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_2O 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†	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 $P \leq 0.05$ by the least square means test.

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 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 inlcuded 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.

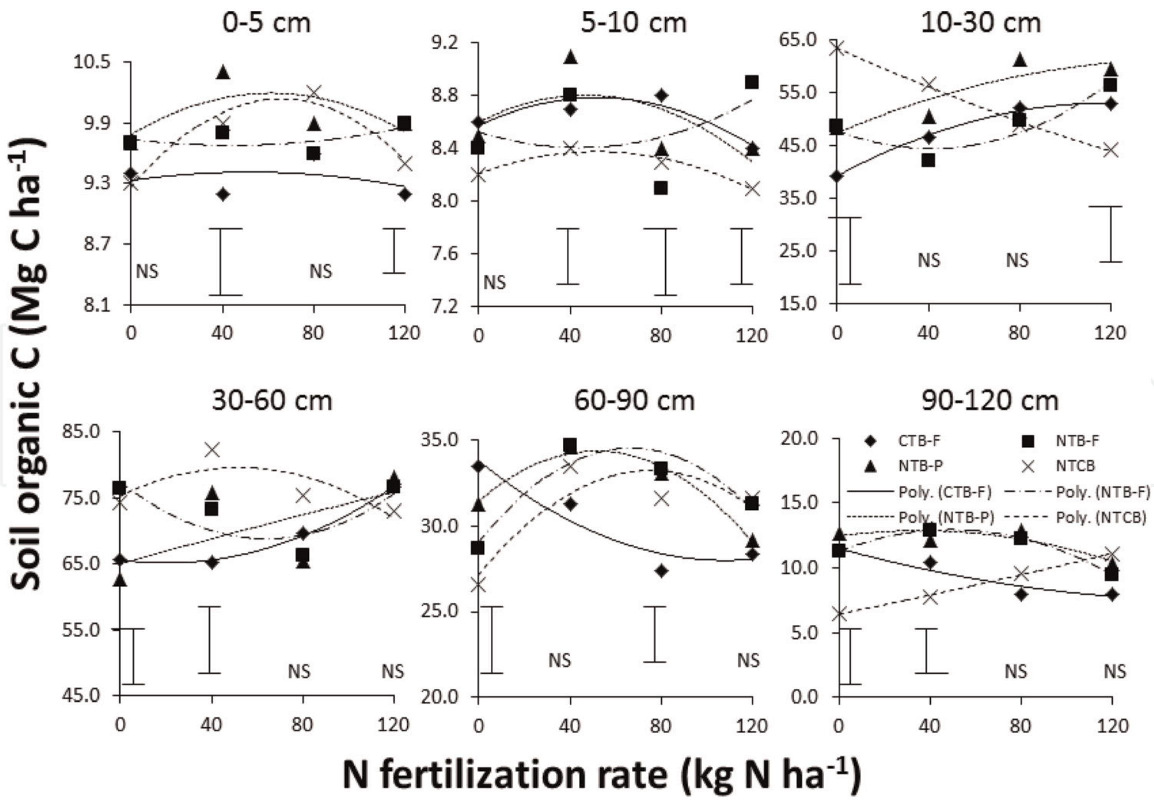

Figure 1.
Soil organic C at the 0–120 cm depth as affected by 6 years of N fertilization rates to malt barley in various cropping systems in eastern Montana, USA. CTB-F denotes conventional till malt barley-fallow; NTB-F, no-till malt barley-fallow; NTB-P, no-till malt barley-pea; and NTCB, no-till continuous malt barley. Vertical bars denote least significant difference between tillage and cropping sequence treatments within a N rate at P = 0.05 [24].

Crop rotation†	STC at 0–125 cm (Mg C ha^{-1})
CD	394.6a‡
D-C-D-P	395.4a
D-D-C-P	387.1a
D-F-D-P	395.4a
D-D-F-P	370.2b

†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.

Table 2.
Soil total C (STC) at the 0–125 cm depth after 6 years as affected by crop rotation in eastern Montana, USA [19].

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 NO_3-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

Crop rotation[a]	STN (Mg N ha^{-1})							
	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[b]	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

[a]*Crop 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.*
[b]*Numbers followed by different letters within a column are significantly different at* $P \leq 0.05$ *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].

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 NO_3-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 to 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 NO_3-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 −129 to 69 kg N ha^{-1}, but those of hairy vetch and hairy vetch/rye ranged from 92 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.

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	9	13	9	10	9	9
Ammonia volatilization	12	9	9	8	8	13	9	9	8	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 (±5)A	16 (±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* $P \leq 0.05$.
[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].

Tillage and cropping sequence[a]	Soil depth					
	0–7.5 cm	7.5–15 cm	15–30 cm	30–60 cm	60–90 cm	90–120 cm
pH						
NTCW	5.33ab[b]E[c]	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

**Significant at P = 0.05.*
***Significant at P = 0.01.*
****Significant at P = 0.001.*
[a]*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.*
[b]*Numbers followed by the same lowercase letter within a column among treatments in a set are not significantly different at P ≤ 0.05.*
[c]*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

Crop rotation[a]	NO_3-N content at various depths (kg N ha^{-1})						
	0–5 cm	5–10 cm	10–20 cm	20–50 cm	50–88 cm	88–125 cm	0–125 cm
CD	2.47a[b]	1.81a	2.43a	8.49a	9.37a	9.17a	33.87a
DCDP	1.82a	1.22b	1.94b	6.47a	7.77a	6.71b	26.32b
DDCP	1.86a	1.19b	1.93b	5.97a	8.07a	6.38b	25.59b
DFDP	1.90a	1.37b	2.20a	6.59a	9.62a	8.64ab	30.60a
DDFP	1.74a	1.28b	2.29a	6.27a	8.63a	6.65b	27.02b

[a]Crop rotations are CD, continuous durum; DCDP, durum-canola-durum-pea; DDCP, durum-durum-canola-pea; DDFP, durum-durum-flax-pea; and DFDP, durum-flax-durum-pea.
[b]Numbers followed by different letters within a column are significantly different at $P \leq 0.05$ by the least square means test.

Table 6.
Soil NO_3-N content at the 0–125 cm depth as affected by crop rotation and cultural practice averaged across years from 2006 to 2011 in eastern Montana, USA [28].

Cover crop†	Biomass yield (Mg ha^{-1})	Concentration		Content		C/N ratio
		C (g kg^{-1})	N (g kg^{-1})	C (kg ha^{-1})	N (kg ha^{-1})	
2000						
Weeds	1.65d‡	370b	15b	587d	25d	24b
Rye	6.07b	430a	15b	2670b	68c	29a
Vetch	5.10c	394ab	33a	2006c	135b	12c
Vetch/rye	8.18a	366b	38a	3512a	310a	10c
2001						
Weeds	0.75d	391b	20b	277d	15b	20c
Rye	3.81b	448a	8d	1729b	32b	57a
Vetch	2.44c	398b	32a	964c	76a	12c
Vetch/rye	5.98a	434a	14c	2693a	84a	32b
2002						
Weeds	1.25c	375b	18b	476c	23b	21b
Rye	2.28b	434a	11b	986b	25b	40a
Vetch	5.16a	361b	36a	2094a	167a	10c
Vetch/rye	5.72a	381b	33a	2260a	186a	11c

†Cover crops are rye, cereal rye; vetch, hairy vetch; vetch/rye, hairy vetch and rye biculture; and weeds, winter weeds.
‡Numbers followed by the same letter within a column of a year are not significantly different at $P \leq 0.05$.

Table 7.
Effect of cover crop species on aboveground biomass yield and C and N contents in cover crops from 2000 to 2002 in central Georgia, USA [36].

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

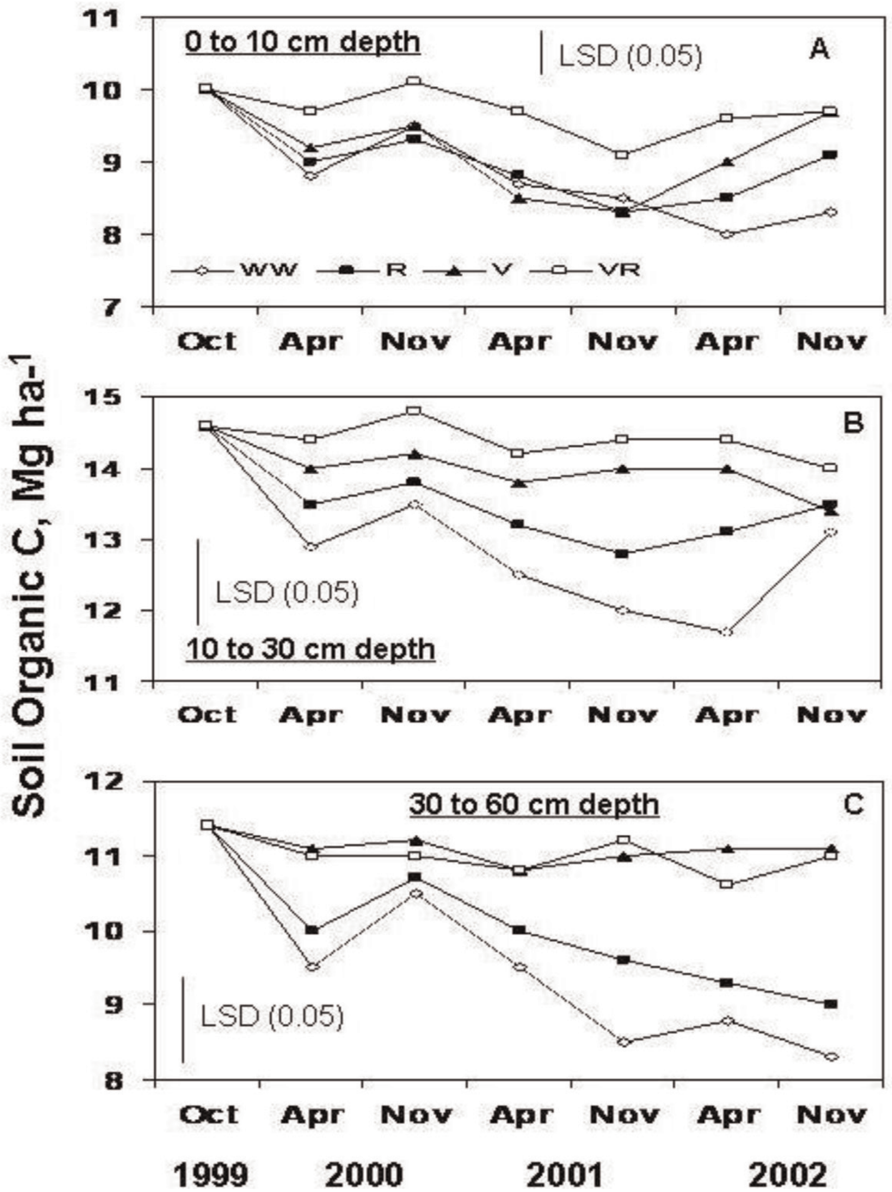

Figure 2.
Effect of cover crop on soil organic C at the (A) 0-10 cm, (B) 10-30 cm, and (C) 30-50 cm depths in a chisel-tilled system (October 1999–November 2002, central Gerogia, USA). R denotes cereal rye; V, hairy vetch; VR, hairy vetch and rye biculture; and WW, winter weeds. Vertical line with LSD (0.05) is the least significant difference between cover crops within a sampling date at P = 0.05 [12].

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.

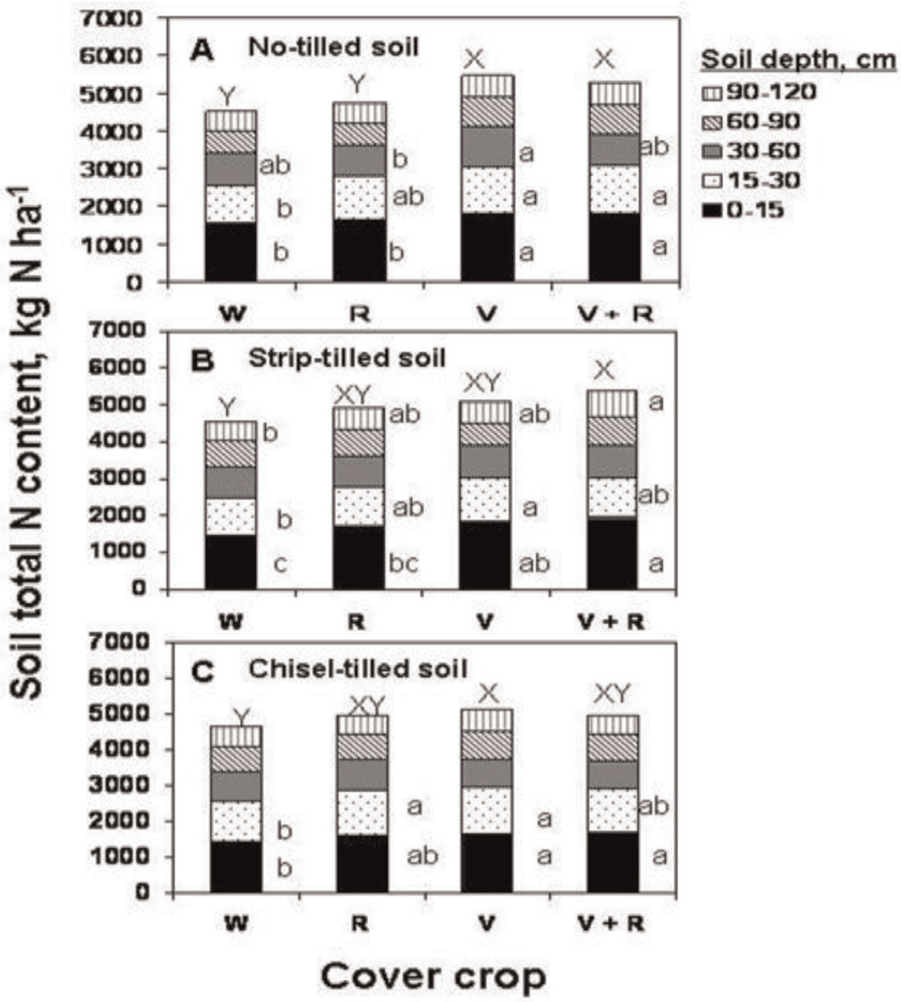

Figure 3.
Effect of cover crop on soil total N at the 0–120 cm depth in (A) no-tilled, (B) strip-tilled, and (C) chisel-tilled soils after 3 years in Central Georgia, USA. R denotes cereal rye; V, hairy vetch; V + R, hairy vetch and rye biculture; and WW, winter weeds. Bars followed by the same lowercase 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 [34].

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

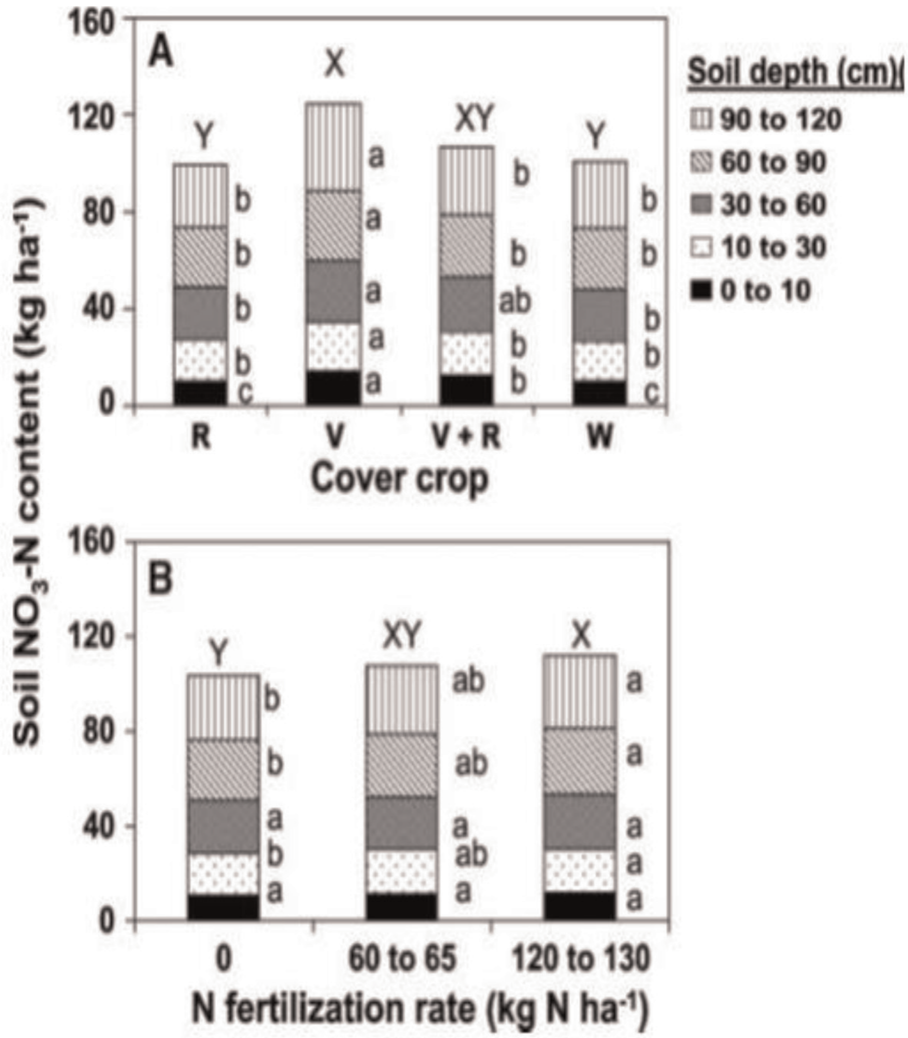

Figure 4.
Effect of (A) cover crop and (B) N fertilization rate on soil NO_3-N content at the 0–120 cm depth in Central Georgia, USA. R, denotes cereal rye; V, hairy vetch; V + R, hairy vetch and rye biculture; and W, winter weeds. Bars followed by the same lowercase letter within a soil depth are not 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 $P \leq 0.05$ [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 NH_4-N + NO_3-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 NH_4-N + NO_3-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 $P \leq 0.05$.

Table 8.
Effect of cover crop on N loss from crop residue and soil N (NH_4-N + NO_3-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].

Parameter	Cover crop				Regression analysis[a]	
	Winter weeds	Rye	Hairy vetch	Hairy vetch/rye	R^2	*P*
2000 cotton						
Lint yield	—	—	—	—	0.25	0.67
Lint N uptake	—	—	—	—	0.25	0.67
Biomass yield	−13	30	149	93	0.96	0.13
Biomass N uptake	−21	2	165	92	0.99	0.06
Soil inorganic N	−60	−190	220	140	0.64	0.40
2001 sorghum						
Lint yield	7	−64	107	179	0.96	0.12
Lint N uptake	25	−67	167	150	0.96	0.14
Biomass yield	32	−168	194	194	0.99	0.02
Biomass N uptake	69	−84	192	83	0.98	0.08
Soil inorganic N	59	12	116	71	0.86	0.25
2002 cotton						
Lint yield	—	—	—	—	0.28	0.82
Lint N uptake	—	—	—	—	0.24	0.87
Biomass yield	−21	−61	139	205	0.96	0.12
Biomass N uptake	−35	−13	134	160	0.97	0.11
Soil inorganic N	−74	5	176	160	0.70	0.37

[a]*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 (NH_4-N + NO_3-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].

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

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	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, NH_4NO_3; and PL, poultry litter.
§Numbers followed by different letters within a column in a set are significantly different at $P \leq 0.05$ by the least square means test.

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[a]	N source[b]	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	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)[c]		—	—	0.24	0.24	24
Means	AN	1.55b[d]	1.59a	3.65b	−0.04b	−4b
	PL	1.65a	1.59a	4.07a	0.38a	38a

[a]*Tillage is CT, conventional till; MT, mulch till; and NT, no-till.*
[b]*N source is AN, ammonium nitrate; and PL, poultry litter.*
[c]*Least significant differences between treatments at $P = 0.05$.*
[d]*Numbers followed by the same letter within a column in a set are not significantly different at $P \leq 0.05$.*

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].

Cropping system	N source	Total crop biomass	Total N uptake
	100 kg N ha^{-1}	(Mg ha^{-1})	(kg N ha^{-1})
Rye/cotton-rye/cotton-corn		137.0a†	1544a†
Cotton-cotton-corn		110.2b	1247b
	NH_4NO_3	133.3a	1502a
	Poultry litter	111.8b	1289b

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

Table 12.
Effects of cropping system and N source on total biomass (stems + leaves) residues of rye, cotton, and corn and N uptake from 1997 to 2005 in Alabama, USA [39, 40].

Year	Cropping sequence† (Mg ha^{-1})			Weed management‡ (Mg ha^{-1})			Mean
	CSW	SW-F	WW-F	Chem.	Mech.	Graz.	
Annualized grain yield							
2004	5.55a§A¶	2.90aC	3.53aB	3.92aA	4.01aA	4.05aA	3.99a
2005	2.68bA	1.83bB	1.15eC	1.84cA	1.92bA	1.90bA	1.89b
2006	2.57bA	1.45cB	1.70 dB	1.89cA	1.90bA	1.92bA	1.90b
2007	1.86cB	1.18cC	2.95bA	1.89cA	2.03bA	2.00bA	2.00b
2008	2.61bA	1.56bcC	2.22cB	2.09bA	2.17bA	2.14bA	2.13b
Mean	3.05A	1.78C	2.31B	2.32A	2.42A	2.40A	
Annualized biomass yield							
2004	6.60aA	3.10aC	3.57aB	3.61aAB	3.41aB	3.89aA	4.42a
2005	3.28bA	1.65bB	1.94bcB	2.52bA	2.17bcA	2.19bA	2.29b
2006	2.96cA	1.57bcB	1.64cB	1.79bB	2.51bA	1.87bcB	2.06bc
2007	2.18dA	1.55bcB	2.25bA	1.78bA	2.21bcA	2.00bA	2.00c
2008	1.92dA	1.17cB	1.49cAB	1.08cB	1.91cA	1.58cA	1.53d
Mean	2.58A	1.49C	1.83B	1.79B	2.20A	1.91B	

†Cropping sequences are CSW, continuous spring wheat; SW-F, spring wheat-fallow; and WW-F, winter wheat-fallow.
‡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 the same lowercase letters within a column in a set are not significantly different at P ≤ 0.05.
¶Numbers followed by the same uppercase letters within a row in a set are not significantly different at P ≤ 0.05.

Table 13.
Effects of cropping sequence and weed management practice on annualized wheat grain and biomass (stems + leaves) yield from 2004 to 2008 in western Montana, USA [49].

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 NO_3-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**).

Weed management†	**SOC content (Mg C ha^{-1})**						
	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
Mech.	17.3a	17.4a	58.2ab	38.0a	35.8a	37.0a	203.5a
Graz.	16.9a	17.7a	54.2b	36.1a	31.2a	31.4ab	187.5a
STN content (Mg N ha^{-1})							
Chem.	1.69a	1.89a	6.48a	4.96a	3.58a	2.79a	21.40a
Mech.	1.61a	1.74b	5.91a	5.00a	3.43a	2.99a	20.55a
Graz.	1.53a	1.79ab	6.33a	5.60a	3.86a	2.87a	22.09a
NO_3-N content (kg N ha^{-1})							
Chem.	12.6a	12.4a	20.6a	16.0a	18.9b	38.0a	118.6a
Mech.	10.3a	12.0a	21.1a	14.5a	28.8a	37.6a	124.4a
Graz.	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 $P \leq 0.05$ by the least square means test.

Table 14.
Soil organic C (SOC), total N (STN), and NO_3-N contents at the 0–120 cm depth after 5 years of weed management experiment initiation in western Montana, USA [50].

Soil P, K, and SO_4-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 NO_3-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

Chemical properties	Soil depth	Weed management (WM)†		
		Chem.	Mech.	Graz.
P content (kg ha^{-1})	0–5 cm	34.5a‡	35.7a	30.8a
	5–10 cm	30.4a	29.3a	17.8b
	10–30 cm	81.2a	80.7a	40.1b
K content (kg ha^{-1})	0–5 cm	263a	271a	222b
	5–10 cm	176a	191a	139b
	10–30 cm	792a	859a	577b
pH	0–5 cm	6.45a	6.94a	6.72a
	5–10 cm	6.31a	6.64a	6.51a
	10–30 cm	7.06a	7.34a	7.31a
EC (S m^{-1})	0–5 cm	0.035a	0.037a	0.035a
	5–10 cm	0.024a	0.024a	0.024a
	10–30 cm	0.025a	0.026a	0.27a
Ca content (Mg ha^{-1})	0–5 cm	2.05a	2.06a	2.08a
	5–10 cm	2.14b	2.31a	2.25ab
	10–30 cm	10.70b	11.70ab	12.90a
Mg content (kg ha^{-1})	0–5 cm	278a	288a	304a
	5–10 cm	362b	382ab	417a
	10–30 cm	2619a	2593a	2640a
Na content (kg ha^{-1})	0–5 cm	11.7a	12.5a	12.8a
	5–10 cm	15.2b	15.2b	18.4a
	10–30 cm	84.8ab	76.6b	95.0a
SO_4-S content (kg ha^{-1})	0–5 cm	8.5ab	10.0a	7.4b
	5–10 cm	9.0ab	10.6a	7.1b
	10–30 cm	34.0ab	40.8a	28.8b

†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 the same letter within a row in a set are not significantly different at $P \leq 0.05$.

Table 15.
Effect of weed management practice on soil nutrients, pH, and electrical conductivity (EC) at the 0–30 cm depth after 5 years of experiment initiation in western Montana, USA [49].

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

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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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