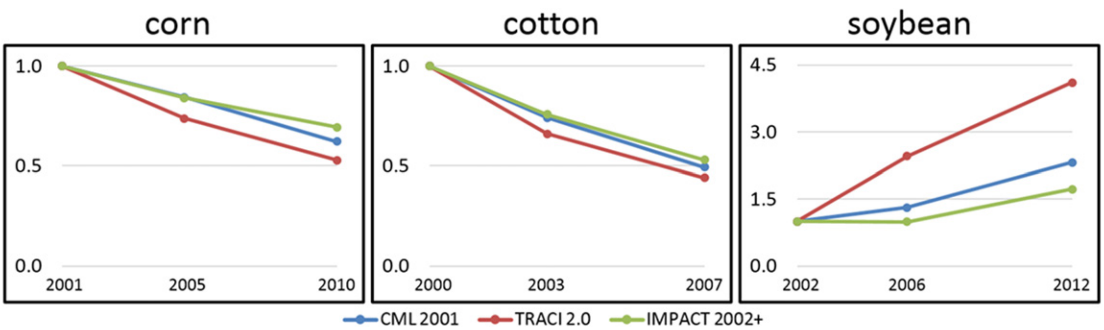

Figure 5. Changes in freshwater ecotoxicity impact per ha crop production using different LCIA characterization models, with a moderate runoff and leaching rate (i.e., 0.5%) assumed. Results for different years were normalized to that for the base-year.

LCA results. By evaluating the relative ecotoxicity potential of a large number of pesticides, we found that the use of GM crops have contributed to significant declines in corn and cotton's freshwater ecotoxicity impact. This finding provides an opportunity for better assessing the tradeoffs between the potential impacts of GM and conventional crops, as opposed to comparisons based mainly on the total quantity of pesticides applied [61]. Additionally, our results suggest that updates on agricultural inventory data can be done selectively, with regular updates needed for impact categories that are highly dynamic, such as pesticide related ecotoxicity. Studies relying on single-year and outdated data may inaccurately portray a crop's ecotoxicity impact; even just a few years of data age may substantially under or overestimate the ecotoxicity impact. This also implies that we should exercise caution when interpreting an LCA study in which ecotoxicity impact of agricultural processes plays an important role in the overall conclusion. Broadly, our study highlights the importance of understanding the dynamics in the input and output structure of a process or a technology in LCA [72, 73].

The focus of our study was to evaluate how environmental impacts of agriculture might have changed in the past decade. Our results that show decreasing freshwater ecotoxicity impacts for corn and cotton are not intended to prove that GM crops are overall more ecologically friendly than conventional crops. Other impacts of GM crops that could not have been evaluated due to the limitations of the current LCIA methods should also be taken into consideration in such comparisons. Current LCIA methods, for example, are not able to properly evaluate potential adverse effects of *Bt* toxin on populations of non-target species and elevated risk of species invasiveness through genetic modifications [74]. In addition, it should be noted that the trend of decreasing ecotoxicity impact is unlikely to continue for cotton and corn. Due to the dominant use of HR and *Bt* crops, pests and weeds have evolved to be increasingly resistant [75, 76]. As a result, farmers may need to resort to earlier pest control practices that rely more on conventional pesticides, hence increasing crops' freshwater ecotoxicity impact. Nevertheless, the dynamics of pest management, and associated ecological impacts, further corroborates the importance of understanding the dynamics of agricultural systems.

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