Chapter

Nitrogen Fertilization II: Management Practices to Sustain Crop Production and Soil and Environmental Quality

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Abstract

Improved management practices can be used to sustain crop yields, improve soil quality, and reduce N contaminations in groundwater and the atmosphere due to N fertilization. These practices include crop rotation, cover cropping, application of manures and compost, liming, and integrated crop-livestock system. The objectives of these practices are to reduce the rate of N fertilization, enhance N-use efficiency, increase crop N uptake, promote N cycling and soil N storage, and decrease soil residual N. This chapter discusses improved management practices to reduce N fertilization rate, sustain crop yields, and improve soil and environmental quality. The adaptation of these practices by farmers, producers, and ranchers, however, depends on social, economic, soil, and environmental conditions.

Keywords: crop yields, environmental quality, management practices, nitrogen fertilizer, nitrogen-use efficiency, soil quality

1. Introduction

Legume-integrated crop rotations provide opportunity to reduce N fertilizer rates due to increased N supply by legume residues to succeeding crops compared with nonlegume monocropping [1, 2]. As little or no N fertilizer is applied to legumes during their growth, inclusion of legumes in rotation with nonlegumes helps to reduce the overall N rate for a crop rotation, which increase farm income by reducing C footprints and lowering the cost of N fertilization [1, 3]. Legumes also fix atmospheric N and release it for as long as 3 years, increasing yields of succeeding crops compared with nonlegume crops in crop rotations [4]. Crop rotations also reduce disease, pest, and weed infestations [5], improve soil structure and organic matter storage [6], increase water-use efficiency [7], and enhance soil health through microbial proliferation [8]. Crop rotation can also increase N uptake efficiency of diverse crops and reduce soil residual N compared with monocropping [2].

Cover cropping has many beneficial effects on sustaining crop yields and improving soil and environmental quality. Cover crops planted after the harvest of cash crops use soil residual N, reducing N leaching. The additional residues supplied by cover crops increase soil organic matter and fertility [9, 10]. Legume cover crops reduce N fertilization rates and enhance crop yields, but nonlegume cover crops are
more effective on enhancing C sequestration [11, 12]. Similarly, integrate crop-livestock system, while reducing feed cost and supplying meat, milk, and wood, enhances N cycling and soil fertility, and control weeds [13, 14].

Continuous application of NH$_4$-based N fertilizers to nonlegume crops can reduce soil pH compared with legume-nonlegume crop rotations where N fertilizer is not applied to legumes [15]. After 16–28 years of management implications, soil pH was reduced by 0.22–0.42 from the original level in continuous nonlegumes compared with crop rotations containing legumes and nonlegumes [15]. Soil acidification from N fertilization to crops primarily results from (1) increased removal of basic cations, such as calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na) in crop grains and stover due to increased yield; (2) leaching of soil residual NO$_3$-N, Ca, and Mg; and (3) microbial oxidation (or nitrification) of NH$_4$-based N fertilizers that release H$^+$ ions [16]. Alkalinity produced during plant uptake of N or conversion of inorganic N to organic form, however, can partly or wholly counter the acidity from nitrification [17]. Increased toxicity of aluminum (Al), iron (Fe), and manganese (Mn) and reduced availability of most nutrients, such as P, Ca, Mg, K, and Na, during acidification can reduce crop growth and yield [18].

Here we discuss various management strategies to reduce N fertilization rates, increase N-use efficiency, and decrease N leaching and N$_2$O emissions due to N fertilization. These practices will reduce the cost of N fertilization while sustaining crop production and reducing soil and environmental degradation.

2. Management practices

Management practices that reduce N fertilization rates without affecting crop yields and quality are needed to reduce soil and environmental degradation, as soil degradation is directly related to increased N rates. Some of these practices include crop rotation, cover cropping, application of manure and compost, and integrated crop-livestock system. These practices can increase N inputs, reduce N fertilization rates, conserve soil organic matter, and enhance soil health and environmental quality without affecting crop yields compared with traditional management practices. We discuss these practices as follows.

2.1 Crop rotation

Crop rotations that include legumes and nonlegumes in the rotation can substantially reduce N fertilization rates compared with nonlegume monocropping because legumes supply N to the soil due to their greater N concentration from atmospheric N fixation than nonlegumes. As no N fertilizer is applied to legumes, overall N fertilization rate is lower for the legume-nonlegume rotation than continuous nonlegumes while still maintaining crop yields. Sainju et al. [19] observed that annualized crop biomass and grain yields under rainfed condition were similar or greater with legume-based rotations that included pea, durum (Triticum turgidum L.), canola (Brassica napus L.), and flax (Linum usitatissimum L.) than with continuous durum ([Table 1]). Crop rotation is an effective management practice to control weeds, diseases, and pests [7]; reduce the risk of crop failure, farm inputs, and duration of fallow; and improve the economic and environmental sustainability of dryland cropping systems [20]. Diversified crop rotations can efficiently use water and N compared with monocropping [7, 21]. For instance, wheat and barley can efficiently utilize soil water in wheat-pea and barley-pea rotations than continuous wheat and barley. This is because pea uses less water than wheat and barley, resulting in more water available for succeeding crops in the rotation [7, 21].
Crop rotation can enhance or maintain soil organic C and N levels compared to monocropping. Both soil C and N stocks can be influenced by the quality and quantity of residue returned to the soil from crops involved in the rotation [12, 22]. Crop rotation can sequester C at 200/120 kg C ha\(^{-1}\) year\(^{-1}\), reaching equilibrium in 40–60 years compared with monocropping [23]. Sainju [24] found that soil organic C at 0–5 and 5–10 cm was similar in no-till malt barley-pea rotation (NTB-P) and no-till continuous malt barley (NTCB), both of which had greater soil organic C than no-till malt barley-fallow (NTB-F) and conventional till malt barley-fallow (CTB-F) due to greater amount of crop residue returned to the soil and reduced mineralization of soil organic matter (Figure 1). Similarly, Sainju et al. (2017d) found that soil total C at 0–125 cm was similar to continuous durum and rotations that included durum, canola, pea, and flax, except D-D-F-P (Table 2). Soil total N at 0–120 cm was greater with spring wheat-pea rotation than continuous spring wheat (Table 3) [25].

In an experiment evaluating the effects of crop rotation and cultural practice (traditional and ecological) on N balance in dryland agroecosystems, Sainju et al. [26, 27] observed that N fertilization rates were lower with legume-based crop rotations (D-C-D-P, D-D-C-P, D-F-D-P, and D-D-F-P) than nonlegume monocropping (CD) (Table 4). Traditional cultural practices included conventional till, recommended seed rate, broadcast N fertilization, and reduced stubble height and ecological practices included no-till, increased seed rate, banded N fertilization, and increased stubble height. They found that both total N input and output were greater with legume-based rotations than nonlegume monocropping due to pea N fixation and increased grain N removal. As a result, N balance was positive, indicating N surplus in legume-based rotations, and negative, indicating N deficit in nonlegume monocropping. This suggests that external N input is lower to sustain crop yields in legume-based crop rotations than nonlegume monocropping.

Legume-nonlegume rotation can also resist soil acidification compared with continuous nonlegumes. Sainju et al. [18] reported that soil pH at 0–7.5 cm after 30 years of experiment initiation was 0.13–0.44 greater and at 7.5–15.0 cm was 0.11–0.29 greater with spring wheat-barley/pea rotation (FSTW-B/P) than continuous spring wheat (NTCW, STCW, and FSTCW) (Table 5). They explained this as a result of lack of N fertilization to pea and reduced N fertilization rate to spring wheat following pea whose residue supplied N to spring wheat because of higher M concentration than spring wheat and barley residues. Soil residual NO\(_3\)-N, which can pollute groundwater through leaching, was lower with legume-based crop rotations containing durum, canola, pea, and flax than continuous durum (Table 6), suggesting that legume-based crop rotations can reduce N fertilization rate and the potential for N leaching compared with nonlegume monocropping.

### Table 1.
Effect of crop rotation on average annualized crop biomass (stems and leaves) and grain yields of durum, canola, flax, and pea from 2006 to 2011 in eastern Montana, USA (Sainju et al., 2017d).

| Crop rotation† | Annualized biomass yield (Mg ha\(^{-1}\)) | Annualized grain yield (Mg ha\(^{-1}\)) |
|---------------|------------------------------------------|-----------------------------------------|
| CD            | 3.32b‡                                   | 1.77a                                    |
| D-C-D-P       | 4.02a                                    | 1.76a                                    |
| D-D-C-P       | 3.90a                                    | 1.70a                                    |
| D-F-D-P       | 3.39b‡                                   | 1.63ab                                   |
| D-D-F-P       | 3.56b‡                                   | 1.54b                                    |

†Crop rotations are CD, continuous durum; D-C-D-P, durum-canola-durum-pea; D-D-C-P, durum-durum-canola-pea; D-F-D-P, durum-flax-durum-pea; and D-D-F-P, durum-durum-flax-pea.
‡Numbers followed by different letters within a column are significantly different at P ≤ 0.05 by the least square means test.

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2.2 Cover cropping

Cover crops have been grown successfully in regions with mild winter to provide vegetative cover for reducing soil erosion. Cover crops are usually grown in the fall after the harvest of summer cash crops and have many benefits for sustaining crop yields and improving soil and water quality. Winter cover crops use soil residual N that may otherwise leach into groundwater after crop harvest in the fall, thereby reducing soil profile NO₃-N content and N leaching [29, 30]. Summer cover crops are grown in the summer to replace fallow when no other crops are grown. Depending on the species, cover crops can maintain or increase soil organic C and N.
by providing additional crop residue which increases biomass C and N inputs to the soil [9, 10, 12] and sequester atmospheric C and/or N, thereby reducing the rate of N fertilization to summer crops [9, 10]. Other benefits of cover crops include increased soil aggregation and water infiltration capacity [31], improved water holding capacity [32], and reduced soil erosion [33] compared with no cover crop.

Integrating legumes in crop rotations can supply N to succeeding crops and increase crop yields compared to nonlegumes or no cover crop rotations [10]. In contrast, nonlegume cover crops are effective in increasing soil organic C through increased biomass production compared with legumes or no cover crop [9, 10, 12]. Nonlegumes also reduce NO3-N leaching from the soil profile better than legumes, or no cover crop do [29]. As none of the cover crops are effective enough to provide most of these benefits, i.e., to supply N, sustain crop yields, increase soil organic matter, and reduce N leaching, a mixture of legume and nonlegume cover crops is ideal to supply both C and N inputs in adequate amounts that help to improve soil and water quality by increasing organic matter content and the potential for reducing N leaching compared with legumes and increase crop yields compared with nonlegumes [12, 34, 35].

Sainju et al. [36] found higher biomass yield with hairy vetch/rye (Secale cereale L.) mixture than rye, hairy vetch, or winter weeds, and N concentration in the mixture similar to hairy vetch, except in 2001 (Table 7). As a result, they observed greater biomass C and N contents with hairy vetch/rye mixture than rye and winter weeds and similar or greater than hairy vetch. The C/N ratio of cover crop biomass, which measures the decomposition rate of the residue, was similar between hairy vetch/rye mixture and hairy vetch.

Because of increased C supply, soil organic C at 0–10 and 10–30 cm was also greater with hairy vetch/rye than other cover crops (Figure 2). At 30–60 cm, soil organic C was greater with hairy vetch/rye than other cover crops, except hairy vetch. Soil total N at 0–15, 15–30, and 0–120 cm was also greater with hairy vetch and hairy vetch/rye mixture than other cover crops (Figure 3). Similarly, soil residual NO3-N content at 0–120 cm was greater with hairy vetch than other cover crops and is slightly greater than that with 120–130 kg N ha−1 (Figure 4). Nitrogen loss at 0–120 cm during the winter fallow period from November to April was lower with hairy vetch/rye than other cover crops (Table 8). Nitrogen fertilizer equivalence of rye and winter weeds for cotton and sorghum ranged from 69 to 220 kg N ha−1 (Table 9), suggesting that hairy vetch and hairy vetch/rye can increase cotton and sorghum yields similar to those by 92–220 kg N ha−1 [11]. These results suggest that hairy vetch/rye mixture can produce crop yields similar to hairy vetch.

| Crop rotation* | 0–5 cm | 5–10 cm | 10–20 cm | 20–40 cm | 40–60 cm | 60–90 cm | 90–120 cm | 0–120 cm |
|---------------|--------|---------|----------|----------|----------|----------|----------|---------|
| CW            | 0.82   | 0.91    | 1.46     | 2.34b    | 2.11     | 2.29b    | 2.11     | 12.03b  |
| W-P           | 0.85   | 0.90    | 1.53     | 2.66a    | 2.24     | 2.55a    | 2.23     | 12.96a  |
| W-B-P         | 0.79   | 0.86    | 1.44     | 2.43ab   | 2.17     | 2.35b    | 2.22     | 12.17b  |
| W-B-C-P       | 0.81   | 0.88    | 1.47     | 2.54a    | 2.26     | 2.51a    | 2.10     | 12.62ab |

*pCrop rotations are CW, continuous spring wheat; W-P, spring wheat-pea; W-B-P, spring wheat-barley hay-pea; and W-B-C-P, spring wheat-barley hay-corn pea.

*Numbers followed by different letters within a column are significantly different at P ≤ 0.05 by the least square means test.

Table 3.
Soil total N (STN) at the 0–120 cm depth after 6 years as affected by crop rotation in eastern Montana, USA [25].

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| Parameter                               | Traditional (kg N ha\(^{-1}\) year\(^{-1}\)) | Ecological (kg N ha\(^{-1}\) year\(^{-1}\)) |
|----------------------------------------|---------------------------------------------|-------------------------------------------|
|                                        | CD\(^a\) | D-C-D-P\(^a\) | D-D-C-P\(^a\) | D-F-D-P\(^a\) | D-D-F-P\(^a\) | CD        | D-C-D-P        | D-D-C-P        | D-F-D-P        | D-D-F-P        |
| N inputs                               |         |                |                |                |                |          |                |                |                |                |
| N fertilization rate                   | 83A\(^b\) | 62B            | 59B            | 52B            | 54B            | 87A       | 60B            | 63B            | 55B            | 56B            |
| Pea N fixation                         | 0C       | 84AB           | 76B            | 80AB           | 75B            | 0C        | 84AB           | 78B            | 87A            | 82AB           |
| Atmospheric N deposition                | 14       | 14             | 14             | 14             | 14             | 14        | 14             | 14             | 14             | 14             |
| N added by crop seed                   | 3        | 3              | 3              | 3              | 3              | 3         | 3              | 3              | 3              | 3              |
| Nonsymbiotic N fixation                | 5        | 5              | 5              | 5              | 5              | 5         | 5              | 5              | 5              | 5              |
| Total N input                          | 105B     | 167A           | 156A           | 154A           | 150A           | 109B      | 166A           | 162A           | 164A           | 159A           |
| N outputs                              |         |                |                |                |                |          |                |                |                |                |
| Grain N removal                        | 49B      | 62A            | 57AB           | 54AB           | 55AB           | 52AB      | 65A            | 64A            | 63A            | 54AB           |
| Denitrification                        | 12       | 10             | 9              | 8              | 8              | 9         | 13             | 10             | 9              | 9              |
| Ammonia volatilization                 | 12       | 9              | 9              | 8              | 8              | 9         | 13             | 9              | 9              | 8              |
| Plant senescence                       | 5        | 7              | 6              | 6              | 6              | 6         | 7              | 7              | 7              | 6              |
| N leaching                             | 9        | 12             | 12             | 12             | 12             | 9         | 12             | 12             | 12             | 12             |
| Gaseous N (NO\(_x\)) emissions        | 2        | 3              | 3              | 3              | 3              | 2         | 3              | 3              | 3              | 3              |
| Surface runoff                         | 1        | 2              | 1              | 1              | 1              | 1         | 2              | 2              | 2              | 2              |
| Total N output                         | 91B      | 105A           | 98AB           | 92B            | 94AB           | 96AB      | 107A           | 107A           | 103A           | 94AB           |
| Changes in N level\(^c\)              | 14B      | 62A            | 58A            | 62A            | 56A            | 13B       | 59A            | 55A            | 61A            | 65A            |
| N sequestration rate (0–125 cm)\(^d\) | 50       | 45             | 42             | 46             | 43             | 52        | 48             | 46             | 44             | 40             |
| N balance\(^e\)                        | –36 (±11)B | 17 (±3)A       | 36 (±4)A       | 16 (±4)A       | 13 (±3)A       | –39 (±12)B | 11 (±3)A       | 9 (±2)A        | 17 (±4)A       | 25 (±5)A       |

\(^a\) Crop rotation are CD, continuous durum; D-C-D-P, durum-canola-durum-pea; D-D-C-P, durum-durum-canola-pea; D-F-D-P, durum-flax-durum-pea; and D-D-F-P, durum-durum-flax-pea.

\(^b\) Numbers followed by the same letter within a row are not significantly different at P ≤ 0.05.

\(^c\) Changes in N level = total N input – total N output.

\(^d\) Determined from the linear regression analysis of soil total N (STN) at 0–125 cm from the year 2005 to 2011.

\(^e\) N balance = changes in N levels – N sequestration rate (0–125 cm).

Table 4.
Annual N balance due to the difference between total N inputs and outputs and N sequestration rate under dryland agroecosystems from 2005 to 2011 in eastern Montana, USA [26, 27].
The mixture can also increase soil organic matter and reduce N fertilization rate and the potential for N leaching compared with rye and winter weeds. Therefore, legume-nonlegume cover crop mixture can provide several benefits, such as reducing the cost of N fertilization, maintaining crop yields, enhancing soil organic matter, and reducing N leaching compared with either cover crop alone or no cover crop.

2.3 Application of manure and compost

Manure and compost are rich sources of nutrients, and their application can increase soil organic C and total N, improving soil quality and crop production compared to no fertilizer application [37, 38]. Sainju et al. [39, 40] compared soil organic C and total N after 10 years of poultry litter with inorganic N

| Tillage and cropping sequencea | Soil depth          |
|-------------------------------|---------------------|
|                               | 0–7.5 cm | 7.5–15 cm | 15–30 cm | 30–60 cm | 60–90 cm | 90–120 cm |
| pH                            |          |          |          |          |          |          |
| NTCW                          | 5.33abE  | 6.50abD | 7.60C    | 8.35B    | 8.58A    | 8.75A    |
| STCW                          | 5.05bE   | 6.15bD  | 7.58C    | 8.25B    | 8.63A    | 8.70A    |
| FSTCW                         | 5.02bE   | 6.33bD  | 7.80C    | 8.30B    | 8.68AB   | 8.73A    |
| FSTW-B/P                      | 5.46aE   | 6.44bD  | 7.60C    | 8.15B    | 8.51A    | 8.59A    |
| STW-F                         | 5.73aE   | 7.03aD  | 7.65C    | 8.25B    | 8.50AB   | 8.66A    |
| **Contrast**                  |          |          |          |          |          |          |
| NT vs. T                      | 0.29     | 0.26     | –0.09    | 0.08     | –0.08    | 0.04     |
| CW vs. W-F                    | –0.68*** | –0.88**  | –0.08    | 0.01     | 0.13     | 0.04     |
| CW vs. W-B/P                  | –0.43*   | –0.11    | 0.20     | 0.15     | 0.16     | 0.14     |
| **Buffer pH**                 |          |          |          |          |          |          |
| NTCW                          | 6.45bE   | 7.10abD | 7.43C    | 7.60B    | 7.70AB   | 7.73A    |
| STCW                          | 6.38bE   | 7.00bD  | 7.43C    | 7.58B    | 7.68A    | 7.70A    |
| FSTCW                         | 6.43bE   | 7.05bD  | 7.45C    | 7.60B    | 7.70AB   | 7.73A    |
| FSTW-B/P                      | 6.66aD   | 7.13abC | 7.44B    | 7.58B    | 7.69AB   | 7.70A    |
| STW-F                         | 6.80aE   | 7.24aD  | 7.44C    | 7.59B    | 7.66AB   | 7.72A    |
| **Contrast**                  |          |          |          |          |          |          |
| NT vs. T                      | 0.05     | 0.08     | –0.01    | 0.01     | 0.01     | 0.01     |
| CW vs. W-F                    | –0.43*** | –0.24**  | –0.01    | –0.01    | 0.01     | –0.01    |
| CW vs. W-B/P                  | –0.24*   | –0.08    | –0.01    | 0.03     | 0.01     | 0.03     |

aSignificant at P = 0.05.
bSignificant at P = 0.01.
***Significant at P = 0.001.

FSTCW, fall and spring till continuous spring wheat; FSTW-B/P, fall and spring till spring wheat-barley (1994–1999) followed by spring wheat-pea (2000–2013); NTCW, no-till continuous spring wheat; STCW, spring till continuous spring wheat; and STW-F, spring till spring wheat-fallow. CW represents continuous wheat; NT, no-till; T, till; W-B/P, spring wheat-barley/pea; and W-F, spring wheat-fallow.

Numbers followed by the same lowercase letter within a column among treatments in a set are not significantly different at P ≤ 0.05.

Numbers followed by the same uppercase letter within a row among soil depths in a set are no significantly different at P ≤ 0.05.

Table 5.
Effect of tillage and crop rotation combination on soil pH and buffer pH at the 0–120 cm depth after 30 years of experiment initiation in eastern Montana, USA [18].

The mixture can also increase soil organic matter and reduce N fertilization rate and the potential for N leaching compared with rye and winter weeds. Therefore, legume-nonlegume cover crop mixture can provide several benefits, such as reducing the cost of N fertilization, maintaining crop yields, enhancing soil organic matter, and reducing N leaching compared with either cover crop alone or no cover crop.

2.3 Application of manure and compost

Manure and compost are rich sources of nutrients, and their application can increase soil organic C and total N, improving soil quality and crop production compared to no fertilizer application [37, 38]. Sainju et al. [39, 40] compared soil organic C and total N after 10 years of poultry litter with inorganic N
fertilizer applications, both applied at 100 kg N ha⁻¹ to corn and cotton (Tables 10 and 11). They found that soil organic C and total N at 0–20 cm were greater with poultry litter application than inorganic N fertilization, regardless of tillage practices. As a result, poultry litter application sequestered C at 461 kg C ha⁻¹ year⁻¹ and N at 38 kg N ha⁻¹ year⁻¹ compared to 38 kg C ha⁻¹ year⁻¹ and 4 kg N ha⁻¹ year⁻¹, respectively, with N fertilization. As poultry litter also supplied C at 1.7 Mg C ha⁻¹ year⁻¹ [40] and only 60% of N from poultry litter was available
to crops in the first year [37], Sainju et al. [39, 40] reported that part of non-mineralized C and N from the litter converted to soil organic C and N, thereby increasing their levels with poultry litter application. In contrast, little or no C was supplied by inorganic N fertilizer, and most of N supplied by the fertilizer can either be taken up by the crop or lost to the environment through leaching, denitrification, and volatilization.

Because of lower N availability from poultry litter as a result of reduced N mineralization, total aboveground biomass and N uptake of corn, cotton, and rye cover crop were lower with poultry litter application than inorganic N fertilization (Table 12). Although soil health and quality can be improved with poultry litter application through organic matter enrichment, crop yields can be lower compared with N fertilization. For enhancing soil and environmental quality and sustaining crop yields, both inorganic N fertilizer and manure/compost should be applied as a mixture in balanced proportion as per crop demand after analyzing soil NO$_3$-N test to a depth of 60 cm. This could reduce N fertilization rate and undesirable consequences of N fertilization on soil and environmental quality.
2.4 Integrated crop-livestock system

Integrated crop-livestock systems were commonly used to sustain crop and livestock products throughout the world before commercial fertilizers were introduced in 1950 [41]. The system is still common among producers in developing countries, especially in Africa and Asia where fertilizers are scarce and expensive [42, 43]. The integrated crop-livestock system has the potential to improve soil quality and sustain crop yields [41, 44]. The major benefits of the system are (1) production of crops, meat, and milk, (2) production of crop residue for animal feed, (3) production of manure to apply as fertilizer, (4) use of animals as draft power for tillage, and (5) control of weeds and pests [41, 42].

Animal grazing during fallow periods in wheat-fallow systems can be used to effectively control weeds [14] and insects, such as wheat stem saw fly [Cephus cinctus Norton (Hymenoptera: Cephidae)] [13]. The animal usually grazes on crop residues and weeds during the fallow period. Although grazing can reduce the quantity of crop residue returned to the soil, the number of animals grazed per unit area can be adjusted in such a way that crop residue cover in the grazing treatment will be similar to that in the conservation tillage system where soil erosion is minimal [14]. Animal feces and urine returned to the soil during grazing can enrich
Figure 4.
Effect of (A) cover crop and (B) N fertilization rate on soil NO₃-N content at the 0–120 cm depth in Central Georgia, USA. R, denotes cereal rye; V, hairy vetch; V + R, hairy vetch and rye biculture; and W, winter weeds. Bars followed by the same lowercase letter within a soil depth are not significantly different between cover crops at P = 0.05. Bars followed by the same uppercase letter at the top are not significantly different between cover crops at the 0–120 cm depth at P ≤ 0.05 [35].

| Cover crop† | Total crop residue and soil N‡ (kg N ha⁻¹) | Total crop residue and soil N§ (kg N ha⁻¹) |
|-------------|------------------------------------------|------------------------------------------|
|             | November 2000 | April 2001 | Loss | November 2001 | April 2002 | Loss |
| Rye         | 5057bc§       | 4888b      | 169b | 4820b         | 4764b      | 56a  |
| Vetch       | 5455a         | 5235a      | 220a | 5323a         | 5244a      | 79a  |
| Vetch/rye   | 5249ab        | 5141a      | 108c | 5222a         | 5182a      | 40a  |
| Weeds       | 4869c         | 4709b      | 160b | 4725b         | 4649b      | 76a  |

†Cover crops are rye, cereal rye; vetch, hairy vetch; vetch/rye, hairy vetch and rye biculture; and weeds, winter weeds or no cover crop.
‡Include soil NH₄-N + NO₃-N + organic N contents at 0–120 cm, and N returned to the soil from cotton biomass (stems + leaves) in November 2000 and cover crop biomass in April 2001.
§Include soil NH₄-N + NO₃-N + organic N contents at 0–120 cm, and N returned to the soil from sorghum biomass (stems + leaves) in November 2001 and cover crop biomass in April 2002.
¶Numbers followed by the same letter within a column are not significantly different at P ≤ 0.05.

Table 8.
Effect of cover crop on N loss from crop residue and soil N (NH₄-N + NO₃-N + organic N contents) at the 0–120 cm depth during the two winter seasons (from November 2000 to April 2001 and from November 2001 to April 2002) in central Georgia, USA [35].
soil nutrients, improve soil quality, and increase crop yields [44]. The distribution of feces and urine by animals during grazing at the soil surface can be uneven; however, distribution can be more uniform with sheep than with cattle grazing [45]. Hatfield et al. [14] reported that sheep grazing during fallow did not affect soil organic matter and nutrient levels compared to the non-grazed treatment in the North Central Montana. Sheep grazing can increase soil bulk density and extractable P and grass yields compared to cattle grazing [45]. Snyder et al. [46] found similar or greater wheat grain yields with and without animal grazing. Similarly, Quiroga et al. [47] observed that 10 years of cattle grazing did not alter soil P concentration in Argentina. In contrast, Niu et al. [48] in Australia observed greater soil P and K concentrations in sheep camping than in non-camping sites due to increased animal excreta. Cattle and sheep grazing in the pasture can increase soil P and K concentrations compared to non-grazing [45].

Sainju et al. [49] reported that annualized wheat grain and biomass yields were lower with spring wheat-fallow and winter wheat-fallow rotations than continuous spring wheat due to the absence of crops during the fallow period (Table 13). In

| Parameter | Cover crop       | Regression analysis* |
|-----------|------------------|----------------------|
|           | Winter weeds     | Rye                  | Hairy vetch | Hairy vetch/rye | R² | P |
| Lint yield | —                | —                    | —           | —              | 0.25 | 0.67 |
| Lint N uptake | —            | —                    | —           | —              | 0.25 | 0.67 |
| Biomass yield | —            | 30                   | 149         | 93             | 0.96 | 0.13 |
| Biomass N uptake | —        | 2                    | 165         | 92             | 0.99 | 0.06 |
| Soil inorganic N | —         | —190                 | 220         | 140            | 0.64 | 0.40 |

| Parameter | Cover crop       | Regression analysis* |
|-----------|------------------|----------------------|
|           | Winter weeds     | Rye                  | Hairy vetch | Hairy vetch/rye | R² | P |
| Lint yield | 7               | —168                 | 194         | 179             | 0.96 | 0.12 |
| Lint N uptake | 25           | —168                 | 194         | 150             | 0.96 | 0.14 |
| Biomass yield | 69            | 192                  | 83          | 94              | 0.98 | 0.02 |
| Biomass N uptake | 59           | 12                   | 116         | 71              | 0.86 | 0.25 |
| Soil inorganic N | —       | —190                 | 220         | 140            | 0.64 | 0.40 |

| Parameter | Cover crop       | Regression analysis* |
|-----------|------------------|----------------------|
|           | Winter weeds     | Rye                  | Hairy vetch | Hairy vetch/rye | R² | P |
| Lint yield | —                | —                    | —           | —              | 0.28 | 0.82 |
| Lint N uptake | —            | —                    | —           | —              | 0.24 | 0.87 |
| Biomass yield | —            | —13                  | 134         | 160            | 0.97 | 0.11 |
| Biomass N uptake | —         | —13                  | 134         | 160            | 0.97 | 0.11 |
| Soil inorganic N | —       | 5                    | 176         | 160            | 0.70 | 0.37 |

*Regression analysis of N fertilization rates versus cotton and sorghum yields and N uptake and soil inorganic N.

Table 9. Nitrogen fertilizer equivalence (kg N ha⁻¹) of cover crops and soil inorganic N (NH₄-N + NO₃-N) content at the 0–30 cm depth for cotton and sorghum yields and N uptake from 2000 to 2002 in central Georgia, USA [11].
### Table 10.
Effect of tillage and N source on soil organic C (SOC) at the 0–20 cm depth after 10 years in Alabama, USA [40].

| Tillage† | N source‡ | SOC concentration (g C kg⁻¹) | SOC content (Mg C ha⁻¹) | Changes in SOC from 1996 to 2006 (Mg C ha⁻¹) | C sequestration rate (kg C ha⁻¹ year⁻¹) |
|----------|-----------|-----------------------------|--------------------------|---------------------------------------------|--------------------------------------|
|          |           | 100 kg N ha⁻¹ | 0–10 cm | 10–20 cm | 0–20 cm | 0–20 cm |                           |                         |
| NT       | AN        | 13.5           | 11.0     | 40.1     | 1.47     | 147     |                       |                         |
|          | PL        | 15.9           | 10.5     | 43.7     | 5.10     | 510     |                       |                         |
| MT       | AN        | 15.9           | 11.0     | 42.6     | 3.97     | 397     |                       |                         |
|          | PL        | 15.4           | 10.6     | 42.2     | 3.63     | 363     |                       |                         |
| CT       | AN        | 14.3           | 10.7     | 37.4     | −1.20    | −120    |                       |                         |
|          | PL        | 15.3           | 11.8     | 43.7     | 5.10     | 510     |                       |                         |
| LSD (0.05) |          |                | —        | —        | 3.1      | 3.1      | 310                        |                         |
| Means    | AN        | 14.6a§         | 10.9a    | 40.0b    | 1.41b    | 141b    |                       |                         |
|          | PL        | 15.6a          | 11.0a    | 43.2a    | 4.61a    | 461a    |                       |                         |

†Tillage is CT, conventional till; MT, mulch till; and NT, no-till.
‡N source is AN, NH₄NO₃; and PL, poultry litter.
§Numbers followed by different letters within a column in a set are significantly different at P ≤ 0.05 by the least square means test.

### Table 11.
Effects of tillage and N source on soil total N and N sequestration rate at the 0–20 cm depth after 10 years in Alabama, USA [39].

| Tillageª | N sourceª | STN concentration (g N kg⁻¹) | STN content (Mg N ha⁻¹) | Change in STN from 1996 to 2006 (Mg N ha⁻¹) | N sequestration rate (kg N ha⁻¹ year⁻¹) |
|----------|-----------|-----------------------------|--------------------------|---------------------------------------------|--------------------------------------|
|          |           | (100 kg N ha⁻¹) | 0–10 cm | 10–20 cm | 0–20 cm | 0–20 cm |                           |                         |
| NT       | AN        | 1.23            | 1.03     | 3.44     | −0.23    | −23     |                       |                         |
|          | PL        | 1.52            | 1.02     | 4.19     | 0.49     | 49      |                       |                         |
| MT       | AN        | 1.42            | 1.01     | 3.84     | 0.15     | 15      |                       |                         |
|          | PL        | 1.49            | 0.92     | 3.91     | 0.21     | 21      |                       |                         |
| CT       | AN        | 1.31            | 0.98     | 3.67     | −0.03    | −3      |                       |                         |
|          | PL        | 1.51            | 1.04     | 4.11     | 0.41     | 41      |                       |                         |
| LSD (0.05)ª |          |                | —        | —        | 0.24     | 0.24    | 24                        |                         |
| Means    | AN        | 1.55bª         | 1.59a    | 3.65b    | −0.04b   | −4b     |                       |                         |
|          | PL        | 1.65a          | 1.59a    | 4.07a    | 0.38a    | 38a     |                       |                         |

ªTillage is CT, conventional till; MT, mulch till; and NT, no-till.
ªN source is AN, ammonium nitrate; and PL, poultry litter.
ªLeast significant differences between treatments at P = 0.05.
ªNumbers followed by the same letter within a column in a set are not significantly different at P ≤ 0.05.
In contrast, wheat grain yield was not different among weed management practices where sheep grazing was used among one of the treatments to control weeds along with herbicide application and tillage, although wheat biomass yield was lower with sheep grazing and herbicide application than tillage. Soil organic C, total N, and NO₃-N contents varied among weed management practices and soil depths, but the contents at 0–120 cm were not affected by weed management practices (Table 14).
Soil P, K, and SO4-S contents at 0–30 cm were lower with sheep grazing than other weed management practices, but pH, electrical conductivity, and Ca, Mg, and Na contents were similar or greater with sheep grazing (Table 15). Consumption of crop residue by sheep during grazing, but little P and K inputs to the soil through urine and feces, reduced soil P and K concentrations with sheep grazing compared with other weed management practices [49]. These results suggest that sheep grazing can reduce the cost of animal feed without seriously affecting crop yields and sustain soil organic matter and nutrients compared with other weed management practices, except P and K which need to be added with inorganic fertilizers to eliminate their deficiency. As soil residual NO3-N content was not different among weed management practices, long-term study may be needed to evaluate if animal grazing can reduce N fertilization rate for crop production. However, animal grazing can recycle nutrients and control weeds effectively compared with herbicide application and tillage, thereby saving the cost of fertilization and weed control.

Legumes in the crop rotation can supply N from its residue to succeeding crops, thereby reducing N fertilization rates to succeeding nonlegumes. Also diversified crop rotations can use N and water more efficiently and reduce weed, pest, and disease infestations, thereby enhancing crop yields compared with continuous nonlegume monocropping. Cover crops grown to replace the fallow period can reduce soil erosion, enhance soil organic matter, and help to enrich soil health and fertility. Legume covers crop supply N and reduce N fertilization rate. Application of manure and compost can also enhance soil health and quality; however, additional inorganic N fertilization at lower rate is required to sustain crop yield and quality. Similarly, integrated crop-livestock system can help to reduce N fertilization rate by returning N and other nutrients through urine and feces to the soil during animal grazing without affecting crop yields. Some additional N fertilizer, however, may be required for sustainable crop production, because animals

Table 14.
Soil organic C (SOC), total N (STN), and NO3-N contents at the 0–120 cm depth after 5 years of weed management experiment initiation in western Montana, USA [50].

| Weed management† | SOC content (Mg C ha⁻¹) | STN content (Mg N ha⁻¹) | NO3-N content (kg N ha⁻¹) |
|------------------|------------------------|-------------------------|--------------------------|
|                  | 0–5 cm | 5–10 cm | 10–30 cm | 30–60 cm | 60–90 cm | 90–120 cm | 0–120 cm | 0–5 cm | 5–10 cm | 10–30 cm | 30–60 cm | 60–90 cm | 90–120 cm | 0–120 cm | 0–5 cm | 5–10 cm | 10–30 cm | 30–60 cm | 60–90 cm | 90–120 cm | 0–120 cm |
| Chem.            | 18.3a‡ | 19.2a   | 61.7a | 38.0a | 32.2a | 29.1b | 198.4a |         | 1.69a   | 1.89a | 6.48a | 4.96a | 3.58a | 2.79a | 21.40a |         | 12.6a   | 12.4a | 20.6a | 16.0a | 18.9b | 38.0a | 118.6a |         |
| Mech.            | 17.3a  | 17.4a   | 58.2ab | 38.0a | 35.8a | 37.0a | 203.5a |         | 1.61a   | 1.74b | 5.91a | 5.00a | 3.43a | 3.99a | 20.55a |         | 10.3a   | 12.0a | 21.1a | 14.5a | 28.8a | 37.6a | 124.4a |         |
| Graz.            | 16.9a  | 17.7a   | 54.2b | 36.1a | 31.2a | 31.4ab | 187.5a |         | 1.53a   | 1.79ab | 6.33a | 5.60a | 3.86a | 3.87a | 22.09a |         | 9.9a    | 10.9a | 18.7a | 17.5a | 23.2ab | 35.0a | 115.2a |         |

†Weed management practices are Chem., chemical where weeds were controlled with herbicide applications; Graz., grazing where weeds were controlled with sheep grazing; and Mech., mechanical where weeds were controlled with tillage.
‡Numbers followed by different letters within a column are significantly different at P ≤ 0.05 by the least square means test.
return only a part of nutrients through urine and feces to the soil, while most of the crop residue grazed is used to increase the live weight of the animal. The choice of the management practice to reduce N fertilization rate to crops depends on soil and climatic conditions and social, cultural, and economic perspectives of the producers.

2.5 Liming

Soil acidification can be reduced by applying lime. However, lime is bulky and requires in large amount to neutralize soil acidity. The transportation cost to carry lime from manufactures to farms is also high and especially so in hilly regions.
where roads are few or lacking. As a result, it is expensive to apply lime and most producers in developing countries cannot afford to apply it. Furthermore, neutralization of soil acidity with lime application is only temporary in nature. This suggests that lime should be applied frequently to neutralize acidity, which increases the cost of production. The best practice to reduce soil acidity is to reduce the rate of N fertilization. Several management practices, such as legume-nonlegume crop rotation, cover cropping, application of manures and compost, and integrated crop-livestock system, can reduce N fertilization rate without affecting crop yields.

3. Conclusions

Degradation in soil and environmental quality can be mitigated, and crop yields can be sustained by reducing N fertilization rates and using novel management techniques that increase N cycling and N-use efficiency. These techniques include legume-nonlegume crop rotation, cover cropping, application of manures and compost, and integrated crop-livestock system. Soil acidity can be neutralized by lime application, but the effect is temporary. It is expensive to apply lime, and many producers in developing countries cannot afford to do so. Adaptation of these techniques to specific places depends on soil and climatic conditions and social, cultural, and economic perspectives of the producers.
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