Nitrogen

Review

Ecological Management of the Nitrogen Cycle in Organic Farms

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Abstract: Nitrogen availability is among the major limiting factors for the production of organic crops. A central goal of organic farming, according to certification standards, is to rely on ecological and biological principles to build and maintain soil health. Nitrogen is among the most complex nutrient elements with respect to its different chemical forms and its flow within the environment at the soil, microbial, plant, aquatic, and atmospheric levels. Because, from an ecological perspective, all production variables on the farm are interrelated, a challenge for scientists and practitioners is to better understand nutrient cycles on the farm with respect to how particular production practices may improve N availability during particular stages of crop growth while minimizing potential environmental losses that may lead to contamination of the groundwater and aquatic habitats or to undesirable greenhouse gas emissions. Here, based on a selected review of the literature, we evaluate N cycles at the farm level and present key ecologically-based management strategies that may be adopted to improve internal N cycles. Given the location-specific nature of most ecosystem interactions, a participatory agroecology approach is proposed that incorporates the knowledge of indigenous and traditional cultures to better understand and design resilient and socially-equitable organic systems.

Keywords: agroecology; intercropping; legumes; microbial activity; nitrogen cycles; organic matter; organic farming; tillage

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1. Introduction

Due to its relative high demand, nitrogen (N) is among the major limiting production factors in organic farming [1–3]. From a biophysical standpoint, N is among the most complex nutrient elements with respect to its movement within the environment, within the farm, and with respect to the timing of its availability for plant uptake [4]. Historically, N inputs have contributed to increased crop yields, resulting in an increased global per capita grain production of about 40% over the past 60 years, and its use contributes to supplying about 40% of the global human dietary protein [5]. The use of chemical N in the United States increased from an average of about 2 kg ha^{-1} yr^{-1} in 1940 to about 90 kg ha^{-1} yr^{-1} in 2015 [4]. Despite its prominence as an important nutrient for crop production, and its respective contribution to the human diet, N also has considerable potential adverse effects on the environment, including reliance on fossil fuels for its manufacture. In its different chemical forms, N pollution causes groundwater pollution; eutrophication of aquatic habitats; acidification of soils, streams, and lakes; destruction of the ozone layer; decreased biodiversity; and contributes to greenhouse gas emissions and global warming [5–7].

Prior to World War II, before the introduction of chemical fertilizers, farmers relied largely on natural N sources, agricultural systems were decentralized, and nutrients used to largely cycle within the farm or local farming area [8]. The advent of the chemical fertilizer industry led to a greater reliance on synthetic N fertilizer and to the centralization and specialization of agriculture, resulting in a disruption of the pre-war traditional nutrient cycles. The reliance on the use of external chemical inputs with the advent of industrial agriculture led to the adoption of vegetationally simplified monocultures that disrupted traditional soil biological and nutrient cycles and reduced the complexity of biotic and abiotic interactions. Concurrent patterns of erosion and salinization due to improper soil, nutrient, and irrigation management practices also led to global problems of land degradation, loss of soil fertility, and productivity declines [9]. Even though a substantial body of scientific literature has been published over the past 70 years on N, considerable knowledge gaps persist with respect to its environmental fate and use on the farm, and thus chemical N fertilizer studies continue to be a mainstream of agronomic research [4,10,11].

The dynamics of soil N flows and crop uptake become considerably more complex in agricultural systems that rely on natural sources of N. Important questions regarding the nutrient dynamics on soils that rely on natural N sources include an understanding of the total amount of N available for crop uptake during the entire growing season; the synchrony or amount available to meet crop needs during critical stages of crop growth; the ability of crops or cropping systems to improve nitrogen use efficiency (NUE); as well as a better understanding of biotic and abiotic interactions [12], with the goal of optimizing N cycle dynamics within the farm.

Organic farming relies on ecological processes with the goal of minimizing the use of external inputs by closing nutrient cycles and improving the efficiency of resource utilization within the farm or farming area [13,14]. Considerable ongoing research is being conducted to better understand the complex dynamics of the N cycle in organic farms [3]. From a practical perspective, a better understanding of N cycles will help organic farmers improve crop productivity, quality, and economic returns, while minimizing excessive system N losses and potential adverse environmental impacts [15].

While organic farming refers to farms that have undergone formal certification by national or international agencies [1], it should be recognized that a substantial number of subsistence or small-scale farmers, especially in the tropics, rely on minimal or no chemical N sources, often at inorganic N rates below 10 kg ha^{-1} [16–20]. Thus, information on improved nutrient cycles under organic farming is also relevant for subsistence farmers, and inversely, information on farming techniques followed by traditional or indigenous farmers that rely on local N sources should also provide insight on management strategies to further close the N cycle on commercial organic farms.

This paper reviews key ecologically-based management strategies followed by organic and subsistence farmers to improve N cycles and NUE. An earlier review of the balance approach used for N management in vegetable crops is provided by Tei et al. [21], and a perspective on N cycles in organic farms in North America is provided by Carr et al. [1]. Additional analyses of the N cycle under a range of organic farm systems have been provided [14,22,23].

2. Nitrogen Cycles in Organic Farms

At the farm level elemental N transforms into different compounds as it cycles through the agroecosystem [24]. Nitrogen losses may occur through the atmosphere, leaching, or via runoff into surface waters. Atmospheric N losses are in the form of ammonia, nitric oxide, and nitrous oxide gases. Under intensive conventional agricultural systems reactive N losses from the system may reach 150 to 250 kg ha^{-1} yr^{-1} [5,8]. Estimates indicate that the adoption of ecological farming practices could reduce N farm losses by 70–90% [25].

Organic farming aims to close N cycles by increasing its reliance on biological N fixation and by the recycling of nutrients within the farm in the form of organic amendments and crop residues, as well as through effective management practices such as the adoption of improved crop varieties, organic mulches, crop rotations, intercropping, agroforestry, reduced tillage, integrated, or mixed crop-livestock systems, and the use of cover crops [26–28].

Atmospheric N becomes available to plants via a series of microbial transformations in the soil [24,29]. The N cycle thus involves the transformation of atmospheric N into N soil forms available for plant uptake and the further volatilization of surplus soil N back into the biosphere. Thus, NUE can be improved by adopting production, nutrient, and water management practices that optimize the use of locally available N sources and minimize N losses from the system. To optimize N use in organic systems, a greater understanding is required of the external and internal feedback mechanisms that control the regulation of N soil levels, including the impact of long-term management practices on N dynamics within the farm [30].

Nitrogen found in decomposing organic matter (OM) is converted from the amino-N form (NH_2) to ammonium (NH_4^+) by decomposing soil microorganisms. Ammonium ions in the soil are adsorbed by negatively charged clay particles and can be released based on the cation exchange characteristics of the soil. As part of the process of nitrification, released NH_4^+ is converted, via microbial activity, into nitrite (NO_2^-) and subsequently into nitrate (NO_3^-). As nitrate is negatively charged, it does not attach to clay particles, and thus remains in the soil solution. Ammonium, especially when manure is applied in the field, may be volatilized, when it is not adsorbed to soil particles nor transformed into NO_3^-. Nitrate and NH_4^+ in the soil solution are the main forms of N taken up by plants, with organic N forms also taken up by plants, albeit to a lesser degree. The N content in plant tissues ranges from 1 to 6% by dry weight. Nitrate-N that is not taken up by plants, because it is soluble, may be leached below the root zone, resulting in possible pollution of the groundwater and aquatic habitats. In instances when nitrate is not leached or taken up by plants, it may be converted to dinitrogen (N_2) or nitrous oxide (N_2O) gases by heterotrophic bacteria. Denitrification occurs primarily when the soil is saturated with water [24,31,32].

Sources of organic N in the soil include crop residues as well as soil OM [33]. As organic compounds, soil N is found in the form of amino acids, proteins, and nucleic acids. Plants can uptake and metabolize amino acids as an N supply in their form as single organic molecules, but their role as part of the total N budget has not been fully determined [34]. Soluble organic N (SON) is an important N pool in the soil and is thus an important component of the overall N cycle. Levels of SON have been estimated to represent 30–50% of total soluble N (TSN) levels in agricultural soils, and the levels of SON increase under organic farming. Plants can directly uptake organic N from the SON pool, and thus SON should be included as part of the total plant N budget determination [29]. As with mineral N sources, SON also undergoes the microbially driven processes of mineralization, immobilization, and potential leaching in the case of temporal surplus N levels. Factors that affect the SON levels include OM content, pH, total N, the C/N ratio, and environmental conditions and farming management practices [34].

Biological N fixation, carried primarily by soil microorganisms in symbiotic association with plants and to a lesser degree by free-living bacteria, is the primary source of N input for plants. The N-fixing bacteria fix N, providing NH_4^+ and NO_3^- to the host plant. Other microbes involved in the soil N cycle include ammoniating bacteria that convert organic N to NH_4^+ which is in turn converted to NO_3^- by nitrifying bacteria. In addition, mycorrhizal fungi metabolize arginine into urea, which is then converted to NH_4^+ [35]. Soil microbes and fauna are thus major drivers of the N cycle, both through the processes of N fixation, mineralization for the release of NH_4^+ from soil OM for plant uptake, and through the process of N immobilization, which reduces the availability of N to plants [24,36]. The addition of OM to the soil in the form of crop residues and organic amendments is another primary N source, and its availability for plant uptake or immobilization is similarly enhanced and driven by macrofauna, such as earthworms and springtails, and by microbial activity [1,26,28,29].

3. Organic Farming Fertilizer Practices

To meet certification standards, organic farmers rely on the use of composted manures, organic amendments and crop residues, natural nutrient sources, and cultural management practices such as rotations and the planting of cover crops for nutrient management on their farms [1,22,27]. Important challenges for organic farmers with respect to N fertilization include: (a) meeting the total demand for N required during the entire cropping cycle; (b) synchronizing or matching the amount of N needed during critical stages of crop growth [37,38]; and (c) understanding N release rates under the co-application of multiple N sources [2,39]. For example, a coriander (*Coriandrum sativum* L.) crop that received a baseline compost application (6.4% N content), showed greater yields when it received supplemental N applications [40], as was also observed with organic tomatoes [41].

Fertilizer recommendations for N are frequently made based on crop uptake information available from the scientific literature, which indicates the total amount of nutrient uptake at specific yield targets [42–44]. Data points used to develop N rate recommendations include N inputs, N tissue content, and yields at each respective N input level to obtain a yield response curve [45]. However, for each crop species, nutrient uptake will vary depending on cultivar, location, production practices, growing season, and environmental conditions.

Organic N management recommendations have been adapted, as a first approximation, based on studies conducted under conventional systems [46,47]. However, given the considerable differences between conventional and organic systems, N calibration studies specifically conducted under organic farming conditions are needed to better understand and optimize the nitrogen use efficiency (NUE) in organic farms [1,48]. With a nutrient balance approach, the N recovery rate efficiency can be determined, based on the imports, or total amount of initially available or applied N versus the system exports or crop N uptake rates [1,21,23,27].

A challenge for organic farmers is the need to synchronize the N release pattern from organic amendments with the N uptake demand during particular crop growth stages [49–51]. To meet periods of high N demand and minimize overapplications during periods of low N demand, a better understanding is needed of the N mineralization rates, over time, from the soil OM as well as of the varied organic N sources used on the farm [50,51]. One strategy to improve the synchronization of N fertilization with crop uptake during periods of high demand is to make an application of baseline N in the form of composts or pelleted manure and complement it with applications of readily available liquid-based N sources during periods of high demand [39,52]. Similarly, a combination of chicken manure, azolla, and straw compost, sources with differential N mineralization rates, optimized the growth and yield of organic rice in Central Java, Indonesia [48].

The NUE index determines the ability of a crop to maintain productivity under a limited supply of N, and to minimize losses from surplus N applications. Nitrogen Use Efficiency may be improved by modifying fertilizer or irrigation practices, such as by applying liquid organic fertilizers during periods of high crop demand [50,52]. However, as compared with conventional systems, the concept of NUE increases markedly in complexity under organic farming because there is an intricate interplay of several N sources, such as biological N fixation, organic fertilizers, soil OM, and atmospheric deposition, all within a complex array of edaphic and environmental interactions [53].

Given that there are varietal differences, within most species, in their efficiency to uptake nutrients, the breeding of crops for adaptation to organic farming may include selection for traits that improve NUE [52,54–56]. Traits that may improve NUE in soils with relatively low levels of available N, as compared to conventional systems, include plants that have an inherent capacity for internal N conservation while maintaining adequate yields; the ability to maintain photosynthetic activity during periods of nutrient stress; increased N partitioning to the fruit or grain; the ability to uptake N at relatively low soil N levels; and root systems with improved microbial interactions that may facilitate improved soil N extraction [52,55,57]. An N-balance study conducted in Germany found increased

NUE in organic vs. conventional farms, helping to reach the goal of establishing closed nutrient cycles [23].

4. Organic Matter and N Mineralization Rates

Building organic matter (OM) content, soil quality, and biology are central foundations of organic farming, and guidelines to maintain and improve soil OM levels are outlined as part of organic farming certification standards [1,50,58]. As a reservoir of nutrients and of microbial activity, OM is a driver of nutrient cycles on the farm. In North America, surveys have corroborated the emphasis on building OM levels on organic farms, finding that the top 30 cm of the soil layer in organic farms contained 22% more organic carbon and 20% more total N than conventional farms [1], which likely explains the greater level of microbial biodiversity found in organic systems [6].

Soil OM is divided into two major fractions, including the labile or active fraction, which decomposes more rapidly; and humus, which is more stable and decomposes over long periods of time, up to hundreds of years. Humus helps to improve the soil physical structure and serves as a long-term source of nutrients. The labile soil fraction, composed of partially or recently decomposed organic residues, is considered the active component of OM. Nitrogen in the labile soil fraction is more readily mineralized and thus has a direct impact on short-term crop uptake demands [50]. The main forms of organic N in soils, such as amino acids, chitin, proteins, DNA, RNA, and sugars, are found in the labile fraction as well as in humus [33]. A long-term study conducted in Davis, California, showed that after 14 years under organic nutrient management, consisting of legume rotations and composted manures, the soil accumulated 1000 kg ha^{-1} of N in the OM on the top 15 cm of the soil layer, which allowed for the slow release of mineralized N over subsequent years [59,60]. The same study found that under long-term organic nutrient management, the N balance (N inputs minus N removal during harvest) was 119% greater, N losses were 80% lower, and the OM content was 33% greater, compared to the conventional treatments [60].

Soil microbial and fauna activity in the soil is enhanced with organic amendment applications and through cultural management practices such as crop rotations, organic mulching, planting cover crops, and conservation tillage [1,61]. Soil microorganisms and fauna process the labile OM fraction, resulting in the gradual release of NH_4^+. Nitrifier microorganisms then oxidize NH_4^+ into NO_3^-. Organic matter increases the soil cation exchange capacity (CES), serves as a slow-release nutrient reservoir for plant uptake, improves the soil buffering capacity by moderating pH levels, and promotes soil microbial activity, resulting in improved soil nutrient cycling. Thus, improved soil health with greater OM contents results in greater N mineralization rates, crop yields, and quality [62].

The mineralization process from organic into inorganic forms of plant-available N contributes to the overall total crop N budget, representing the principal N input provided by organic fertilizers [33]. The challenge for N management on organic farms is the ability to quantify mineralization rates over time as affected by the interacting effects of field history, soil pH, soil moisture, temperature, organic amendment applications, tillage intensity, and the properties of the organic materials. In general, the net N mineralization rates of OM are in the range of 2–5% in annual crop systems, able to provide a partial or substantial portion of the total crop N uptake demand [8,49]. However, the need to synchronize the rates of mineralized N with particular periods of crop uptake demand remains a challenge for organic farmers. Variables that affect the rate of N mineralization in the soil include the quality of the partially decomposed crop residues and amendments. In general, soils high in OM are more likely to host rich microbial and fauna diversity and activity, resulting in more available N for plant uptake and more efficient nutrient cycles [49,63]. Levels of reported mineralized N from OM include 31 to 107 kg ha^{-1} during different periods of mineralization [64]; 40 to 123 kg ha^{-1} including residual levels from the previous crop [65]; 1 to 2 kg ha^{-1} dy^{-1} in conventional coastal soils of California [59]; and 30–70 kg ha^{-1} yr^{-1} on sandy soils with 1–2% of OM [66].

With respect to amendments applied on the farm, in general, less than 50% of the N will be mineralized and available for plant uptake, referred to as the Plant Available N (PAN), during the first year after application [43]. In general, for animal manures that are incorporated into the soil, 60 to 80% of the N will become available for plant uptake during the first year after application, and from 40 to 50% when broadcasted [43]. The mineralization rate from green manures ranges from immobilization to over 50%, depending on the environmental conditions and the C/N ratio. With sunn hemp (*Crotalaria juncea* L.) residues incorporated during the early fall in Florida, U.S. (24 °C soil temperature), a quick release of N was observed during the first three weeks after incorporation, increasing extractable NO^{-3}-N levels by 20–94%, compared to a fallow control. In turn, composts often show relatively low mineralization rates, and annual applications are more likely to gradually build soil fertility and N pool levels in the long term [37]. On the other hand, to meet periods of high crop demand, applications of organic fertilizers with a high (3–10%) N content and a low C/N ratio <10 are recommended, which may release 70% of the total N during the first 15 days after application [27].

Under favorable conditions, amendments high in N will mineralize faster, while those with lower N levels and a high C/N ratio will do so more slowly [2,33]. It is thus important that the mineralization rates of individual amendments be well characterized so that farmers can predict and prepare an N budget for their crops.

The processes of N mineralization and immobilization occur concurrently in the soil and are affected by the quality characteristics of the residues or amendments (such as C/N ratios), environmental and soil physicochemical conditions, production practices, inorganic N availability, and microbial activity [28,34]. Amendments or residues with a high C/N ratio >30 result in N microbial immobilization, making it unavailable for plant uptake. In turn, the levels of soluble organic N (SON) in the soil are indicators of soil fertility and regulators of N mineralization as they are part of an intermediate step in the mineralization of organic into inorganic $NH_4{}^+$-N [34]. In general, with respect to the use of organic fertilizers, the initial N content of the fertilizer is proportional but does not always predict its levels of N release or mineralization [67].

Long-term trials determined that optimum corn yields, under different tillage systems, were obtained when 23–26 mg N kg^{-1} soil was available on the top 30 cm of the surface soil layer [33]. This type of data, for different crops and under different production systems, based on OM and amendment mineralization studies, is necessary to develop a N budget and fertility management recommendations under organic production systems. However, with organic farming, the procedure to predict the available soil N concentrations at a given point in time is extremely complex because multiple N processes are occurring concurrently, such as ammonia volatilization, denitrification, immobilization, mineralization, and nitrification.

Because of the complexity of understanding soil N dynamics when several N sources are provided, such as N fixation and organic amendments, the development of N mineralization models, such as via first-order kinetic prediction models [2], may help to fine-tune the use and application rates of organic fertilizers [68]. Additional variables that should be incorporated into N mineralization models under organic or subsistence systems include the effect of soil microbial activity, vegetational diversity, and management practices on the N cycle and release patterns over time [39,69]. A further level of complexity is added to the dynamics of N mineralization when a combination of two or more organic fertilizers or amendments are applied concurrently, a practice that may help to synchronize the uptake of N during periods of high demand [39].

5. Nitrogen Inputs in Organic Farming

5.1. Organic Amendments

Organic amendments are among the most relied-upon low-cost N sources for organic farmers. The OM added with amendments serves as a source of slow-release N and also helps to promote soil microbial activity, which in turn drives N cycles [1,28,63]. Organic amendment applications alone are often not sufficient to meet N requirements during peak crop demand periods, and so their use is often complemented with high-soluble N organic fertilizers such as fish or feather meal or with leguminous crop residues that are also high in soluble organic N [34]. Many small-scale farmers in the tropics also rely on the use of amendments as an integral part of their nutrient management program. For example, a survey of 500 cocoa farms in southern Ghana showed that 48% applied poultry manure and 40% compost amendments along with other nutrient management practices such as fallows, mulching, and crop rotation [70]. The N content and mineralization rate of several organic nutrient sources are shown in Table 1.

Table 1. Nitrogen content of several organic amendments used by organic and subsistence farmers.

Product [1]	N Content (%)	C/N Ratio	N Mineralization (% of Organic N Applied)	Citations
Alfalfa Hay	2.5–3.3	11–21	65–80% (90–360 dy)	[71–73]
Blood meal	12–13	3.5	92, 60–68 (99, 60 dy)	[2,34,43,72]
Bone meal	4.2	3.5–3.8	25 (99 dy)	[2,72]
Castor bean meal	5–7.5	6–9	NA [2]	[34,71,72]
Compost	0.7–2.5	11–64	5–55% (100–360 dy)	[2,34,50,74]
Crop Residues (Fresh)	1.6–4.4	8–24	Variable	[74]
Feather Meal	14–16	3.6	78, 55–65 (99, 60 dy)	[2,43,75]
Fish Meal	10–14	4.5	29, 55–65 (99 dy)	[2,43,71,72,75]
Manure, cattle, fresh	0.8–3.2	16–21	13 (60 dy)	[34,43,71]
Manure, poultry, fresh	2.8–4.6	4–22	13, 60–80 (99 dy, 360 dy)	[2,34,71,76]
Residues, legumes	2–4.6	10–20.7	60–76 (180 dy)	[77]
Vetch, Hairy, *Vicia villosa*	3–4	9.8–13	63–80% (>70 dy)	[71,78,79]

[1] In general, organic fertilizers with a high (3–10%) N content, and a low C/N ratio <10 may release 70% of the total N during the first 15 days after application [27]. [2] High CO_2 mineralization rates reported (7× greater than for cattle manure), indicating high potential N mineralization rates [80].

5.1.1. Composts

The quality of composts varies widely depending on the raw organic materials used for their preparation, on the composting process, its maturity, and on the environmental conditions during preparation. While composts may be relied upon as the sole N source, especially for crops with low uptake demands, in general supplemental applications with higher fertilizer N sources are required. Nitrogen in composts is found in more stable forms than it is in manures, with less likelihood of losses from leaching or runoff. The N content of composts is about 1–2%, on a dry weight basis, and the release rates for the following crop after application range from about 5 to 55% [2,50]. Composts with a C/N ratio of 12–20 are deemed to have reached maturity, optimal for field application, while ratios above 25 may lead to N immobilization [2]. As an example of N release rates during the first year of application, compost applied at a rate of 60 t ha^{-1}, with a 35% moisture content, 2% N content, and a 10% N release rate would provide an N rate of about 80 kg ha^{-1}. The high application rates required to meet the crops' N demand thus may be impractical, economically prohibitive, and thus farmers may need to rely on supplemental high-N sources. Nevertheless, annual compost applications provide multiple benefits, as a source of slow release of N and other nutrients for months or years, and improve the soil OM content and microbial and fauna activity. More typical compost application rates are in the range of 5 to 10 t ha^{-1}, top-dressed or incorporated into the soil prior to planting. Early-season compost applications may provide the N uptake needed during the first 4–5 weeks after planting [50] and contribute to the long-term buildup of OM and soil quality. Compost applications may interact with other N management practices on the farm. For example, compost treatments were found to down-regulate legume N fixation rates by 15 to 20%, compared to the rates observed with crops receiving inorganic N sources, a response that may be affected by legume species [30,81]. However, compost applications, as part of these long-term trials, also resulted in increased levels of labile C and N and increased soybean yields compared to treatments receiving inorganic N [30].

5.1.2. Manures

Manure is a primary source of N in organic farming and for subsistence farmers in the tropics who follow chemical-free agriculture. Because of food safety considerations, its use as a raw product is restricted in organic farming for short-season crops, or for a specific period of time prior to the harvest of long-season crops. Manures may also be applied to cover crops prior to the planting of cash crops and may also be composted or aged prior to application to meet organic certification standards. The physicochemical and biological characteristics of manures are highly variable due to many factors, including the source of manure, feed, and management practices [43]. Manure is also subject to N volatilization in the form of ammonia and to leaching as NO_3^-.

Because of its variability, periodic analysis of the N content of manures is necessary to determine appropriate application rates. The potential rates of volatilization need to be taken into account, depending on whether the manure is surface applied or incorporated. Poultry manure has a greater N content in general, of about 3–4%, and is more readily available than other manure sources. The uric acid, present in poultry manure, readily converts to NH_4^+ and to NO_3^-, which may lead to leaching losses and thus reduced NUE if its release is not synchronized with crop uptake. A field experiment with poultry manure applied at rates containing 85 to 170 kg ha^{-1} of N resulted in the release of 43–53% of the N during the growing season [76]. Chicken manure releases relatively large amounts of N during the first 4–6 weeks after application, with rates declining thereafter. Manure application rates thus need to be synchronized to match N release rates with crop uptake demands to minimize environmental losses. Thus, in the case of nutrient sources with rapid mineralization rates, applications may be delayed until later in the growing season to match the timing of N release rates with periods of high crop N demand.

Long-term manure applications also result in greater soil OM levels, improving the long-term pool and slow-release of N. Annual applications of composted poultry manure of 20 t ha^{-1} over 10 years increased soil OM by about 8.5 t ha^{-1}, compared to conventional systems. However, the quality and source of manure will have a considerable impact in terms of its contribution to OM [49]. By following proper management practices such as crop rotations and planting cover crops and by relying on manure sources from integrated crop-livestock systems, farmers may be able to maximize internal N cycling and rely solely on local sources of N without external imports [15].

5.2. Legumes and Nitrogen Fixation

Nitrogen provided by biological N fixation is a primary N source in organic farms and on subsistence farms in the tropics. Legume cover crops in general can fix 75 to 200 kg ha^{-1} per year [8,35], but rates can range from 20 to 390 kg ha^{-1} [82]. In general, from 10 to over 50% of the N in cover crops is released for the following crop, depending on several residue qualities and environmental variables [49]. A profile of some leguminous crops used by organic and subsistence farmers is shown in Table 2.

Table 2. Example of some legumes and agroforestry species used as an N source by organic and subsistence farmers [1].

Species	N Fixation Rates (Kg ha^{-1})	Tissue N Content (%)	C/N Ratio	Biomass (t ha^{-1})	Citations
Canavalia ensiformis	133	4.8	15	10–25	[83–85]
Centrosema macrocarpum	70	2.2–2.5	18.6	4–6.6	[86–89]
Cowpea, *Vigna unguiculata*	70–350	1.5	12	2–6	[82,86,88,90,91]
Faba bean, *Vicia faba* L.	120–310	3.8	11	4.7	[82,88]
Gliricidia sepium	166	2–5	10–18	10.5	[77,92–95]
Lablab purpureus	80–140	2.2–4.2	11–34	2.5–10	[86,91,96,97]
Mucuna pruriens	150–230	2.2–2.5	12.3	2–8	[88,91,98–100]
Mungbean, *Vigna radiata*	220	2–2.2	6–26.5	3–5.5	[88,89,101]
Peanut, *Arachis hypogea*	30–200	2.5	23	22	[84,88,102,103]
Pigeon pea, *Cajanus cajan*	40–250	2.5–3.5	14.2	10–40	[86,88,104,105]
Sunn hemp, *Crotalaria juncea*	180–250	2–4.1	13–24	6–24	[84,88,91,93]
Stylosanthes guianensis	115	1.5–3	13.5–14.5	4–11	[86,88,100]

[1] The values reported in this table should be treated with caution. Actual N values and mineralization rates for particular species can vary considerably depending on the production system, environment, soil history and fertility, growing season, germplasm, and other variables.

The levels of soil N mineralization from N fixation may result in yields similar to those obtained with crops receiving inorganic N sources [106]. However, as with the application of organic amendments, the timing of N release by legume residues is an important consideration to synchronize the release rates with crop uptake demands and to prevent environmental losses [3,28]. The rates of N fixation are affected by several variables, such as plant species, strain of symbiotic bacteria, soil moisture, environmental conditions, and existing soil N residual levels [8,107]. In turn, important variables that affect the release of N from legume residues include the C/N ratio, method of incorporation, temperature, and soil moisture. Legume cover crops normally have a C/N ratio <20, which results in faster mineralization rates compared to other organic amendments [108]. The major N fixing organisms are the Rhizobium bacteria, which form symbiotic relationships, mostly with Legume species but also with some cereal crops, such as maize, rice, sugarcane, and wheat [34,109,110]. Lower rates of N fixation also occur in agricultural soils with both aerobic and anaerobic bacteria species, as well as by symbiotic non-nodulating bacteria such as *Azotobacter* and *Azospirillum* and blue-green algae [34,111].

In addition to their contribution to the N budget, the incorporation of legume residues also helps to improve soil quality, including OM content and microbial activity, which drive soil N cycling processes and plant uptake [108,112]. To further improve the benefits and effectiveness of legume cover crops, interplanting with non-legume cover crops may result in improved soil fertility, including improved soil aggregate stability and microbial activity, and may also reduce the risks of nitrate leaching [106,108,113].

The effectiveness and rates of N fixation and its contribution to plant growth are affected by the particular legume species and vary by location. On an experiment with organic greenhouse tomatoes in Northern Greece, a faba bean (*Vicia faba* L.) legume cover crop, combined with farmyard manure (FYM), resulted in improved yields of the subsequent tomato crop, compared to the use of beans (*Phaseolus vulgaris* L.) or cowpeas (*Vigna unguiculata* (L.) Walp.) in the rotation [114]. A baseline application of FYM resulted in improved tomato yields when combined with the faba bean residues compared to a compost/residues treatment, likely due to the greater N mineralization rates from the FYM compared to the compost treatment. This experiment highlighted the challenge of synchronizing the release of N from legume residues to match the N crop uptake demand, as also observed in a faba bean-tomato experiment in Italy [38]. During the early tomato growth stages, there was a surplus of soil mineral N, and during the later stages of crop growth, an N deficit was observed. However, the faba bean residues provided a steadier N supply over the growing season as compared to the other legume species [114]. The legume species $\times$ cropping sequence $\times$ system design interaction are thus strong determinants to improve yields and synchronize N mineralization with crop uptake demands, as observed in legume-based rotations on small subsistence farms in Uganda [112] and Malawi [115]. Overall biological N fixation contributes to the farm N budget and also improves NUE, especially under intercropping systems [116–119].

5.3. Contribution by Non-Legume Cover Crops

The planting of non-leguminous cover crops is a standard management practice for soil conservation and nutrient management on organic farms [49]. Non-legume cover crops contribute to the N cycle in numerous ways, including by scavenging residual levels of mineralized soil N [116,120], reducing erosion, improving soil structure and organic content, and stimulating microbial activity as their residues are incorporated or surface-applied as mulches, cycling N for subsequent crops. Deep-rooted cover crops help to mine and redistribute nutrients from the lower soil profile, reducing nitrate leaching and cycling N within the active root zone for subsequent crops.

The periodical use of cover crops increases the active soil labile fraction, which serves as a slow-release N reservoir for subsequent crops [49]. The rate of N mineralization from cover crop residues after termination is affected by several factors, including their composition, C/N ratio, tillage system, and environmental conditions. As with the reliance on other organic amendments, the rate of nutrient release from cover crop residues is not always synchronized with the stage of crop growth, and thus the timing of residue applications needs to be considered to better meet the timing of peak N uptake demands [43]. Strategies to better synchronize the release of N, according to crop uptake demand include the timing of planting and stage of cover crop termination, as well as alternative planting schemes, such as the interplanting of different cover crop species with different N contents and C/N ratios, along with the supplemental application of other organic amendments [49].

A rotational study conducted over a period of six years in California showed that a cereal rye (*Secale cereale*) cover crop produced 9 t ha^{-1} yr^{-1} of biomass and cycled an average of 123 kg N ha^{-1} yr^{-1}, while reducing nitrate leaching by 70%, indicating the potential of non-legume cover crops to contribute to the soil OM content and to the N cycle [59,121]. The following lettuce crop in the rotation obtained 22% of the N found in the rye residues, while 60% of N was incorporated into the soil OM, indicating that the N in this grass species is released gradually over time, which may better match the N uptake demand of long-term crops [59,121]. Mustard (*Brassica*) cover crops, in turn, may absorb N in the range of 130 to 180 kg ha^{-1} and the timing of its release after incorporation is intermediate between that of legumes and grasses, representing another strategy for the timing of N release rates, by intercropping diverse cover crop species [59]. Likewise, a study with a mustard (*Brassica hirta*) cover crop in Washington state, U.S., showed that N uptake ranged from 90 to 140 kg ha^{-1}, and that about 30% of the N in the cover crop (30–40 kg N ha^{-1}) was released for the following crop in the rotation [122].

6. System Design: Intercropping Systems Improve N Cycles

6.1. Ecological Interactions within Species in Intercropping Systems

Crop diversification studies have shown a consistent positive impact on farm nutrient cycles [116,123]. Intercropping, an integral part of indigenous or traditional cropping systems in many parts of the world, is characterized by vegetation diversification, which may improve resource and N utilization on the farm through a variety of interrelated ecophysiological mechanisms [26,54,124,125]. By growing intercrops with complementary growth characteristics, referred to as interspecific facilitation [119,126], such as variations in canopy architecture, root growth, crop phenology, or the timing of nutrient uptake, the different intercrop species are able to exploit particular ecological niches, referred to as niche partitioning, in space and time [117,126]. Interspecific facilitation allows for the complementary use of resources among intercrop species, leading to improved use of resources, such as N [117,124,127,128]. Intercropping further increases agroecosystem and yield stability [129] by moderating pest levels, improving soil quality [119], and changing environmental conditions within the farm, allowing the intercrops to maintain levels of productivity that correspond with the productive capacity and socioeconomic conditions of the agroecosystem and to maximize resource and nutrient use efficiency. Improved nutrient acquisition in intercropping systems also occurs through the well-documented process of facilitative interactions, in which a crop species modifies the growing environment, such as by increasing the levels of microbial activity or of nutrients in the rhizosphere, to benefit the growth of a companion species [117,124,128].

Because of its potential to improve crop productivity and build more resilient production systems [128], intercropping is also a mainstay on many organic farms. However, considerable location-specific research is required to identify the adapted crop genotypes, often observed with indigenous landraces, that show the needed phenotypic plasticity and complementarity differentiation traits that will optimize resource utilization and productivity under intercropping systems [117,124,126].

Benefits provided by intercropping include increased productivity on an area basis [124,126,127], a more diverse soil microbial activity that improves N cycles, the creation of biological and chemical buffers to minimize system disruptions, as well as the provision of several ecosystem services [130].

Long-term studies have indicated that increased vegetational diversity in intercropping systems results in greater carbon and N soil pools, due in part to a greater root biomass [119]. Intercropping systems, by promoting vegetation diversification in time and space, promote similarly dynamic soil microbial activity, which serve as ecological drivers of soil quality and of the soil N cycle. Long-term intercropping systems have shown increased soil C levels by 4% and N levels by 10%, indicating a corresponding increase in soil microbial activity [128].

6.2. Nitrogen in Legume-Based Intercropping Systems

The incorporation of legumes in intercropping systems improves N cycling and the yield of companion non-leguminous crops [124,126]. The mutual benefit obtained by legume and non-legume species in intercropping systems is a classic example of facilitative interactions among intercrops. Non-legume species such as maize and wheat release root exudates, which stimulate rhizobial nodulation in companion legume crops and also deplete N pools from the root zone, further stimulating N fixation by the legume intercrop [117,119,124,126]. This phenomenon was illustrated in relay intercropping experiments with pea (*Pisum sativum*) and maize conducted in Gansu Province, in northwestern China (with maize planted 2–3 weeks after the planting of peas), showing that pea N fixation rates were increased by 36%, seed N content by 34%, and residues N content by 23% when compared to a pea monoculture, while the intercropped maize had a 9% greater N canopy content compared to the monoculture maize, highlighting the mutualistic facilitative interaction [130]. Root biomass in the intercropped maize was also 78% greater compared to the monoculture maize. A partition analysis of the data determined that root growth interactions among the intercrops contributed 143% to the increased root growth in maize, with nutrients and water sharing contributing 80% to the intercropped maize root biomass [130].

The interactions between legumes and their non-legume intercrops, however, are species-specific ranging from competition to facilitation of N fixation. Thus, the amount of N transferred from intercropped legumes to non-legume crops will depend on their particular interaction, degree of "coexistence", or level of competitiveness. An intercropping experiment conducted in Hebei Province, China, with sorghum (*Sorghum bicolor*) and maize, intercropped in all possible combinations with alfalfa (*Medicago sativa*), soybean (*Glycine max*), and mung bean (*Vigna radiata*), illustrated the effect of genotype interactions on the performance of the N cycle in intercropping systems [126]. Among the legumes, the greatest N fixation rates were obtained with soybean, the legume N transfer to the cereal intercrops was higher for maize than for sorghum, and the most effective legume–cereal combination was observed with the maize-soybean system. Rates of N transfer from legume to non-legume species in the intercrops ranged from 0.5–4 g N m^{-2}, with the rates varying depending on species [126].

A key dynamic in the N cycle under intercropping is thus the direct transfer of N among species, especially under legume and non-legume intercrops. Maize–legume intercropping studies report that rates of N transfer from the legume intercrops to maize range from 6–27% [131] to 11–20% of N in the aboveground maize biomass [132]. While the literature reports an overall wide range of 0–73% N transfer rates between legumes and cereals, depending on a number of variables [35], a more realistic range is between 0–15% [118]. Methods of nutrient transfer between companion species include direct root contact, arbuscular mycorrhizae, and diffusion [118,132,133].

Intercropping greenhouse pot experiments conducted in Germany with radiolabeled ^{15}N showed that 90% of the N rhizodeposition transfer from legume to non-legume species occurred via direct root contact, compared to 10% via arbuscular mycorrhizal transfer. Under conditions of root exclusion between species, the proportion of N transferred via arbuscular mycorrhizal was increased [134]. The bidirectional transfer of N between species has also been reported, based on pot experiments, which could further improve NUE under intercropping systems by meeting intercrop N demands during periods of high uptake demand [35,133]. In instances where there is no direct root contact between species, arbuscular mycorrhizae may thus play a greater role in the transfer of N between species [118,132], as reported in a ^{15}N isotopic tracing pot experiment [135].

In general, studies have shown that intercropping results in greater productivity per area, increased NUE, and reduced N system losses from leaching when compared to monoculture controls [119,120,127,136]. An intercropping study under organic farming with faba bean (*Vicia faba* L) and cabbage (*Brassica oleracea* var. capitata) showed that the intercropping system had greater productivity on an area basis, cabbage yields, system N accumulation, and greater frequency and intensity of root growth in faba bean, stimulated by the presence of the cabbage roots; and a greater NUE. The intercrops in the study showed root growth niche differentiation, with the faba bean root system reaching <1 m deep and the cabbage root system reaching >1.75 m, which may help to minimize leaching and optimize the N cycle [127]. The selection of adapted legume species with complementary root growth patterns and resource use among intercrops is thus important to match the species N fixation and mineralization rates with the nutrient uptake patterns of the component intercrops [127,137].

An evaluation of three forage legume species and strip-tillage under intercropped wheat grown organically illustrates the complex interrelationship of multiple production variables that may affect the timely release of N during periods of high nutrient demand [138]. Intercropping three forage species, black medic (*Medicago lupulina* L.), white clover (*Trifolium repens* L.), and Egyptian clover (*T. alexandrinum* L.) with wheat under two tillage systems and in rotation with oats (*Avena sativa* L.), showed that the legumes did not supply enough N to meet the wheat uptake demands. A differential response was observed with respect to legume species, with increased wheat yields obtained with Egyptian clover mulch residues compared to the other legume species [138]. Nevertheless, cereal-legume intercropping in general increases the protein content of the cereal intercrops (11.1%) compared to levels observed under cereal monocultures (9.8%), with no differences observed for protein content among treatments on the legume intercrops [124].

Intercropping studies conducted under organic farming conditions have shown improved N dynamics and use efficiency, especially under low N input systems, indicating their potential for increased adoption under organic farming systems [119,124,127,137,139]. However, while it has been explored mostly with two-species models [47], considerable additional research is needed to better understand the underlying mechanisms that determine the N cycle of component species under intercropping systems, given the large number of variables and interactions involved, such as genotype, environment, and pedoclimatic conditions.

7. Management Practices That Affect the Nitrogen Cycle

Soil and cropping management practices can be adopted in organic farming as part of an integrated cultural management program with the goal of improving biological diversity and internal nutrient cycles [140]. Among the production variables that can be managed or incorporated to improve N cycles are crop species and cultivar selection, timing of operations, soil preparation, water and nutrient management, crop rotations, cover crops, integrated animal-cropping systems, as well as the use of external nutrient sources. To understand and model N flows within the system, the level of complexity increases markedly in organic farming, given the large number of variables and their interactions in both time and space. The complexity, number of variables, and level of high-order interactions involved increase further, given that farms are often subdivided into multiple diversified production plots, with each plot consisting of several crop species and often relying on a combination of multiple nutrient sources, including residual soil levels, based on the individual field history [39].

7.1. Tillage

Tillage has a considerable impact on the N cycle given its effect on microbial and macrofauna soil activity, increased mineralization, and possible N losses from soil erosion, leaching, and surface runoff [19]. Conservation tillage represents an alternative soil management practice to reduce environmental N losses, attenuate N mineralization rates, and increase soil carbon content, structure, biological diversity, and N pools compared to conventional tillage [33,141]. The increased levels of soil residues that remain in the soil from soil conservation practices improve soil quality in the form of increased soil OM content, aggregation, improved water infiltration, microbial activity, and mineralized nutrient levels [142]. A no-till and cereal–legume intercropping experiment conducted in central Mozambique showed 1.4% OM and 0.09% N content after 5 years, compared to respective levels of 0.2% and 0.02% under continuous monoculture maize [143]. A fourteen-year experiment conducted in northern France showed increased microbial and macrofaunal activity from both organic and conservation tillage systems when compared to conventional tillage [144]. A 31-year-old experiment conducted in Tennessee, U.S.A., also showed increased microbial activity, activity of enzymes associated with the N cycle, soil N, and overall soil quality under no-till than conventional treatments [145]. Experiments with conservation tillage under organic farming confirm the feasibility of improving soil quality, soil N content, and yields compared to conventional tillage [146], even though considerable further adaptive research is necessary [147,148].

The rate of N mineralization from crop residues, which is driven by microbial activity [29], varies by crop species and needs to be taken into account based on expected crop uptake demand, with legumes in general showing a faster decomposition rate than cereal crops [33]. The effect of conservation tillage on the soil N pool, however, is also determined by the particular soil and agroclimatic conditions as well as the field and soil management history [141]. Due to the relatively lower N mineralization rates observed under conservation tillage, N uptake demands may not be met during peak demand periods, as observed in an organic cereal strip tillage experiment [138]. While conservation tillage improves long-term soil quality and N cycling, considerable research is required to better synchronize the timing and rate of soil N mineralization with crop uptake demands as affected by variables such as cover crop species, planting dates, and timing of termination [6,19,142,148,149].

7.2. Crop Rotations Impact on N Cycles

Crop rotations, by providing temporal vegetational diversification, are an integral foundation to improve soil fertility and N cycles in organic farming [26,150]. A survey of organic farmers in northern Europe showed that over 90% of farmers incorporated cover crops as part of their rotations to provide N for the following crop [149]. Crop rotations provide several ecosystem services and may increase cereal crop yields by 20% compared to monocultures [128]. Benefits of crop rotations include increased yields and NUE, especially when legumes are included in the rotation; a healthier microbial activity that results in improved soil health; and reduced weed and pest pressure, which reduces plant stress and thus improves NUE [26,151]. Crop rotations allow for the selection of crops in the planting sequence with complementary N uptake requirements, including root systems that explore different depths of the soil profile, optimizing N cycles in time and space, and minimizing environmental losses [26].

When compared to conventional systems, crop rotations followed by organic farmers tend to foster improved N cycling by having a greater vegetational diversity, including a greater reliance on cover crops and catch crops (which uptake and conserve residual soil N from previous crops); a greater reliance on leguminous crops and on intercropping; and organic farmers tend to rely on longer duration rotations than conventional growers [152]. A two-year sweet corn-cabbage rotation experiment on two distinct soils showed similar yields between organic and conventional treatments when both systems received adequate N applications. The incorporation of sweet corn residues after harvest further increased soil N pools by 4 to 7% under the organic system, becoming available for the subsequent cabbage crop in the rotation [153]. A three-year crop rotation experiment conducted in Portugal indicated that the proper combination of nutrient sources (compost, green manure, or organic fertilizer) with the cropping sequence can optimize the synchronization between N mineralization rates with the timing of crop uptake demand [27].

A two year rainfed soybean-millet rotation experiment was conducted twice in Ethiopia, with two distinct soybean varieties receiving several rates of farmyard manure (FYM) [154]. Overall, the FYM treatments increased soybean yields by 85 to 190%, compared to the untreated controls, by providing nutrients and improving soil moisture retention. Over the different growing seasons, the study identified a Climate × Cultivar × Cropping system interaction with an early maturity soybean variety and low FYM rates optimizing nutrient use and subsequent millet yields during a year with a short rainfall season and in a field with low fertility, plausibly due to a greater mineralization rate of soybean residues; and with a later maturity soybean variety and high FYM rates becoming more optimal during a longer-rainfall season and a more fertile soil, indicating that a long rainy season and fertile soil can support the more vigorous growth of a late maturing soybean variety, resulting in greater overall system productivity [154].

7.3. Additional Nitrogen Management Practices

Depending on the environment and local production practices, organic farmers may adopt a number of additional production strategies to enhance natural biological and ecological processes and improve N cycling on the farm. Many of these strategies, at the local level, are derived from production practices developed over millennia by indigenous populations in close adaptation to the local environmental conditions, a complex knowledge system of ethnoscience that promotes system resilience based on biodiversity and the regulation of nutrient cycles [155,156].

7.3.1. Agroforestry Systems

Agroforestry, a system followed by indigenous cultures, is an integral part of organic farming systems in several countries in the tropics for the production of crops such as coffee and cocoa. Agroforestry systems, by relying on vegetation diversification, promote soil conservation [6,18], N cycles [157], and reduced environmental losses [158]. As with other diversified production systems, the selection of compatible companion species is important to optimize NUE and cycling under agroforestry systems [159]. The selection of companion species, with respect to their interaction with other variables such as light interception, also needs to be considered to improve N cycles under organic agroforestry [12,160]. Agroforestry systems, when combined with supplemental N sources, such as organic mulch residues, can also be adopted for the production of annual cash crops, resulting in increased productivity as compared to conventional monocultures [161]. A list of some agroforestry species commonly observed in organic and subsistence farms, especially in the tropics, and their respective tissue N content is presented in Table 3.

Table 3. Percent Nitrogen (N) tissue content from the foliage of several agroforestry species.

Crop Species [1]	Nitrogen Leaf Tissue Content [2] (%)	Source
Calliandra calothyrsus	2.8%	[92]
Calliandra	3.0%	[162]
Cassia reticulata	2.6%	[92]
Cassia siamea	2.3%	[92]
Gliricidia sepium	3.4%	[92]
Inga edulis	2.5%	[92]
Leucaena leucocephala	3–3.7%	[92,94]
Sesbania sesban	1.4%	[92]
Senna siamea	2.0%	[94]
Tephrosia	2.8%	[162]

[1] Sampling locations included Hawaii [92]; Tanzania [94]; and Rwanda [162]. [2] Reported N mineralization rates for legume residues have ranged from 32%, after 15 days [100]; 50% for *Gliricidia* residues after 6 months [163]; 80% after 8 weeks with residues having a 10 C/N ratio [164]; and 83% 360 days after placement on the soil surface [100].

7.3.2. Integrated Crop-Livestock Systems

To further optimize the N cycle on organic systems, it has been proposed that more farms adopt integrated crop-livestock and crop-aquaculture systems [165–167], such as the traditional crop-pig aquaculture and rice-duck aquaculture systems observed in some parts of Asia [168]. Integrated systems have historically been an integral part of traditional farming systems by providing economic diversification, resilience, and reduced economic risks in areas affected by adverse social and climatic conditions [169]. A multi-year integrated crop-livestock and rotation system evaluated in Matto Grosso do Sul, Brazil, showed enhanced soil microbial diversity, activity of N cycling genes, and increased soil quality, which likely contributed to more efficient N cycles [170], as also observed in an integrated no-till and intercropping system in Brazil's Cerrado region [171]. An N cycling study conducted in Germany found a greater NUE on crop-livestock integrated farms than both crop-only organic and conventional farms [23]. Integrated crop-livestock systems may be established not only within the farm but also among farms in space and time on a landscape basis [172]. However, to optimize the adoption of integrated or mixed crop-livestock systems, considerable research is required to evaluate the many production variables and interactions that affect crop productivity, nutrient cycles, as well as food safety considerations [173].

8. Strategies to Reduce System N Losses

Depending on the production practices, N environmental losses may occur with organic farming, as they do with conventional systems. Management guidelines outlined by certification standards strive to close the N cycles on organic farms to minimize undesirable N losses. The only desirable N loss from organic farms is from crop uptake. Reports are available with tables of crop N uptake for given yield targets [42,43]. These estimated crop uptake numbers, often obtained from several sources under conventional systems, likely need to be adapted based on the local conditions, distinct crop varieties, N uptake patterns, and production systems found under organic farming [1]. A nutrient balance approach, represented by the outputs subtracted by the N inputs from the different possible sources, may be followed to identify target crop yields and minimize possible surplus N levels [21,27], as well as to determine the system NUE [23].

8.1. Leaching

Surplus N in the soil profile may lead to nitrate accumulation, which is prone to leaching below the root zone. Surplus N of 200–300 kg N yr^{-1} has been reported for conventional systems, which indicates the considerable potential environmental risks from groundwater contamination and the release of greenhouse gases [63]. Organically managed soils have shown reduced nitrate leaching and enhanced NUE compared to conventional ones [1,174]. Some comparative studies have found leaching levels to be about 4.5 to 5.5 times greater in conventional versus organic systems [63].

Potential problems with the management of N in organic farms concern the potential lack of synchronization of N available in the soil from several concurrent sources, such as OM, amendments, or residue applications, with the timing of crop uptake, resulting in potential surplus N and potential losses during parts of the production cycle [63,74,107]. In general, organic nutrient management practices result in reduced risks of N leaching. However, high organic amendment application rates or farms with insufficient vegetation cover (<30%) during periods of heavy rainfall may increase the risk of leaching on organic farms [175].

8.2. Erosion and Runoff

Soil N may also be lost through runoff and erosion. Studies to date have shown improved soil quality, conservation, and reduced erosion in organically managed compared to conventional soils, such as in long-term observations in the U.S.A. and Europe [63,176,177]. The reduced erosion observed in several studies for organic systems may be explained by the reduced tillage intensity, the use of organic amendments and residues, and the inclusion of cover crops in the rotations, all of which help to improve soil aggregate stability [6]. A long-term organic experiment conducted in Switzerland showed that overall, organic practices reduced sedimentary recovery by 30% compared to conventional systems. Moreover, organic plots with reduced tillage showed 60% lower recovery than organic plots that received tillage, indicating that higher levels of ground cover and OM content were key variables to reduce erosion levels [177]. Crop diversification in the form of cover crop rotations, intercropping, and agroforestry is also effective to reduce soil erosion [178,179]. In a 10-year citrus experiment conducted on 25° sloping lands in the Gorges area of central China, 3–18 mg L^{-1} N soil losses occurred primarily from runoff and sediment loss. Management and diversification strategies that reduced runoff, sediment loss, and N losses compared to conventional controls included the establishment of contour rows, hedgerows, organic mulches, and intercropping with a perennial legume groundcover [180]. Another citrus experiment conducted with simulated rainfall showed that a perennial legume ground cover reduced total N, nitrate-N, and ammonia-N losses by 25.5%, 74.6%, and 90.7%, with a reduction in erosion and runoff losses of 91.5% and 25.5%, respectively, compared to the bare-ground controls [181].

8.3. Emissions

Surplus soluble N may volatilize via the microbial denitrification process into greenhouse gases such as nitrous oxide (N_2O) and N_2. Nitrous oxide is considered to be the most potent greenhouse gas, as it is 300 times more effective than CO_2 at capturing atmospheric heat. Several studies have shown lower N_2O emissions rates on organic farms, with one study finding 66% lower rates than on conventional farms, while higher emissions have been reported for some horticultural organic crops [6,63,123]. N_2O emission rates under organic farming thus vary by the type and management intensity of the cropping system. In addition, high emission rates may occur on organic farms when large amendment rates are applied, resulting in high temporary soil N surplus levels above the rates needed to meet crop uptake demand. The inclusion of legume catch crops as an N source to replace the partial use of organic amendment applications has been proposed as a strategy to reduce N_2O emissions on organic farms [6].

9. Prospects for Managing the N Cycle under Subsistence Agriculture

The underlying biogeochemical mechanisms that determine N cycles under organic systems are, in general, similar, as a first approximation, to those observed under subsistence production systems, given the variations observed based on farming system, vegetational diversity, geographical location, soil types, microbial activity, and environment. Most of the research on the N cycle in agriculture has been conducted in temperate regions and on conventional systems, with an increasingly lesser degree on organic and subsistence farms in the tropics. Furthermore, an obstacle to better understanding N cycles under organic and subsistence systems in the tropics, is the challenge of developing a research methodology under highly diversified systems with respect to time, space, and socioeconomic conditions. Conversely, the farming techniques developed by indigenous cultures over millennia have often resulted in production systems with optimized N and resource use efficiency, information that could provide insights for the improvement of the N cycle under modern organic and conventional production systems [156,182]. A representative list of several N management-related practices that are followed under subsistence agricultural systems is presented in Table 4.

Table 4. A sample of studies and adoption of nitrogen management practices under subsistence agriculture [1].

Cultural Practice	Reported Variables	Citations
Intercropping with legumes	N dynamics	[112,183]
Intercropping	N cycle and flow analysis	[184–186]
Manure and crops residues	Mineralization rates	[85]
Legume Rotation & Intercrops	N dynamics	[115,171,187]
Shifting cultivation	N and nutrient dynamics	[188–190]
Integrated, crop-livestock systems	N contribution	[123,191]
Agroforestry Systems	N dynamics	[94,159,192]
Organic Mulches	N dynamics, soil fertility	[88,193]
Soil and nutrient conservation	Erosion, runoff prevention	[178,192,194]
Prospects for organic agriculture	Economics, sustainability, food security, adoption	[13,195,196]

[1] Subsistence agriculture here refers to farms, especially in tropical regions, that rely on little or no external inputs [16–20].

10. Conclusions

The goal of striving toward closed nutrient cycles in organic farming is articulated as part of national and international certification standards, which prescribe a diversity of management practices to build soil fertility and organic matter. Management features that promote internal nutrient cycling include the buildup of soil organic matter and a corresponding increase in soil biodiversity, the reliance on biological N fixation, vegetational diversity in time and space, reduced tillage intensity, crop-livestock integration, the selection of adapted germplasm, and the adoption of integrated cultural practices that maximize NUE [54,116,123,130,197].

While ecologically-based production practices can result in improved nutrient utilization, for adoption on a wider scale, including by resource poor farmers in tropical regions, organic farming should include social contexts that promote food security and sovereignty [198], along with gender and social equity, in line with the framework of agroecology [123,195,197,199,200]. A basic agroecology tenet is the focus on redesigning agricultural systems by adopting ecological principles to improve N cycles rather than by following an input-substitution approach that relies on external N sources, as is done within the production paradigm of conventional agriculture [201].

Despite the advances over the past few decades [54,119], considerable gaps exist with respect to both the research methodology and our understanding of high-order synergistic interactions and N dynamics on diversified organic farms. Since the advent of industrial agriculture after World War II, agricultural science has focused its research on reductionist science. Ecological-based approaches are thus required to evaluate hypotheses such as those involving diversity and resilience to design improved agroecological systems [123]. Given the large number of variables, management practices, and diverse farming systems, considerable knowledge gaps thus exist with respect to N cycling in organic systems, especially in the tropics. Some of the more pressing research directions include the understanding and design of vegetation diversification strategies; system interactions such as between weeds and crops; long-term residual effects of management practices; cover crop and cash crop germplasm evaluation under diversified systems; improved modeling studies to better understand N mineralization patterns under diversified vegetation systems; N uptake synchronization; as well as evaluating the effects of climate change adaptation on N cycle dynamics [1,123].

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