Introduction to Assessing Environmental Impact of Organic Cropping Systems through Life Cycle Assessment

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Introduction

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Agriculture has been recognized as a critical contributor to environmental challenges, including climate change, biodiversity loss, and water quality decline. Farming systems are complex, influenced by interactions between crops, pests, nutrient application, soil types, climate, and management practices. The environmental performance of a farming system must consider the direct impact of management practices as well as the manufacturing of inputs. This bulletin introduces the core concepts associated with life cycle assessment (LCA), an approach used to evaluate the environmental performance of manufacturing or production systems, in this case, organic cropping systems.

Cropping systems refer to the types and sequence of crops grown, as well as the methods used to cultivate them over time and space.[1] Cropping systems can differ in their impact on greenhouse gas (GHG) emissions and other environmental performance indicators. Organic crop production systems can be more heterogeneous in farm size, production practices, yields, and efficiencies in comparison to conventional agricultural systems. [2] Therefore, it is essential to evaluate how organic cropping systems perform under various production conditions and management practices to understand their environmental impact. Such information may reveal how organic systems can be improved to meet climate-related goals and reduce environmental impact.

What is Life Cycle Assessment (LCA)?

Life cycle assessment is a framework and methodological tool used to quantitatively analyze and model the environmental performance of a commercial product through the supply chain. [3,4,5] The International Organization for Standardization (ISO) established ISO 14040 and 14044, which define general principles and specific requirements to conduct an LCA. [3] An LCA consists of four main steps: **1)** defining goal and scope, **2)** life cycle inventory (LCI) analysis, **3)** life cycle impact assessment (LCIA), and **4)** life cycle interpretation (Figure 1). [3] The LCI includes a detailed inventory of material and energy inputs and outputs associated with a production system. The LCI is then used with one or more impact assessment methods to estimate how these flows contribute to a range of global- to regional-scale impacts on renewable and non-renewable resources, human health, and environmental degradation.

To date, LCA has been used to help understand impact contributions arising from a wide range of food products and associated production activities. [6,7,8,9,10] LCA has been used extensively to determine the environmental impacts of conventional crops, [11,12,13] but has not been applied to the same extent for organic management.

More recently, LCA studies have compared the performance of organic and conventional production systems based on environmental indicators, quantifying GHG emissions and energy use,[7,8,9,10,14] identifying 'hotspots' of environmental impacts[2,7,8,9,15] and best management practices, proposing mitigation strategies for efficiency and environmental protection.[7,15,16]

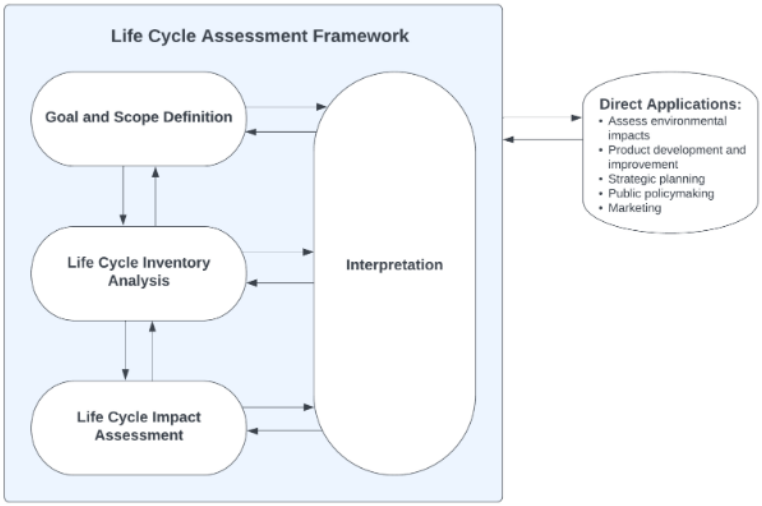

Figure 1: The four stages of the Life Cycle Assessment (LCA) framework under the ISO 14040 and 14044 guidelines: 1) Goal and Scope definition, 2) Life Cycle Inventory (LCI) Analysis, 3) Life Cycle Impact Assessment (LCIA), and 4) Life Cycle Interpretation

Methodological Considerations of LCA in the Context of Organic Cropping Systems

Step 1. The Functional Unit and System Boundary

A common issue in an agricultural LCA, regardless of the management system, is choosing a unit of analysis to compare impacts (i.e. the functional unit). From a standardized LCA perspective, the functional unit must be chosen based on the 'function' of the system.[17,18] The most common basis of analysis is a mass-based functional unit, expressed as impacts per 1kg or 1t harvested crop or finished product (e.g. bread, pasta, etc.).

Another critical decision to make when conducting an agricultural LCA is choosing the boundary of analysis (i.e. the system boundary) (Figure 2). Most often, the system boundary in both conventional and organic crop LCAs is 'cradle-to-farmgate,' which includes impacts associated with seed inputs, nutrient inputs and field operations (i.e. application of plant protection and fertilizer products, harvesting, tillage, land rolling, sowing, and weeding) and their associated energy inputs, land use, field-level emissions and soil organic carbon change. These activities are referred to as 'foreground processes' as they are at the forefront of the analysis of the cropping system. However, it also includes emissions associated with 'background process', such as the manufacture or production of fertilizers, soil amendments, seeds, pesticides, farm machinery and infrastructure, maintenance inputs, and transport of of inputs to the farm.[7,10,19,20,21,22,23,24,25] The system boundary can differ based on the goal of the LCA. For example, a few studies have conducted a cradle-to-retail gate LCA, which also included processing, packaging, and transportation beyond the farmgate.[8,26] However, these studies identified crop production as the most significant contributor to environmental impacts throughout the product's life cycle.[8,26]

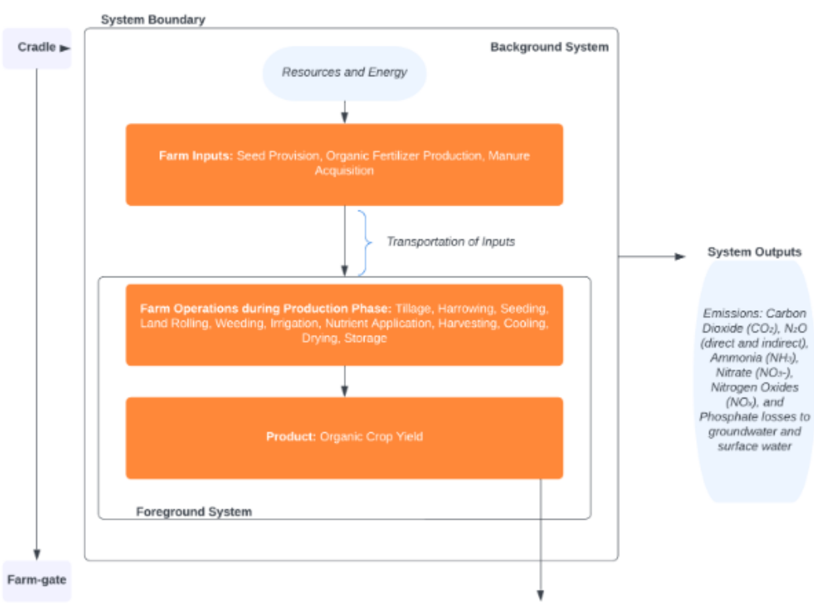

Figure 2: Life cycle flow diagram of an organic cropping system with a system boundary from cradle-to-farmgate for an individual crop. The agricultural phase is the foreground system, which includes seed inputs, nutrient inputs and application, field operations, land use, and their associated field-level emissions and soil organic carbon change. The background system and upstream processes include resources and energy such as fossil fuel use, electricity, the production of seed inputs, mineral amendments, and manure inputs.

Step 2. Life Cycle Inventory (LCI) - Data Gathering

It is not possible to collect all of the actual data from every process and input associated with a farm, much less get a representative sample from across many farms. As a result, data to build the life cycle inventory and conduct the analysis are collected from sources including databases such as 'ecoinvent' (leading LCI database), census and statistical data, published values, primary data collection through field experiments, and surveys/interviews of farm managers, agronomists, and experts in the field. Although readily available data makes it easier to conduct an LCA, it may not represent farm-level environments, such as soil and climate conditions, land management practices, and crop yields specific to each cropping system. Specific data, such as historical on-farm records and current production data from farmers, are most appropriate for determining resource use and emissions, while published and publicly available data can be used to determine the background and post-farmgate impacts.

Environmental Impact Categories

Step 3: Life Cycle Impact Assessment (LCIA)

In Step 3, life cycle inventory data is converted into a set of potential impacts. In this phase, the LCIA establishes a link between the organic cropping system and its potential impacts on the environment, human health and resource depletion. The use of distinct impact categories allows for the environmental impacts of systems to be easily compared with one another (Table 1).

What is Global Warming Potential (GWP)?

Global warming potential (GWP) is one of the most common measures of environmental impact. All gases that are categorized as greenhouse gases (e.g. carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), etc.) have a global warming potential (GWP) value, which measures how effective each gas is at trapping heat in the Earth's atmosphere relative to carbon dioxide. GWP normalizes the impact of emission of different GHGs to a standard unit. Carbon dioxide is the most dominant GHG and is therefore used as the standard of reference for other GHGs. A carbon dioxide equivalent, abbreviated as CO_2-eq, is a metric measure used to standardize the GWP values of each greenhouse gas to the equivalent amount of carbon dioxide with a baseling GWP of 1. This is calculated by multiplying the amount of gas by its accompanying GWP. For example, the GWP for methane is 25, and for N_2O, the GWP is 298. So, emissions of 1 tonne of methane equal 25 tonnes of CO_2, and 1 tonne of nitrous oxide equals 298 tonnes of CO_2.

Other Relevant Impact Categories

Most of the current applications of LCA in organic cropping systems have only quantified GWP [8,10,23,24] or GWP and energy use. [7,27] However, as more quantitative studies become available on emissions and impacts of organic crop production, more impact categories are being analyzed (Table 1). The context-dependent nature of agricultural LCAs means that more data is needed to reflect specific farm conditions and their environmental impacts.

Table 1: Examples of impact categories used in LCAs.

Impact Category	What Does it Measure?	Indicator: What Needs to be Measured?	Expressed As...
Global Warming Potential	A metric used to measure how effective each greenhouse gas is at trapping heat in the Earth's atmosphere, relative to carbon dioxide	Carbon Dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O)	kg CO_2 equivalent
Energy Use & Fossil Fuel Depletion	The consumption and depletion of non-renewable and abiotic resources	Fuel and energy use	MJ Deprived
Ozone Depletion	A measure of how much damage a chemical can cause to the ozone later	(Chlorofluorocarbons) CFCs, (Hydrofluorocarbons) HFCs and halons	Kg CFC-11 eq
Terrestrial and Freshwater Ecotoxicity	The influence of toxic compounds on freshwater and terrestrial ecosystems	Heavy metals (e.g., cadmium, lead, copper, and zinc)	Kg 1,4-dichlorobenzene eq (1,4-DB eq)
Terrestrial and Freshwater Acidification	Acidifying of water and soil by contaminating substances	Nitrate (NO_3-), Ammonia (NH_3), and Nitrogen Oxides (NOx)	kg SO_2 equivalent
Freshwater and Marine Eutrophication	The discharge of nutrients, mostly nitrogen and phosphorus, into fresh- and marine water bodies and soil	Phosphate (PO_4^{3-})	kg PO_4 equivalent
Land Use	Use and transformation of land for agriculture	Area of land use	m^2 arable land
Water Use	The withdrawal of water from lakes, rivers, or groundwater that contributes to the depletion of available water	Bluewater use (i.e. surface and groundwater sources)	m^3 world eq
Biodiversity Loss	The decline or disappearance of biological diversity in a certain area over time	Species richness	Potentially Disappeared Fraction of Species (PDF) m^2 yr

Table 2: Contributions of agricultural activities involved in organic crop production to their most relevant environmental impact categories ranked from one to three checkmarks (1 = low impact, 2 = medium impact, 3 = significant impact).

Agricultural Activity	Global Warming Potential (kg CO_2 eq)	Fossil Depletion (MJ)	Acidification (kg SO_2 eq)	Freshwater Eutrophication (kg PO_4^{3-} eq)	Land Use (m^2 a)	Water Use (m^3 eq)	Biodiversity Loss (Species Richness, species per m^2)
Seed Production	X	XX	X	X	XXX		
Organic Fertilizer Production	XX	XX				X	
Field Operations (e.g. sowing, tillage, harvesting, weeding)	X	XXX					XX
Growing Green Manure/Cover Crops In Rotation	XX	XX		XX	XXX		
Fertilizer Use (e.g. compost, manure, mineral amendments, etc.)	XX	XX		X			
Field-level Emissions from Fertilizer Application	XXX		XXX	XXX			XXX
Transportation of Farm Inputs (e.g. manure, equipment)	X	X					
Irrigation						XXX	
Land Use Change							XXX

Components of a cropping system that are studied in LCA

Nutrient Application in Organic Cropping Systems

Nutrient application is an important component of cropping systems in LCA studies. Organic farmers typically manage crop nutrients and soil fertility by applying organic materials such as manure, compost, and biofertilizers. Green manures like red clover, peas, and alfalfa are also grown to cycle nutrients and biologically fix atmospheric nitrogen.[1,28,29] Cover crops like fall rye help to prevent nutrient losses to the environment.[30] Diversifying crop rotations can increase availability of nutrients for crop uptake, reduce erosion, and improve biodiversity.[31] While nutrient management on organic farms can be primarily associated with on-farm activities, some nutrients may be imported from off of the farm, and the impact of manufacturing, delivery, and using these inputs must be considered.

What is the Environmental Impact of Nutrient Application?

Excessive nutrient application and poor management can lead to negative environmental impacts even on organic farms.[32] Through a series of biological and chemical reactions (Figure 3), nitrogen can be lost to the environment by nitrate (NO_3^-) leaching, as N_2O emissions resulting from denitrification under saturated conditions, gaseous losses of ammonia (NH_3) or through runoff and erosion.[33] Similarly, significant pathways for phosphorus loss include surface runoff, erosion, and leaching.[34,35] Notably, warmer temperatures and water-logged soil conditions often exacerbate environmental nutrient losses. Nutrient losses associated with organic fertilizer and manure application, primarily impact water quality, aquatic biodiversity, and air pollution; N_2O emissions, specifically, are a key contributor to global warming and anthropogenic climate change.[36]

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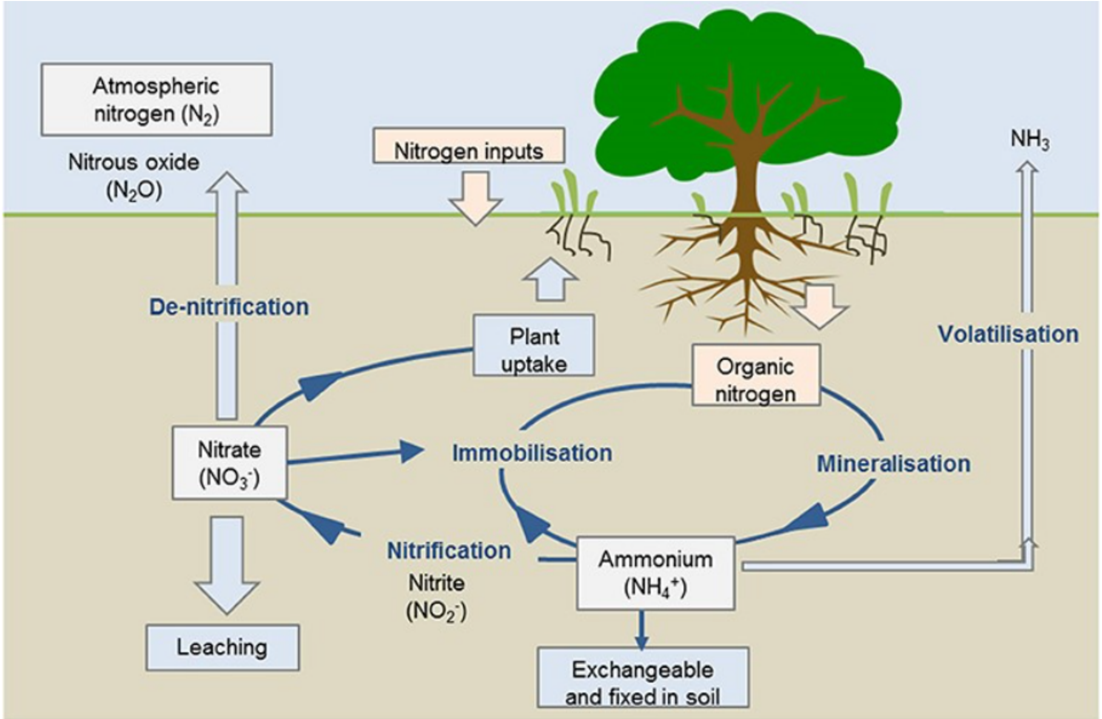


Figure 3: Stages of the nitrogen cycle illustrate how nitrogen from organic sources such as manure, organic fertilizers, and plants themselves cycle through the soil to the crop, water, and air.[49]

Quantifying the Environmental Impact of Nutrient Application in LCAs

When conducting an LCA, direct and indirect nitrogen and phosphorus losses due to nutrient application in organic cropping systems are quantified to understand their contribution to environmental impact categories. For example, nitrogen oxides, nitrate, and ammonia emissions have an impact on the potential acidification of soils and freshwater, nitrous oxide emissions impact global warming potential, and emissions of nitrogen- and phosphorus-containing compounds impact eutrophication potential.[32]

However, some uncertainty is associated with calculating and modeling emissions in LCAs for crop production systems due to the influence of climate, fertilizer type and application method, and soil type.[37] Furthermore, nitrogen emissions in LCA inventories of agricultural crops are based on models that are not currently adapted to organic fertilizers, but are based on assumptions from conventional agriculture. For example amendments may include nitrogen present in simple inorganic nutrients that are available for plant uptake, or complex organic molecules that need time for decomposition to be released. The potential impacts of these two forms of nitrogen are not always distinguished in impact models.

Another challenge relates to how to account for impacts of nutrients derived from recycled sources. Synthetically manufactured nitrogen and phosphorus fertilizers may not be used directly in organic farming. However, manure and other by-products (ex. feather meal) may be sourced from conventional operations that had used feed grown with synthetic fertilizers. As these organic amendments are being applied to provide nutrients, a portion of the environmental impacts associated with the original manufacturing of the nutrient sources must be accounted for. There is not a clear consensus of how these impacts should be accounted for so uncertainty can be addressed by following the IPCC's (2019) Tier 2 modeling guidelines, using country-specific emissions data, published literature, primary activity data, expert opinion, and further LCA analysis techniques that test the sensitivity of results to these uncertainties (referred to as a sensitivity analysis). Sensitivity analysis involves running the model again with various input assumptions to assess the level of impact each assumption has on the results.

Changes in Soil Organic Carbon

Carbon is captured by plants through photosynthesis, and is then consumed by animals and microorganisms above and below ground, which release carbon as CO back into the atmosphere. However, some carbon can be captured and held in the soil. Soil organic matter (SOM) is made up of dead plant, animal, and microbial matter at varying stages of decomposition, and has an important influence on soil health.[38] Since SOM is derived from living organisms, it contains carbon which is referred to as soil organic carbon (SOC). The amount of SOC contained in soils is highly variable, and can substantially affect estimates of net GHG emissions from crop production.[39] Soils can either be a source (i.e. contributor) or sink (i.e. holder) of atmospheric carbon depending on factors such as soil type, management practices (e.g. tillage vs no tillage), organic amendments type, crop type, residue management, green manure planting, and climatic conditions such as temperature, humidity, and precipitation.[40] In organic cropping systems, management practices and production conditions vary considerably among farms and between regions. However, organic farms are expected to improve soil health, and at least maintain soil organic matter through improved nutrient cycling, use of soil-building crops, retaining residues, planting catch crops, and applying livestock manure or compost.[41] Despite the potential of SOC management to play a role in climate change mitigation, only a small fraction of previous LCA studies of organic crop production have quantified SOC changes as part of the net life cycle GHG emissions. Most LCA studies of agricultural production systems do not include SOC changes due to limited consensus on standard procedures and site-specific data availability.[42] While different methods to account for SOC in agricultural LCAs exist, including measurements and carbon models, the method should be chosen based on the study's objectives and the scale of the LCA. Given the importance of SOC in understanding the environmental performance of organic cropping systems, quantifying SOC changes in LCA studies is critical.

"Despite the potential of SOC management for climate change mitigation, only a small fraction of previous organic crop production LCA studies have quantified SOC changes as part of the net life cycle GHG emissions."

Hotspots of Organic Cropping Systems Identified in the LCA Literature

LCA methodology is an appropriate approach for identifying 'hotspots' in the production system. Environmental hotspots are processes or activities that make a significant contribution to total environmental impact results. LCA studies of organic cropping systems have shown that the most significant contributors to GWP are emissions related applications of amendments with nitrogen (Figure 4).[8,21,26,43] Importing nutrients in the form of manure from conventional farm operations means that the LCA must consider a portion of the environmental costs, particularly GWP impact, associated with manufacturing the chemical fertilizers used to grow feed for the livestock. A build-up of nitrogen in the form of nitrate under warm and wet conditions can result in N_2O emissions in organic systems as well as conventional, even if the nitrogen originated from leguminous green manure crops, compost, or manure. Nutrient application also contributes significantly to impact categories other than GWP, including the acidification potential, freshwater eutrophication, and toxicity-related impacts.[21,43,44]

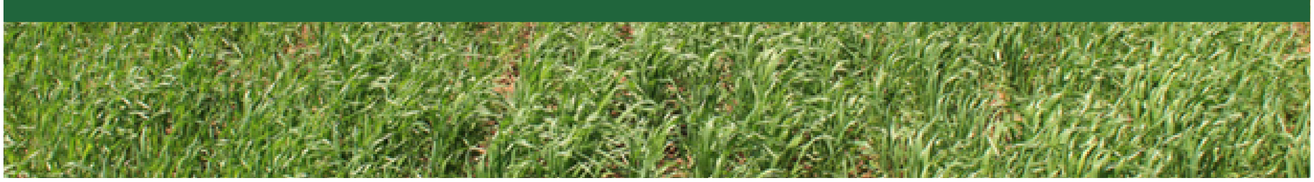
The GWP results from a handful of organic crop production LCAs have also identified considerable impacts from farm machinery and fuel use during cultivation;[8,27] field operations such as tillage, sowing, and harvesting are the main drivers of fossil fuel resource scarcity and energy use.[21,25] However, some of these negative effects could be offset if organic crop production results in SOC accumulation, which would improve the environmental profile of organic crop production systems.[10,45]

Lastly, it is also important to consider that the most common functional unit of cropping systems LCA is crop output. Therefore, impacts are applied per tonne of crop. Meaning if the inputs per hectare are the same for two different crops, the crop with the lower yield will have higher impact per tonne of output. Thus, the results of LCA are highly influenced by crop yield.

Recommendations for Improving Environmental Performance

The environmental performance of organic production systems is dependent on climate, soil type and production practices. Based on the environmental hotspots identified from previous LCA studies, best practices to reduce on-farm energy use and GHG emissions include using low-impact nutrient sources, regular soil testing and careful nutrient management (i.e. monitoring the timing and quantity of nutrients applied and preventing over-application of nutrients, which can be a problem on organic farms, particularly when using compost/manure), using cover crops to avoid nutrient losses, reducing tillage and energy-intensive field operations, using perennial crops and cereal crops to improve SOC, and increasing crop rotation length and complexity to improve soil and ecosystem health.[7,10,43,47] Including a leguminous crop in rotation can reduce or eliminate the need for external nitrogen inputs and, if a green manure, contribute to meeting the nitrogen requirements of the next crop in rotation while breaking pest cycles which reduces need for pesticides, thereby reducing further environmental burdens.[22,44] Management practices should be appropriate for the farm's soil conditions and environment.

"LCA studies of organic cropping systems have shown that the most significant contributors to GWP are on-field activities, specifically, the nitrogen-related emissions from fertilizer application"



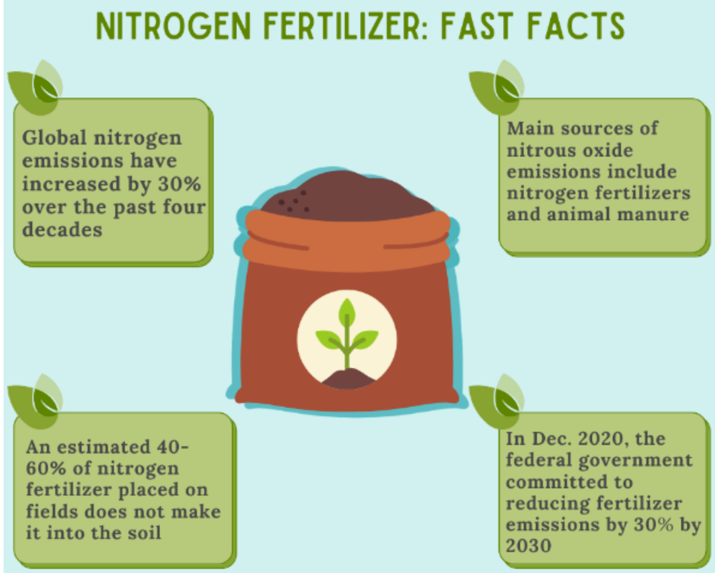


Figure 4: The significance of nitrogen fertilizers in agricultural systems.[46] *Using manure, compost, legume green manures and other N amendments in organic agriculture can produce nitrous oxide which is a potent greenhouse gas and a significant contributor to climate change.* ***Reducing emissions can be accomplished by the four-R method: Right source, Right rate, Right time, and Right place.***

Why LCA Studies of Organic Cropping Systems are Essential in the Context of Research and Practice

Organic 3.0 represents a vision for the future of organic agriculture.[48] This vision includes the feature of continuous improvement towards best practices. LCA studies of organic cropping systems are an important tool for advancing to advance research and supporting producers. Identifying and applying best practices can be achieved through high-quality data, improved representations of organic cropping systems' complexity, consistent methodology, and soil organic carbon reporting.

ABOUT THE ORGANIC SCIENCE CLUSTER

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