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Enhancing environmental sustainability in eastern Canada's corn agroecosystem with controlled drainage and subsurface irrigation

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ABSTRACT

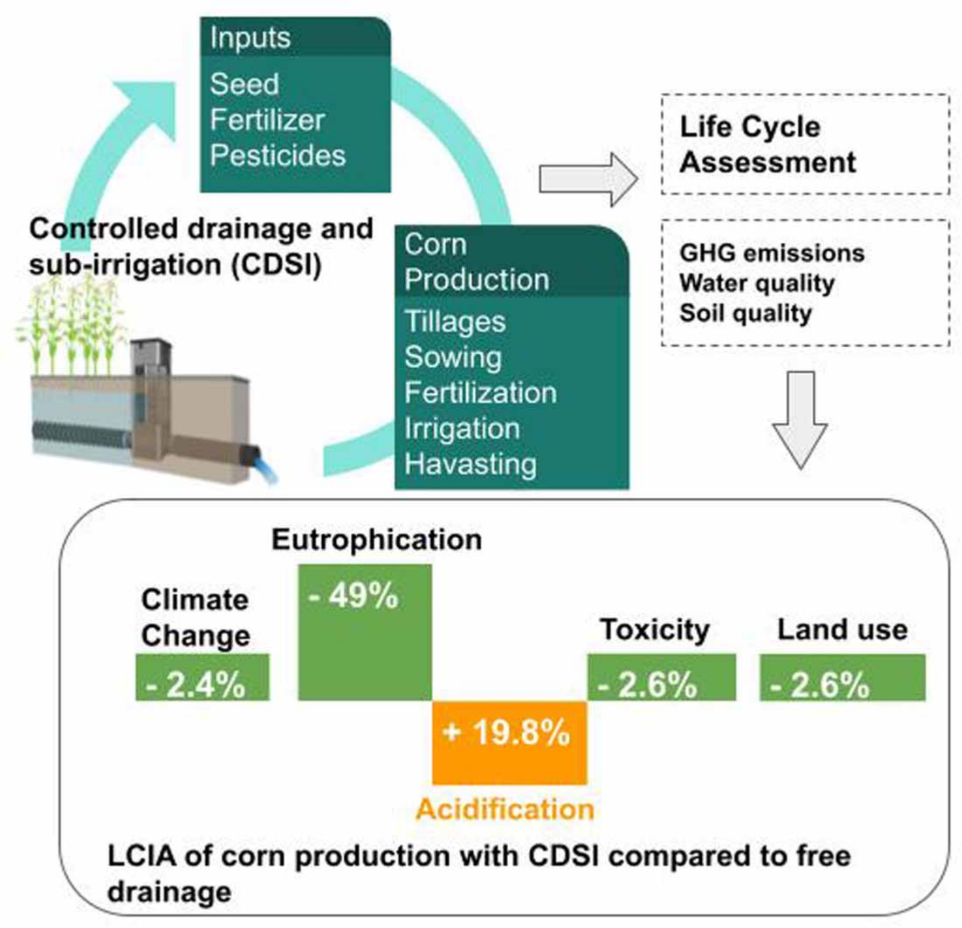
Water table management through controlled tile drainage and subsurface irrigation (CDSI), retrofitting to conventional tile drainage, has been developed to abate the environmental impacts of irrigation and drainage meanwhile supporting agroecosystems and crop productivity. Since the environmental profile of new technologies is a prerequisite to understanding their socio-economic benefits, a life cycle assessment was conducted to assess the environmental impacts of CDSI on corn production for the 2014 and 2015 growing seasons at St-Emmanuel, south-western Quebec in eastern Canada, compared to the free drainage (FD). Inventory flows of corn production with CDSI and FD were developed using biophysical data from field experiments and public databases. Then, environmental impacts were compared for corn production with CDSI and FD, including climate change, eutrophication potential, acidification potential, and toxicity. The assessment results show the environmental benefits of implementing CDSI, particularly in improving water quality. However, potential synergy and trade-offs of climate change, eutrophication, and acidification impacts from the implementation of CDSI, especially under different climatic conditions, should be further monitored to improve the performance of the technology. Nevertheless, CDSI and associated practices can be adopted as adaptation measures in agricultural water management to support agroecosystems and address the challenges posed by environmental impacts.

Key words: agroecosystem, controlled drainage with subsurface irrigation, corn grain, eastern Canada, life cycle assessment, water table management

HIGHLIGHTS

- This study compares environmental impacts of controlled drainage with sub-irrigation (CDSI) and free drainage (FD) for corn agroecosystems in eastern Canada.
- GHG fluxes data from the field were integrated into the life cycle inventory.
- CDSI has positive impacts in reducing environmental impacts of corn production on climate change and eutrophication compared to FD.
- Trade-offs between climate change, eutrophication and acidification may affect CDSI's environmental performance.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The utilization of irrigation and drainage systems in agriculture constitutes a crucial component in increasing water use efficiency and agricultural productivity. However, agricultural production-related environmental issues originating from irrigation and drainage may cause adverse environmental impacts. These detrimental environmental impacts are predominantly recognized as non-point pollution, including soil erosion, diminishing carbon sequestration of farmland, deterioration of water quality, and greenhouse gas (GHG) emissions (King *et al.* 2015, 2018; Plach *et al.* 2018). Research scholars also highlight the importance of understanding irrigation water quality and its impact on long-term productivity, as well as the impact of climate change (reduced rainfall irrigation in particular) on crop productivity (Çadraku 2021; Jabal *et al.* 2022).

The eastern Canadian region has witnessed the widespread adoption of tile drainage for draining the farmland during the spring and fall, due to the low terrain and relatively high precipitation (Morrison *et al.* 2014)[1]. However, free drainage (FD) may operate as pipes for the transportation of nitrates into open ditches and surface waters, increasing the concentration of chemicals (mainly nutrients and pesticides) in agricultural drainage water (Tanji & Keyes 2002). The other environmental risks are also aggravated by this drainage practice, including ammonia volatilization, nitrification and denitrification, and GHG emissions (Kanter *et al.* 2021). Controlled tile drainage and subsurface irrigation (CDSI) has been developed to address the setbacks of conventional drainage systems and improve agricultural water management. CDSI represents an innovative

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[1] Tile drainage technology has been implemented on more than 2.5 Mha of farmland in the eastern Canadian provinces of Ontario and Quebec (Canadian Council for Irrigation and Drainage 2018).

water management solution that can be retrofitted to FD systems, facilitating a flexible structure at the tile outlet[2]. The outlet can be elevated to reserve water in the soil profile during the summer and lowered before planting (and again before harvest) to manage outflow and maintain the desired water table, thereby ensuring a recycled water supply for crop growth.

The implementation of CDSI has shown significant agronomic and environmental benefits (Madramootoo *et al.* 1997; Rasouli *et al.* 2014). Controlled drainage is associated with 4% yield increases for corn and 3% yield increases for soybean crops in the St. Lawrence lowlands region of eastern Canada (Crabbé *et al.* 2012). In addition, studies have shown that CDSI can significantly reduce the annual loads and flow-weighted concentrations of nitrogen (Ritter *et al.* 1995; Elmi *et al.* 2004), retain soil nutrients (Ballantine & Tanner 2013), and decrease in-stream water phosphorus (P) loads (Bishop *et al.* 2005). Although CDSI has been found to decrease total GHG fluxes slightly, CH_4 fluxes may increase strongly[3] (Van Huissteden *et al.* 2006). Recent research has focused on the effects of agricultural water management on GHG emissions (Dinsmore *et al.* 2009; Hooijer *et al.* 2010; Musarika *et al.* 2017; Hagedorn *et al.* 2022).

The topography and soil type of farmland in eastern Canada offer favourable conditions for the adoption of CDSI, particularly in areas with poor drainage[4] (Land Improvement Contractors of Ontario 2008). Nevertheless, the implementation of CDSI faces obstacles due to limited research on its comprehensive environmental benefits. The absence of comprehensive environmental assessments curtails the knowledge of potential benefits and trade-offs of implementing CDSI, discouraging the investment and supportive policies for CDSI. In response to that, this study employed life cycle assessment (LCA) to assess the entire life cycle environmental impacts of a corn agroecosystem under CDSI compared to the status quo of FD in eastern Canada. By comparing the environmental performance of CDSI and FD in the corn agroecosystem, this study aims to provide insight into the potential environmental benefits and/or trade-offs of implementing CDSI. Consequently, this comprehensive assessment may support producers' investment of CDSI and further adoption of beneficial water management practices, concerning the interest of policymakers and other stakeholders.

The rest paper is structed as follows. Section 2 provides a detailed description of the study's methodology, including the research site and the steps taken to conduct a comparative LCA of a corn production system under CDSI and FD. Section 3 presents the results and discussions of the study, with a particular focus on comparing the environmental performance of CDSI and FD. Finally, in Section 4, the conclusions of the study are presented.

2. METHODS

2.1. Research site

This study builds upon long-term field experiments on a 4.2 ha field located in St-Emmanuel (Côteau-du-Lac), Quebec, to investigate the impacts of innovative agricultural water management systems. The topography of the research site is flat, with a slope of around 0.5% (Tait *et al.* 1995). Recent increases in drought conditions, characterized by low rainfall and high evaporation during the summer months, have been observed in the region. Historical monthly precipitation data from Environment and Climate Change Canada (2022) indicate that, from 1993 to 2017, rainfall from May to September was below the 40-year average for most years, with three consecutive years of drought occurring from 1993 to 1995, 2001 to 2004, and 2007 to 2010. These reduced precipitation levels highlight the need for irrigation. However, inadequate irrigation installations in this region have exposed the risks and vulnerabilities of agricultural production to climate change. For example, according to Census of Agriculture (2021), less than 10% of farmland was irrigated in Côteau-du-Lac in 2021, and only 2% in Quebec. The current state of irrigation infrastructure implies the potential benefits of implementing agricultural water management in this region to sustain agriculture under climate change.

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[2] A figure illustration and technical report of the CDSI can be found in Frankenberger *et al.* (2004). More information regarding the technology can be found in the following extension materials: 1. TRANSFORMINGDRAINAGE.org https://transformingdrainage.org/practices/controlled-drainage/; 2. Ontario Soil and Crop Improvement Association https://www.ontariosoilcrop.org/ and https://www.ontariosoilcrop.org/research-resources/research-projects/controlled-tile-drainage/; 3. Controlled Tile Drainage in Ontario – YouTube https://www.youtube.com/watch?v= sGeiOBwRHi8; 4. Controlled Tile Drainage in Eastern Ontario - YouTube https://www.youtube.com/watch?v=8knDWTos1i8.

[3] Wetter soil may increase the anaerobic bacterial decomposition of vegetable matter under water, which produces more CH_4.

[4] The topography of farmland in this region is formed by plains and lowlands, which can refer to The Atlas of Canada through https://atlas.gc.ca/phys/en/index.html. The common soil types in eastern Canada include organic, brunisolic, cryosolic, and podzolic soil. A map of soils in Canada can be found in https://sis.agr.gc.ca/cansis/publications/maps/soc/all/soils/soc_all_soils_2004en.png. CDSI operates well for these soil types to implement on-farm water table management.

In 2014 and 2015, the comparative experiments were conducted for two water management systems in split plots. The base scenario was FD, placing subsurface drainpipes of 76 mm diameter at the centre of each plot and 1 m below the soil surface. The treatment scenario was CDSI, which involved the installation of an excessive manual control structure to manage the water outflow. This device enables the manual addition or removal of stoplogs to maintain the desired water table level. Further details regarding the field experiments and raw data collection can be found in Crézé & Madramootoo (2019).

2.2. Conducting LCA on the corn production with CDSI compared to FD

LCA is a widely used method for the comprehensive evaluation of environmental impacts of various products and processes throughout their entire life cycle. ISO 14040:2006 and ISO 14044:2006 standards define the key stages in the LCA process (Finkbeiner *et al.* 2006), as illustrated in Figure 1. These stages include defining the goal and scope of the study, developing a life cycle inventory, conducting a life cycle impact assessment, and interpreting the results. LCA has been employed to assess a wide range of agricultural production systems, from crop production and processing to various farming practices, leading to its rapid development in the agricultural sector (Caffrey & Veal 2013).

2.3. Goal and system boundaries of the LCA in this study

This study compares environmental impacts of corn production with conventional drainage technology and CDSI using LCA. Specifically, the LCA focused on the cropping system under a new agricultural water management device, which upgraded the base technology to address agricultural sustainability. In other words, this study investigated the differences in environmental impacts between CDSI and FD technologies during the corn production process, which has not been explored in previous agricultural LCA that focus on the environmental outcome of the whole production process.

This study employed a typical corn grain production system suggested by Nemecek *et al.* (2014) to construct the system boundaries for a typical corn production system in North America (see Figure 2). The system boundaries encompassed

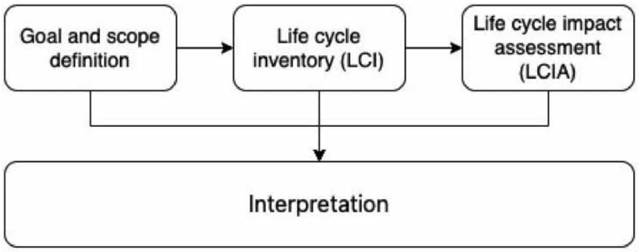

Figure 1 | The flowchart of four stages in LCA (adapted from ISO 14040:2006).

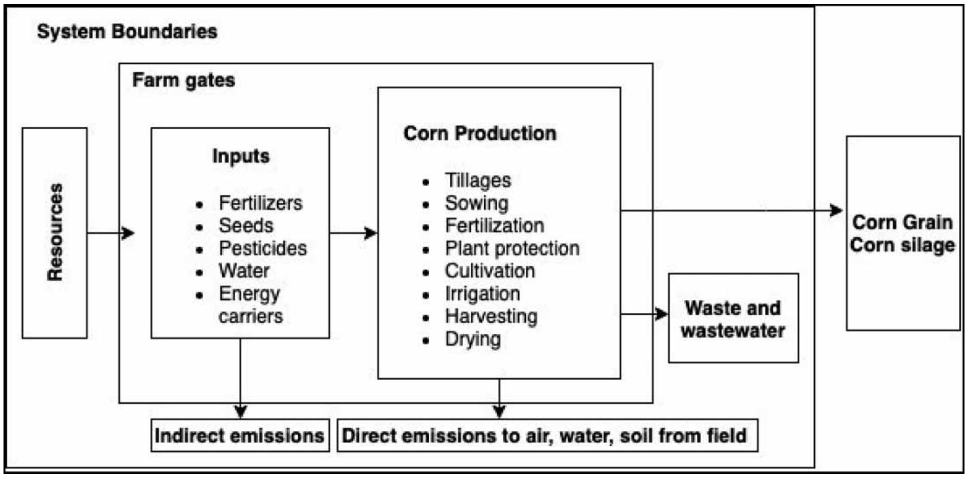

Figure 2 | System boundaries for the grain corn production system (adapted from Nemecek *et al.* (2014)).

the entire life cycle of the corn production system, starting from raw material production to crop harvesting and associated environmental emissions. The farming operations and direct production emissions to air, water, and soil from the field under CDSI and FD, were given particular attention to achieve the LCA goal of understanding and analysing the benefits of implementing CDSI for sustainable corn agroecosystems. Notably, only production processes and outcomes that are directly related to the agricultural water management were assessed in the LCA. Other factors such as farm infrastructure, transportation, and storage were not covered in the system boundaries. Moreover, the equipment used for CDSI was not the focus of this study as an industrial end product, and hence was not included in the LCA system boundaries. This approach allowed for a more focused and precise analysis of the environmental impacts of agricultural water management and a comparison between the two technologies, FD and CDSI, in terms of their sustainability performance.

2.4. Life cycle inventory

Data collection is crucial for developing a life cycle inventory that can assess regional differences in the environmental impacts of corn grain production (Boone *et al.* 2016). On-field nitrogen and pesticide emissions from the cultivation of the crop production systems should be precisely measured. However, because LCA was primarily established for industrial products and operations before being expanded to agriculture, it confronts challenges in investigating the environmental impacts of agricultural production processes (Caffrey & Veal 2013). Agricultural production processes often involve multiple products from a single cropping system, farm management practices, and new agricultural technologies, which can make it difficult to thoroughly examine them in agricultural LCA. Therefore, the foundation of developing agricultural LCA lies in a sufficient and reasonable database that includes all the essential processes of agricultural production, especially agricultural emissions data.

In this study, LCI data were sourced from both field experiments and measurements and existing agricultural LCI databases. This study used raw data and coefficient estimation of inputs to quantify the environmental inventory flows, and to measure and calculate emissions from crop production systems to soil, water, and air.

In terms of field data, this study collected operational and biophysical data during the 2014 and 2015 growing seasons, including fertilizer, herbicide, water use, grain yields and GHG emissions as primary data from corresponding experimental plots with CDSI and FD. Furthermore, emissions to soil and water were collected from a series of earlier studies comparing the environmental impacts of CDSI to FD at the same research site in earlier years, such as soil nitrate-N (NO_3-N) pollution and drainage water NO_3-N concentrations (Elmi *et al.* 2004), and phosphorus pollution in drainage water (Hebraud 2006; Valero *et al.* 2007). The raw emission data for corn production under the CDSI and FD were directly measured from farming experiments and sampling. For example, GHG samples were collected from each experimental spot using field-deployed, vented non-steady-state gas chambers to quantify weekly soil N_2O, CO_2, and CH_4 fluxes (Crézé & Madramootoo 2019). Additionally, a random-effects model was used to control for the influence of different temperatures and soil moisture on GHG emissions between 2014 and 2015. Daily GHG fluxes were weighed using a 40-year average temperature and precipitation. Thus, the inconsistency of climatic conditions between 2014 and 2015 did not reflect in the assessed GHG emissions of corn production under CDSI versus FD controlling time effects (2 years) and individual effects (two technologies). Although direct on-field sampling can only be applied to a few spot measurements due to high research expenditure, it provides a validated primary source for the comparable GHG emissions of corn production under two water management technologies.

This study also utilized the World Food LCA Database (WFLDB) v3.0 (Nemecek *et al.* 2014) and AGRIBALYSE v1.3 (Koch & Salou 2016) to supplement materials and input processes that could not be gathered from field measurements. LCI databases developed in various research formed the basis of a biophysical inventory of corn grain production based on comparable flows. Data from the agricultural LCI databases used in this study contained: (1) NH_3 emissions, (2) heavy metals emissions to agricultural soil, surface water and groundwater, (3) pesticide emissions, and (4) machinery for field operations. Notably, the origin of the supplemental databases was European, thereby limiting their application to different regions. Nevertheless, the use of secondary LCI databases and modeling techniques did not compromise the credibility and accuracy of the study's comparable LCA results, because of this study's reliance on validated data for assessing environmental impacts of corn production under CDSI and FD. Subsequently, input and output flows were established and measured in functional units following the quantitative analysis of resources, energy, and environmental emissions within the pre-defined life cycle boundaries.

2.5. Life cycle impact assessment

The life cycle impact assessment (LCIA) method used in this study was CML 2001, an intermediate point environmental impact analysis method issued by the Environmental Research Center of Leiden University (Guinée 2001). The study calculated the environmental impacts of corn production with CDSI and FD based on CML 2001 impact categories. To assess the net environmental impacts of CDSI implementation, the study compared the environmental impacts of corn production under these two water management systems. These environmental impact categories included land use (measured as Soil Organic Carbon (SOC)), climate change by CO_2 equivalent, eutrophication potential by PO_4^{3-}, acidification potential by SO_2 equivalent, human toxicity and ecotoxicity by 1,4 dichlorobenzenes (1,4-DCB).

3. RESULTS AND DISCUSSIONS

3.1. Life cycle impacts of corn production with CDSI and FD

Environmental impacts were compared for corn production from the 2014–2015 growing seasons with CDSI and FD, including climate change, eutrophication potential, acidification potential and toxicity. The results are reported in Table 1, using the 1-tonne corn grain as the functional unit. Particularly, yearly variations of assessed life cycle impacts of climate change, eutrophication, and acidification are shown in Table 2.

3.1.1. Land use

In terms of land use, corn production with CDSI resulted in an average of 2.55% compared to FD during 2014 and 2015 growing seasons. This reduction can be attributed to the increased yields resulting from the implementation of CDSI, which required the same amount of land resources as FD. This finding underscores the importance of crop yields in assessing agricultural water management systems.

Loss of soil productivity, such as erosion and degradation, can lead to lower crop yields and higher production costs (Pimentel *et al.* 1995). Soil water retention and organic carbon are essential to agronomic productivity (Lal 2020). Thus, CDSI implementation can help conserve soil organic carbon by adjusting soil moisture content instead of allowing soil runoff by FD. Additionally, net removals from cropland play a significant role in GHG emissions mitigation. In Canada, current net removals from cropland in 2019 are 4.2 Mt, 6.2 Mt lower than in 2005 (Environment & Climate Change Canada 2019). The declining net removals of GHG emissions from cropland emphasize the need to reverse the trend of

Table 1 | Comparison of life cycle impacts between corn production with FD and CDSI from 2014 to 2015 growing seasons in eastern Canada

Impact category	Units	FD	CDSI	Diff. (%)
Land use	kg soil organic carbon	3.113	3.033	−2.55
Climate change	kg CO_2-eq.	256.674	250.426	−2.43
Eutrophication potential	kg PO_4-eq.	0.369	0.188	−49.11
Acidification potential	kg SO_2-eq.	0.079	0.094	19.77
Human toxicity	kg 1,4-DCB-eq.	0.180	0.176	−2.55
Terrestrial ecotoxicity	kg 1,4-DCB-eq.	0.081	0.079	−2.55
Freshwater aquatic ecotoxicity	kg 1,4-DCB-eq.	2.920	2.845	−2.55

Note: The negative value of difference for each environmental impact category between corn production systems with CDSI and FD indicates that the corn production system with CDSI indicated fewer environmental impacts than FD; in contrast, the positive value presents the opposite.

Table 2 | LCIA results of climate change, eutrophication potential, and acidification potential impacts between the corn production system with FD and CDSI in 2014 and 2015

		2014		2015	
Impact category	Units	FD	CDSI	FD	CDSI
Climate change	kg CO_2-eq.	222.388	311.157	283.002	203.792
Eutrophication potential	kg PO_4-eq.	0.386	0.235	0.355	0.151
Acidification potential	kg SO_2-eq.	0.068	0.141	0.087	0.059

soil deterioration. In this context, the implementation of CDSI has been found to utilize fewer land resources while enhancing carbon sequestration in farmland.

3.1.2. Climate change

The assessed climate change impacts of producing 1-tonne corn with CDSI and FD in 2014 were 222 and 311 kg, respectively. In 2015, climate change impacts were 283 and 204 kg CO_2-eq. for the corn production system with CDSI and FD. The total GHG emissions from corn production system in this study were about 3,000 kg CO_2-eq. ha^{-1}. This amount corresponds to a low-medium GHG emissions threshold in Farrell *et al.* (2006), which discovered that GHG emissions associated with corn (*Zea mays* L.) production ranged from 2,441 to 4,201 kg CO_2-eq. ha^{-1} $year^{-1}$ by analyzing results from six literature works.

CDSI indicated a modest reduction in climate change impacts for the two growing seasons. The cumulative variation of climate change impacts between corn production with FD and CDSI was 6.25 kg CO_2-eq. t^{-1} $year^{-1}$. In 2014, the life cycle climate change impacts with FD were 40% lower than that with CDSI. However, in 2015, the reverse was observed, as CDSI decreased climate change impacts by 28% relative to FD. Analysis of the variation in the same water management technology between the two growing seasons shows that GHG emissions from the corn agroecosystem with CDSI dropped sharply in 2015, by 107 kg CO_2-eq. t^{-1} $year^{-1}$, accounting for 34% of the GHG emissions from the 2014 CDSI production system. In contrast, total GHG emissions for FD increased by 61 kg CO_2-eq. t^{-1} of corn production in 2015, a 27% rise from 2014. Overall, the corn agroecosystem with CDSI in the growing season of 2015 reached the lowest climate change impacts. The implementation of CDSI resulted in a minor reduction of 2.43% compared to FD in the continuous corn production system during the 2014 and 2015 growing seasons.

3.1.3. Eutrophication potential

Life cycle eutrophication potential impacts of corn production reduced from 0.386 kg PO_4-eq. t^{-1} with FD to 0.235 kg PO_4-eq. t^{-1} with CDSI in 2014 and 0.355 kg PO_4-eq. t^{-1} of FD to 0.151 kg PO_4-eq. t^{-1} of CDSI in 2015, which decreased by 39 and 58% respectively. The environmental performance of CDSI is consistent across the two growing seasons suggest its implementation is an effective measure for reducing the eutrophication potential impacts of corn production.

3.1.4. Acidification potential

The corn production with CDSI vastly increased acidification impacts in 2014. However, in 2015, implementing CDSI caused a 32.15% reduction in the acidification potential impacts compared to FD. Overall, the corn production system with CDSI showed 20% more significant environmental impacts than the conventional FD in the acidification category. The results indicate that the implementation of CDSI may pose a risk in increasing acidification potential impacts. However, the favorable environmental performance of CDSI in the 2015 growing season drives the further investigation into the cause of the inconsistency. Also, the development of proper user guidelines is necessary to improve the environmental performance of CDSI in the acidification category.

3.1.5. Human toxicity and ecotoxicity

The environmental impact measurements of corn production with CDSI were 0.176, 0.079, and 2.845 kg 1,4-DCB-eq. t^{-1} for human toxicity, terrestrial ecotoxicity, freshwater aquatic ecotoxicity, respectively. On average, there was a 2.55% reduction in toxicity compared to FD, attributable to the mitigation of herbicide and pesticide per unit, resulting from increased yields due to CDSI implementation.

3.2. GHG emissions impact analysis of CDSI implementation

Analyzing GHG emissions in the life cycle inventory sheds light on the comprehensive impacts of implementing CDSI and the potential trade-offs between key environmental impact categories. Figure 3 illustrates the relative proportion of GHG emissions, including nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) in the climate change impacts category for corn production system with FD and CDSI. N_2O and CO_2 exhibited similar trends in both systems, with most extensive N_2O emissions occurring in the production with CDSI in 2014. FD explicated only half the CDSI N_2O emissions level that year. However, the highest CO_2 emission level was observed in the corn production system with FD in 2015, while emissions from that with CDSI was 25% lower. In terms of CH_4, negative emissions values indicate lower CH_4 emissions for crop growing compared to the fallowing baseline. Thus, corn production with FD generated less CH_4 emissions than CDSI during both growing seasons. The CDSI production system showed more consistent CO_2 emissions performance than FD, but with

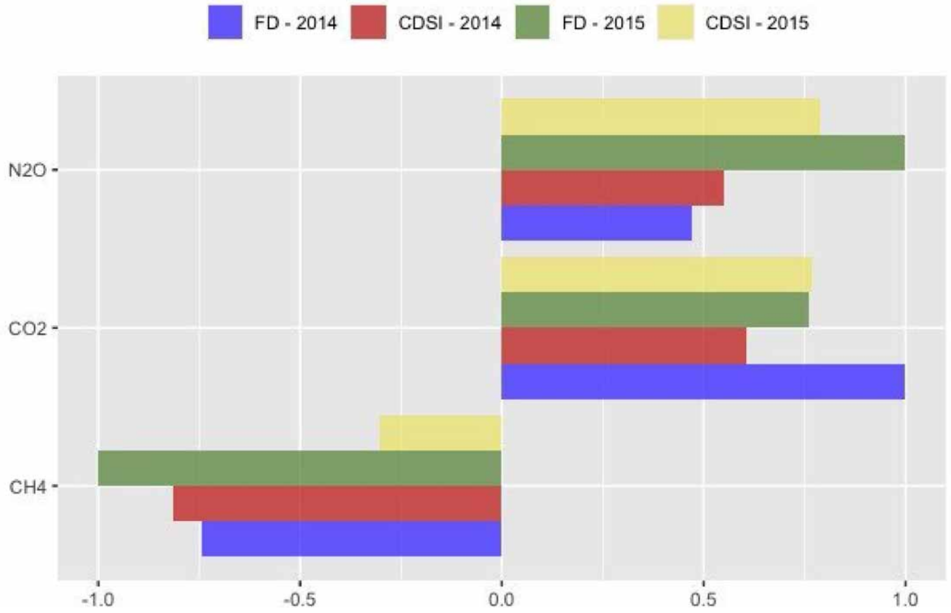

Figure 3 | GHG emissions between the corn production system with CDSI and FD, respectively.

greater variation in N_2O and CH_4. GHG emissions were calculated using preprocessed GHG fluxes, excluding differences in climatic conditions, such as temperature and precipitation, between two growing seasons. Therefore, further investigation into underlying factors such as soil nutrients and plant variety is needed to explain the differences in GHG emissions between CDSI and FD.

Furthermore, inventory for eutrophication and acidification potential impacts was assessed to understand the effects of GHG emissions on other impact categories. Figure 4 shows nitrate (N), phosphorus (P) and N_2O emissions inventory for

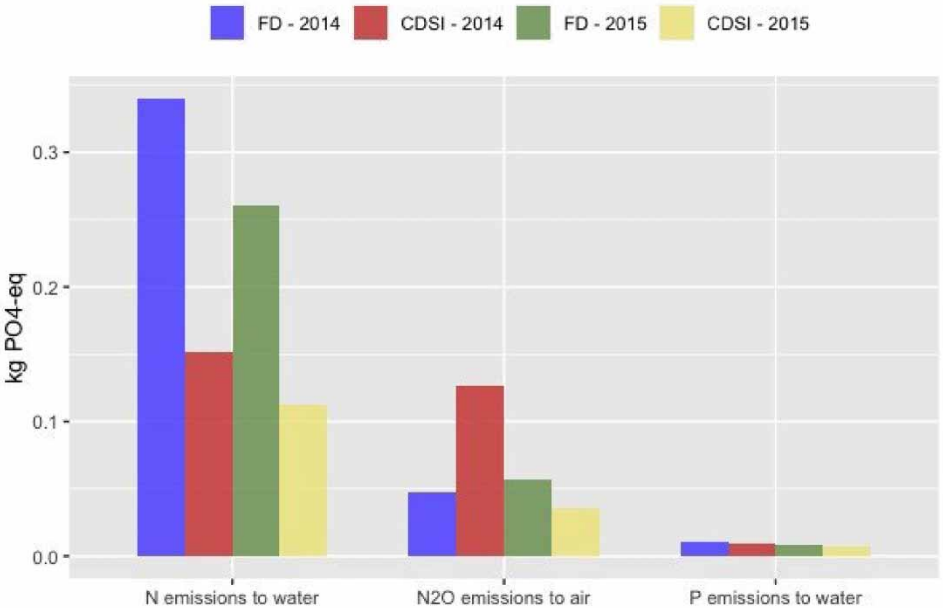

Figure 4 | N, P, and N_2O emissions inventory for eutrophication potential impacts of corn production with FD and CDSI in 2014 and 2015 (kg PO_4-eq. t^{-1} $year^{-1}$).

eutrophication impacts of corn production with FD and CDSI in 2014 and 2015. Nitrate (NO_3-N) leaching into the water from nitrogen fertilizer application in the field was found to be the most significant pollutant, but the implementation of CDSI can effectively mitigate it by 56. P-leaching decreased by around 10% by implementing CDSI compared to conventional drainage. The third fundamental component involved in the inventory of eutrophication impacts was N_2O emissions to air, which can dissolve in water and affect water quality. Its massive emissions from the corn agroecosystem can increase the eutrophication potential impacts. In the 2014 growing season, the difference between the corn production system with FD and CDSI in terms of N_2O emissions was notable. N-leaching accounted for up to 83% of total eutrophication potential impacts for corn production with FD, which was 23% higher than that with CDSI. On the contrary, N_2O emissions accounted for a larger proportion with CDSI than FD, which was 37 and 14%, respectively. The results suggested that despite direct N-leaching lessened for CDSI, N_2O emissions dissolving in water can also raise the eutrophication risks and negatively impact water quality. Therefore, analyzing the interconnections and potential trade-offs between elemental flows is crucial for accurately assessing the life cycle environmental impacts.

The acidification potential impacts of corn production are mainly affected by ammonia (NH_3) volatilization and N_2O emissions from nitrogen fertilizer application. Figure 5 shows that the corn production system with CDSI reduced NH_3 by a slightly 2% in both the 2014 and 2015 growing seasons compared to FD. However, CDSI resulted in substantially higher acidification impacts due to N_2O emissions in 2014. Therefore, a possible higher N_2O emissions level may cause underperforming regarding acidification potential impacts of CDSI. It is important to consider the possible trade-offs between reducing NH_3 emissions and increasing N_2O emissions, when designing the best water management practices. Additionally, the interactions between these nitrogen cycle impacts can drive efforts of implementing CDSI in collaboration with other beneficial management practices for soil conservation.

3.3. Discussions

The results are compared to other agricultural LCA studies of the corn production system to explain the study's reliability. Despite using different LCA methods and research regions, these comparative studies provide an environmental impact range associated with this research. Given the similarity in research region (both in North America) and crop production system (corn grain production), this study employed the results from Kim *et al.* (2009) to compare climate change, eutrophication and acidification impacts on corn grain production.

In Kim *et al.* (2009), GHG field emissions associated with corn grain production ranged from 127 to 625 kg CO_2-eq. t^{-1} $year^{-1}$, which is consistent with the climate change impacts assessed in this study. Moreover, according to Kim *et al.*

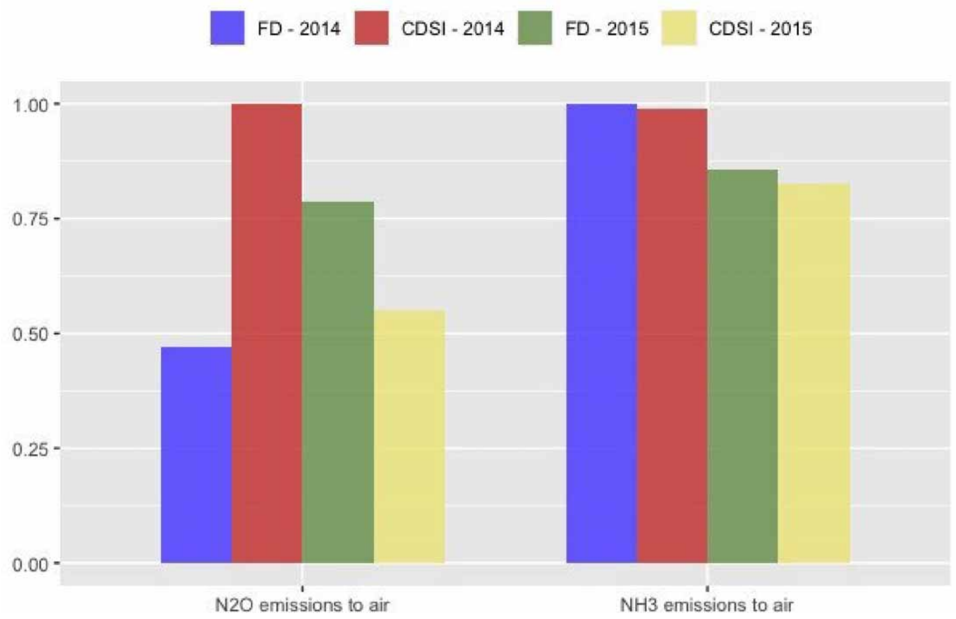

Figure 5 | N_2O and NH_3 emissions in acidification potential impacts of corn production with FD and CDSI.

(2009), eutrophication and acidification associated with corn grain production in US ranged from 0.5 to 2.0 kg PO_4-eq. t^{-1} and 1.5 to 5.8 kg SO_2-eq. t^{-1}, respectively, which are 5–10 times higher than those reported in this study. The discrepancy is partly due to differences in inventory methods used to estimate the emissions. This study used field experiment samples, whereas Kim *et al.* (2009) employed a simulation model to estimate N_2O and N_2 gas emissions from soils resulting from denitrification. Additionally, the study involved water management in the LCA, which was not done in the previous research. Even the base scenario, conventional tile drainage, shows benefits in improving water and soil quality compared to the no-tile drained, demonstrating the environmental benefits of agricultural water management in sustaining agricultural production.

This study emphasizes the environmental benefits of CDSI implementation on water quality and climate change based on the technology's design functionality. As North America experiences a trend of reduced precipitation and increased irrigation demand, adapting conventional irrigation and drainage to handle the upcoming challenge of climate change is crucial (Lobell *et al.* 2008). This is particularly important in the context of growing societal and environmental obligations to develop sustainable agroecosystems with limited natural resources.

Moreover, this study enlightens the potential interrelationships among different environmental impact categories, including co-benefits and trade-offs revealed from biophysical indicators across the assessed categories. For instance, co-benefits reflect on that GHG mitigation can also reduce acidification potential due to fewer N_2O emissions. Nevertheless, trade-offs exist between climate change and eutrophication because reduced N-leaching that may convert into potential N_2O emissions. In other words, the trade-offs imply that CDSI still holds the possibility of transforming decreased N-leaching into added N_2O emissions, thereby generating unfavorable environmental influences on soil and water. The interactions between diverse environmental impacts underscore the need to consider the agroecosystem when assessing CDSI. Also, agricultural water management can incorporate other environmentally beneficial practices (e.g., fertilizer application, no-till or reduced-till farming) to achieve agri-environmental improvements. Thus, as an innovative technology and its associated beneficial management practices, CDSI should facilitate agricultural water management to mitigate the comprehensive environmental impacts in crop production.

4. CONCLUSIONS

This study compares the environmental impacts of the corn production system under controlled drainage with sub-irrigation (CDSI) and conventional tile drainage (FD) in a corn agroecosystem during the 2014–2015 growing seasons in Quebec, eastern Canada. Through LCA, this study evaluates the environmental performance of CDSI as an innovative water management system.

The life cycle impact results show that CDSI had a positive effect on reducing environmental impacts of corn production compared to FD, in the aspects of land use, climate change, eutrophication potential, human toxicity, terrestrial ecotoxicity, and freshwater aquatic ecotoxicity. However, CDSI show underperformance in potential acidification impacts due to higher N_2O emissions, also affecting the climate change impacts in 2014. CDSI generally shows positive impacts on reducing GHG emissions, with consistent CO_2 emissions regarding the climate change impacts category. Moreover, the eutrophication potential impacts resulting from implementing CDSI were significantly reduced due to vastly lowering N and P emissions to water compared to FD. The interactions between various environmental impacts sheds light on the importance of combining water management and fertilizer application. However, improper fertilizer application can cause acidification and eutrophication impacts, along with impacts on N_2O emissions in climate change. Hence, reducing N_2O emissions from CDSI is crucial for comprehensive environmental benefits, and further research is needed to interpret the inconsistency of N_2O emissions for corn agroecosystems with CDSI.

Policy ensuring environmental responsibility in the context of climate change for the society can benefit stakeholders and promote sustainable economic development (Hang 2022). This study has important policy implications, as it provides a comprehensive assessment of CDSI implementation for mitigating agricultural environmental impacts through water management. The results contribute to scientific understanding of environmental impacts of transiting to corn agroecosystem with CDSI assessed on a biophysical basis. Moreover, this study can support further monetary measurement of socio-economic evaluation on CDSI, such as cost–benefit and multi-criteria analysis. Currently, inadequate interest to producers in adopting CDSI due to low investment return of farmland water management infrastructure (Marmanilo *et al.* 2021). However, the environmental assessment in this study highlights the potential benefits of CDSI. Stakeholders, including producers, researchers, technology manufacturers, and policymakers, can refer to environmental benefits and the following monetary evaluation of CDSI to encourage the adoption of CDSI-based water management practices. Consequently, the related agri-environmental policy supporting CDSI implementation may help to fulfill the purpose of reducing the overall agri-environmental impacts.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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