Chapter

Nitrogen Fertilization I: Impact on Crop, Soil, and Environment

Upendra M. Sainju, Rajan Ghimire and Gautam P. Pradhan

Abstract

Nitrogen (N) is a major limiting nutrient to sustain crop yields and quality. As a result, N fertilizer is usually applied in large quantity to increase crop production throughout the world. Application of N fertilizers has increased crop yields and resulted in achievement of self-sufficiency in food production in many developing countries. Excessive application of N fertilizers beyond crops' demand, however, has resulted in undesirable consequences of degradation in soil, water, and air quality. These include soil acidification, N leaching in groundwater, and emissions of nitrous oxide (N_2O), a potent greenhouse gas that contributes to global warming. Long-term application of ammonia-based N fertilizers, such as urea, has increased soil acidity which rendered to soil infertility where crops fail to respond with further application of N fertilizers. Another problem is the groundwater contamination of nitrate-N (NO_3-N) which can be a health hazard to human and livestock if its concentration goes above 10 mg L^{-1} in drinking water. The third problem is emissions of N_2O gas which is 300 times more powerful than carbon dioxide in terms of global warming potential. This chapter examines the effect of N fertilization on soil and environmental quality and crop yields.

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

1. Introduction

Nitrogen (N) is a major limiting factor for sustainable and profitable crop production. However, excessive N application through fertilizers and manures can degrade soil and environmental quality by increasing soil acidification, N leaching, and emissions of ammonia (NH_3) and nitrogen oxide (NO, N_2O, and NO_2) gases, out of which N_2O is considered a highly potent greenhouse gas that contributes to global warming [1, 2]. Nitrogen application more than crop's need can also result in reduced yield [3]. Additional N inputs include dry and wet (snow and rain) depositions from the atmosphere, biological N fixation, and irrigation water. Because crops can remove about 40–60% of applied N, the soil residual N (nitrate-N [NO_3-N] + ammonium-N [NH_4-N]) after crop harvest can be lost to the environment through leaching, denitrification, volatilization, surface runoff, soil erosion, and N_2O emissions [3, 4]. One option to reduce soil residual N is to increase N-use efficiency. Nitrogen-use efficiency for crops, however, can be lower at high N fertilization rates [5]. Improved management practices can increase N-use efficiency, enhance soil N storage, and reduce N fertilizer application which reduce N losses to the environment [4]. An account of N inputs, outputs, and retention in the soil provides N balance and helps to identify dominant processes of N flow in the agroecosystem [4].

Economically profitable crop yields could be achieved by recommended N fertilization rates [6]. However, such a yield potential for a crop varies with soil and climatic conditions, crop species, variety, nutrient cycling, and competitions with weeds and pests [6]. Crop production can be optimized and potential for N losses minimized by adjusting N fertilization rates using soil residual and potentially mineralizable N values. Studies show that ~1–2% of soil organic N in the 0–30 cm depth is mineralized every year [6]. Measuring the actual amount of N mineralized is a time taking process. A commonly used method for measuring soil available N and determining nitrogen rates for crops in semiarid regions of northern Great Plains, USA is based on testing NO_3-N content in soils to a depth of 60 cm after crop harvest in the fall season of the previous year and deduct the value from recommended N rates for the current crop year [7, 8]. In semiarid regions such as Great Plains of USA, N losses to the environment due to N leaching, volatilization, and denitrification during the winter are considered minimal due to cold weather and limited precipitation in the region.

Nitrogen fertilizers are being increasingly applied to crops to enhance their yield and quality in South Asia, where land available for crop production is limited, the proportion of cultivated land to population is low, and the pressure to increase crop yields to meet the demand for growing population is high. Continuous application of N fertilizers to nonlegume crops and excessive application rates in some places have led to undesirable consequences, such as reduced crop yields and degraded soil and environmental quality from soil acidification, N leaching, and greenhouse gas (N_2O) emissions. In this chapter, we discuss the consequences of N fertilization to crop yields and soil and environmental quality.

2. Crop yields, nitrogen uptake, and nitrogen-use efficiency

Nitrogen fertilization can increase crop yields and N uptake compared with no N fertilization. This has been documented for malt barley (*Hordeum vulgare* L.), cotton (*Gossypium hirsutum* L.), and sorghum (*Sorghum bicolor* [L.] Moench) (**Figures 1** and **2**, **Table 1**) by various researchers in Georgia and Montana, USA [9, 10, 14]. It is not unusual to achieve higher crop yield with increased N fertilization rate due to increased soil N availability [11]. Crop yields, however, can remain at similar level or decline with further increase in N rates after reaching the maximum yield. Sainju [9] observed that annualized grain and biomass yields of barley and pea (*Pisum sativum* L.) and their C content maximized at 80 kg N ha^{-1} and then declined, as N rate increased to 120 kg N ha^{-1} (**Figure 1**). Similarly, Sainju et al. [10] reported that malt barley yield and N uptake increased from 0 to 40 kg N ha^{-1} and then declined with further increase in N rates in no-till and conventional till malt barley-fallow rotation (**Figure 2**). In no-till continuous malt barley and malt barley-pea rotation, they found that increased N rate from 0 to 120 kg N ha^{-1} continued to increase malt barley yield and N uptake. Increased soil residual N due to fallow as a result of enhanced soil N mineralization from increased soil temperature and water content resulted in a reduced response of malt barley yield and N uptake with N fertilization in no-till and conventional till malt barley-fallow rotation. A study reported a need of 27 kg of total soil and fertilizer N to produce 1 Mg of malt barley grain in irrigated no-till field in Colorado, USA [11].

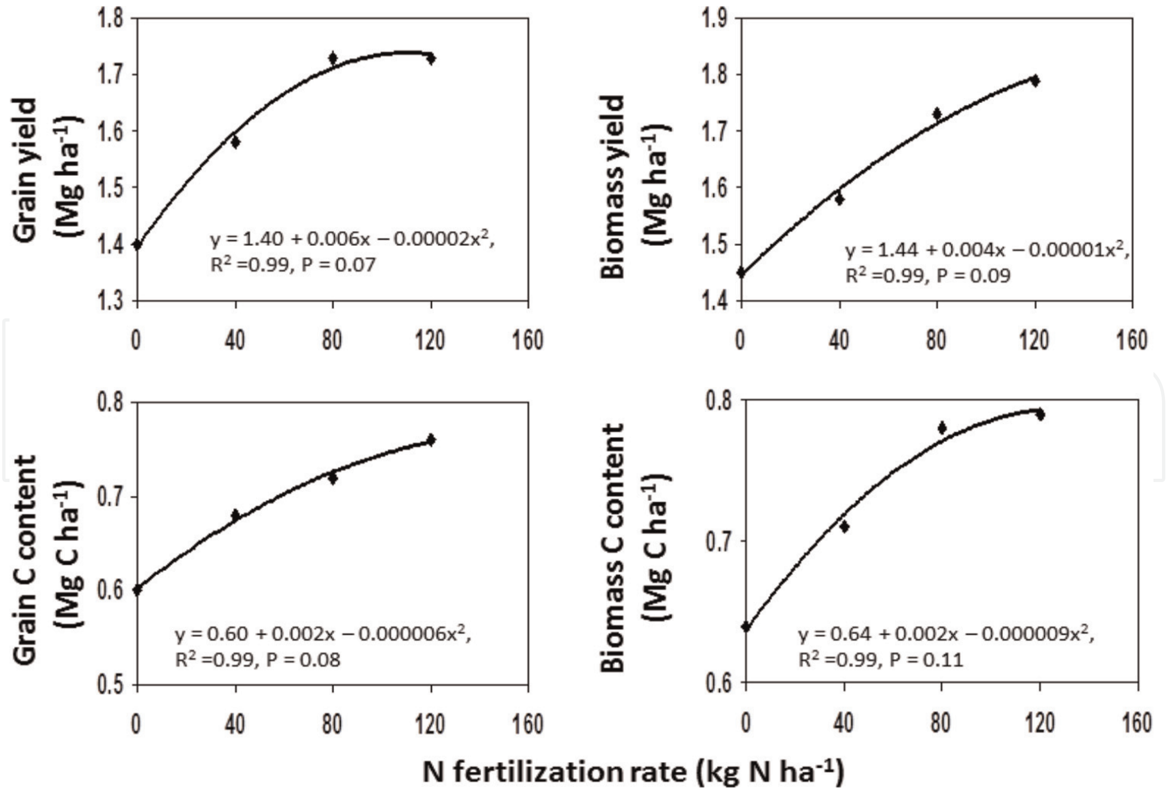

Figure 1.
Annualized grain and biomass yields of barley and pea and C content as affected by N fertilization rate in eastern Montana, USA [9].

Increased N fertilization rate can also increase grain quality, such as protein concentration [10, 11]. Increased N fertilization rates increased malt barley grain yield and protein concentration, but reduced kernel plumpness in Canada [12]. While some studies reported malt barley grain protein concentration of <130 g kg^{-1} with N rate of 168–200 kg ha^{-1} (e.g., [13]) others, observed an increase in protein concentration even with N rates <150 kg N ha^{-1} (e.g., [14]). Grain protein and kernel plumpness are important characteristics of malt barley that need to be maintained at critical levels (grain protein ≤129 g kg^{-1}, kernel plumpness ≥850 g kg^{-1}) for beer production [12]. Therefore, appropriate N fertilization rates are required to malt barley to achieve a balance between optimum grain yield, kernel plumpness, and protein concentration [15].

Sainju et al. [16] evaluated the effect of N fertilization on cotton and sorghum yields and N uptake from 2000 to 2002 in central Georgia, USA (**Table 1**). They found that cotton lint, sorghum grain, and cotton and sorghum biomass yields and N uptake increased from 0 to 60–65 kg N ha^{-1} and then remained either at a similar level or slightly increased at 120–130 kg N ha^{-1}. The response of cotton yield to N fertilization, however, depended on climatic condition, as cotton lint and biomass yields were greater in 2000 than 2002 when the growing season precipitation was below the average. The N fertilizer required for optimizing cotton and sorghum yields varied with the type of tillage and cover crop [16]. Boquet et al. [17] reported that cotton lint yield was lower with no-tillage than surface tillage without applied N, but at optimum N rate, yields were higher with no-tillage. They also found that additional N was required to optimize cotton yield following wheat (*Triticum aestivum* L.) in no-tillage and surface tillage systems without cover cropping, but no N rate was required following hairy vetch cover crop in either tillage practices. Similarly, N fertilization rates to cotton and sorghum can be reduced or eliminated

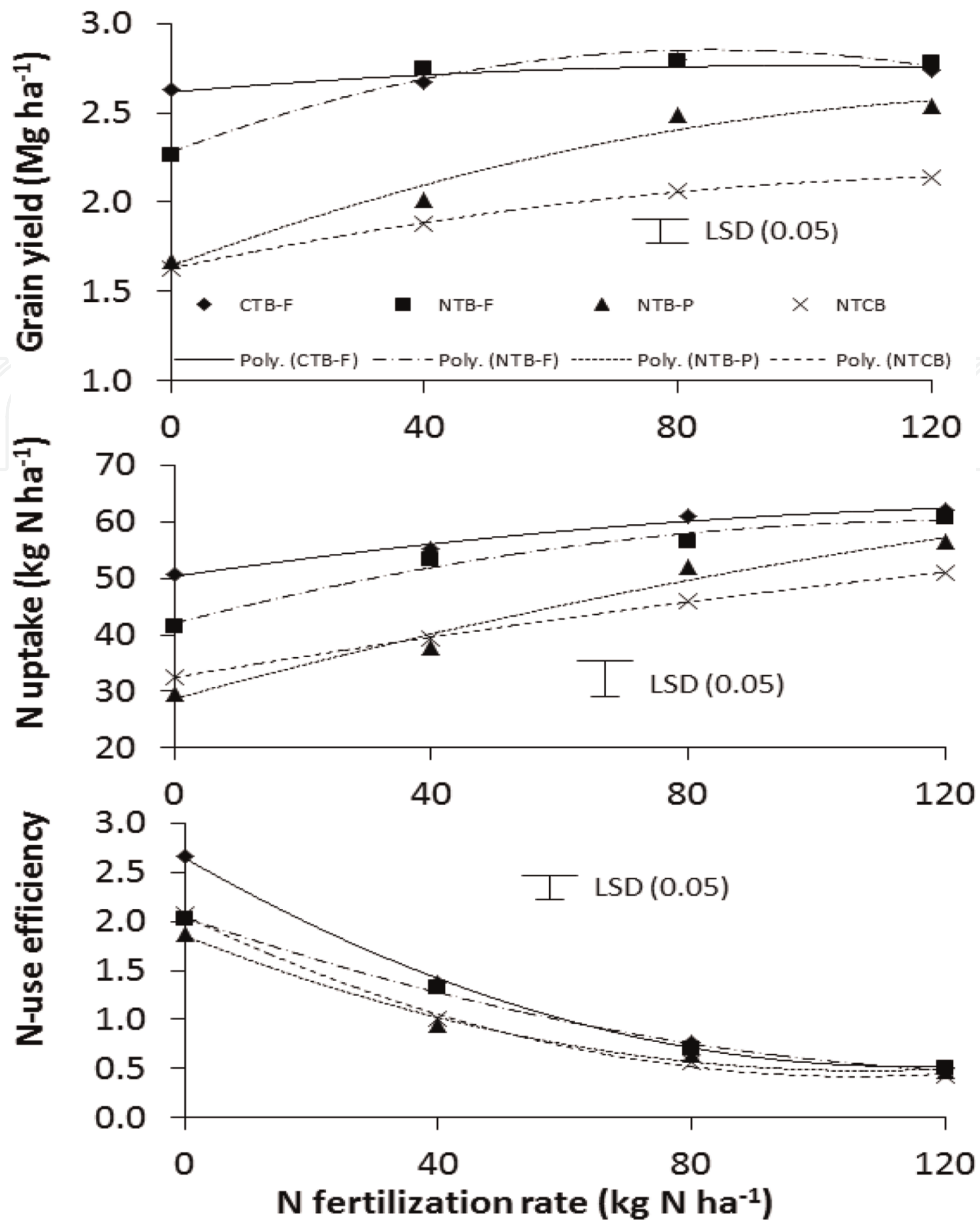

Figure 2.
Effects of cropping sequence and N fertilization rate on malt barley grain yield, N uptake, and N-use efficiency in eastern Montana, USA. CTB-F denotes conventional-till malt barley-fallow; NTB-F, no-till malt barley-fallow; NTB-P, no-till malt barley-pea; and NTCB, no-till continuous malt barley. Vertical bar with LSD (0.05) is the least significant difference between treatments at P = 0.05 [10].

by using legume cover crops, such as red clover (*Trifolium incarnatum* L.) and hairy vetch (*Vicia villosa* Roth), regardless of tillage practices [18]. The high rate of N fertilization can produce excessive vegetative growth that delays maturity and harvest and reduces cotton lint yield and N uptake [19].

Nitrogen-use efficiency, defined as crop yield or N uptake per unit applied N fertilizer, is a useful measurement of the efficiency of N fertilization to crop yields [5]. Enhancing N-use efficiency can maximize crop yield and N uptake with limited use of fertilizer N while reducing N rate and sustaining the environment [3]. Nitrogen-use efficiency, however, can decrease with increased N fertilization rate due to the inability of crops to utilize N efficiently [5]. Sainju et al. [10] found that N-use efficiency by malt barley decreased curvilinearly with increased N fertilization rate (**Figure 2**). Varvel and Peterson [5] reported that N removed by corn and sorghum grain was 50% of the applied N at low N rates and at least 20–30% at high N rates.

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	2000 cotton lint ($kg\ ha^{-1}$)		2000 cotton biomass ($kg\ ha^{-1}$)		2001 sorghum grain ($kg\ ha^{-1}$)		2001 sorghum biomass ($kg\ ha^{-1}$)		2002 cotton lint ($kg\ ha^{-1}$)		2002 cotton biomass ($kg\ ha^{-1}$)	
Treatment	**Yield**	**N uptake**	**Yield**	**N uptake**	**Yield**	**N uptake**	**Yield**	**N uptake**	**Yield**	**N uptake**	**Yield**	**N uptake**
Cover crop[a]												
WW	699b[b]	11b	5200c	124b	2800bc	43ab	12,000ab	133ab	1091a	16a	3667a	74a
R	879a	15a	6300bc	138b	2300c	32b	9400b	81b	940ab	15a	3567a	77a
HV	660b	11b	8200a	239a	3500ab	60a	14,100a	175a	708b	13a	4067a	98a
HV/R	706b	12b	7300ab	194a	4000a	58a	14,100a	138ab	711b	14a	4233a	102a
N fertilization rate ($kg\ N\ ha^{-1}$)												
0	736a	12a	5700b	135c	2800b	41b	11,600b	108b	1021a	17a	3700a	80b
60–65	783a	13a	7000a	178b	3100b	46b	12,400ab	135a	980a	16a	3900a	86b
120–130	689a	11a	7600a	209a	3700a	57a	13,300a	152a	587b	11b	4000a	97a

[a]*Cover crops are HV, hairy vetch; HV/R, hairy vetch/rye; R, rye; and WW, winter weeds.*
[b]*Numbers followed by the same letters within a column in a set are not significantly different at $P \leq 0.05$.*

Table 1.
Effect of cover crop and N fertilization rate on yield and N uptake by cotton lint, sorghum grain, and their biomass (stems + leaves) from 2000 to 2002 in central Georgia, USA [16].

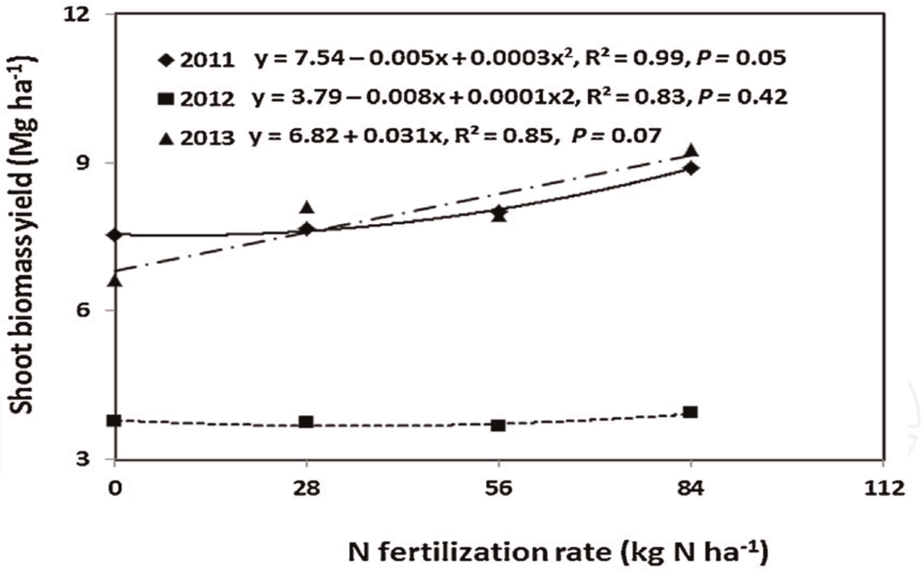

Figure 3.
Linear and quadratic responses of shoot biomass in perennial grasses with N fertilization rates from 2011 to 2013 averaged across grass species in eastern Montana, USA [20].

Nitrogen fertilization can also increase aboveground biomass yield of perennial grasses used for feedstock or bioenergy production. Sainju et al. [20] observed that yields of intermediate wheatgrass (*Thinopyrum intermedium* [Host] Barkworth and Dewey), switchgrass (*Panicum virgatum* L.), and smooth bromegrass (*Bromus inermis* L.) increased linearly or curvilinearly with increased N fertilization rate in 2011 and 2013 (**Figure 3**) when the annual precipitation was near or above the average. Biomass yield, however, did not respond to N fertilization in 2012 when the annual precipitation was below the average. Several researchers [21, 22] reported that maximum switchgrass shoot biomass yield reached at 120–140 kg N ha^{-1} in Iowa and Nebraska, USA, which had 2.5 and 2.2 times, respectively, more annual precipitation than in eastern Montana, USA. Power [23] also observed increased shoot biomass yield with increased N rate for smooth bromegrass in North Dakota, USA.

3. Soil acidification

Application of NH_4-based N fertilizers can increase soil acidity due to the release of H ions during hydrolysis [24]. Increased soil acidity following the application of N fertilizers leads to the development of infertile soils that do not respond well to crop yields with further application of N fertilizers [2, 25], thereby resulting in inefficient use of fertilizers [26]. Sainju et al. [27] reported that, after 30 years of tillage and cropping sequence, continuous application of N fertilizers reduced soil pH at the 0–7.5 cm depth from 6.30 at the initiation of the experiment to 5.73 in spring till spring wheat-fallow (STW-F) and to 5.02 in fall and spring till continuous spring wheat (FSTCW) under rainfed condition in eastern Montana, USA (**Table 2**). A similar decline in soil pH at 7.5–15.0 cm was observed from 6.75 at the initiation of the experiment to 6.15 in spring till continuous spring wheat (STCW). Buffer pH, the buffering capacity of the soil to resist changes in pH and is used to measure lime requirement, also similarly decreased with continuous N fertilization in all treatments. Both pH and buffer pH, however, did not change below 15 cm with N fertilization. Because spring wheat was grown once in 2 years in spring wheat-fallow rotation where N fertilizer was applied only to spring wheat, soil pH

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, 0.01, and 0.001, respectively.
**Significant at P = 0.05, 0.01, and 0.001, respectively.
***Significant at P = 0.05, 0.01, and 0.001, respectively.
[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 $P \leq 0.05$.
[c]Numbers followed by the same uppercase letter within a row among soil depths in a set are no significantly different at $P \leq 0.05$.

Table 2.
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 [27].

was less declined in this treatment than continuous spring wheat where N fertilizer was applied every year. From the same experiment, Aase et al. [28] reported an average decline of pH at 0–7.5 cm from 6.3 to 5.7 after 10 years due to continuous N fertilization.

Ghimire et al. [29] found that soil pH at 0–10 cm after 70 years of N fertilization was 5.70 with 0 kg N ha^{-1} and 5.0 with 135–180 kg N ha^{-1} under winter wheat-fallow in eastern Oregon, USA (**Figure 4**). Reduction in pH with N fertilization decreased with depth, with no significant effect below 30 cm. A study in China, where intensive farming and high rate of N fertilizer was applied for 20 years, showed that soil pH was dropped by 0.30–0.80 units from the original level [30]. In eastern Oregon, USA, application of total N fertilizer at 2.25 Mg N ha^{-1} over the 43-year period lowered soil pH by 0.60 units [31]. Liebig et al. [26] reported that, in

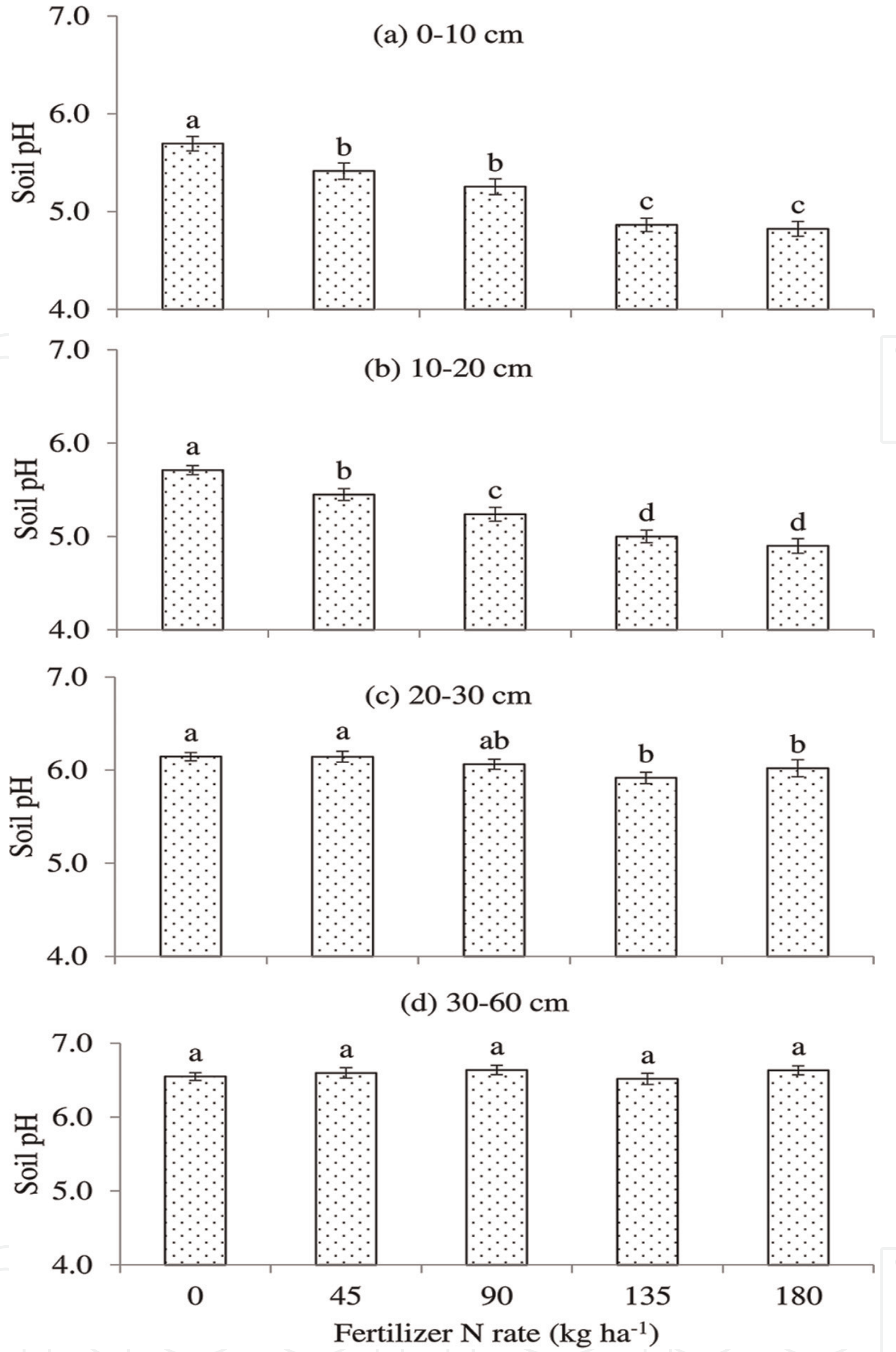

Figure 4.
Soil pH at the 0–60 cm depth from N fertilization rates to winter wheat in the winter wheat-fallow rotation after 70 years in eastern Oregon, USA. Bars with different letters at the top are significantly different at $P \leq 0.05$ [29].

North Dakota, USA, soil pH at 0–7.6 cm was lower under continuous corn than corn rotated with legume and other nonlegume crops because of the increased amount of N fertilizer applied. They recommended that soil samples be collected to a depth of 15 cm for measuring changes in soil pH due to N fertilization.

No-till (NT) system can increase soil acidity more than the conventional till (CT) system [32]. This is due to differences in the amount and placement of N fertilizers in the soil and removal of basic cations through grain and biomass removal between the two tillage systems [32]. Nitrogen fertilizers are usually placed at the soil surface, and N rates are usually higher in NT due to the accumulation of surface residue that partly immobilizes N than CT where fertilizers are incorporated into the soil due to tillage [33]. Because of enhanced soil water conservation, crop yields are higher in NT than CT, especially in dryland cropping systems [34]. As a result, crops remove more basic cations, resulting in increased acidity with NT compared with CT [34]. In contrast, Ghimire et al. [29] reported that soil pH decreased with increased N rate, as tillage intensity increased.

Source of N fertilizer can also have a varying effect on soil acidity. Chen et al. found that soil acidity from N fertilizer sources was in the order $(NH_4)_2SO_4$ > NH_4Cl > NH_4NO_3 > anhydrous NH_3 > urea. Similarly, Schroder et al. [25] reported that anhydrous NH_3 produce more acidity than urea. Others [35], however, observed no significant differences in acidity among $(NH_4)_2SO_4$, NH_4NO_3, anhydrous NH_3, urea, and urea-NH_4NO_3.

4. Soil organic matter

Soil organic matter refers to soil organic C and N and is a crucial component of soil health and quality [36, 37]. Nitrogen fertilization can increase soil organic C and N by increasing crop biomass yield, and the amount of residue returned to the soil [38]. Russell et al. [37], however, reported no difference in soil organic C with N fertilization rate. Sainju et al. [39] reported that 3 years of N fertilization to cotton and sorghum produced various results on soil organic C at the 0–30 cm depth in strip-tilled and chisel-tilled soils in central Georgia, USA (**Table 3**). Soil organic C at 0–10 and 10–30 cm varied with N fertilization rates in strip-tilled soil, but increased in chisel-tilled soil due to differences in tillage intensity. In strip tillage, only crop rows are tilled, leaving the area between rows undisturbed, and N fertilizer is applied in crop rows. In contrast, the land is tilled using discs in chisel tillage after N fertilizer is broadcast. Differences in N fertilization methods between tillage practices probably affected soil organic C due to N fertilization rates.

Sainju [9] observed different trends of soil organic C at the 0–120 cm depth with 6 years of N fertilization rates in various cropping systems in eastern Montana, USA (**Figure 5**). Soil organic C at 0–5 and 5–10 cm peaked at 40 kg N ha^{-1} and then declined with further increase in N rates in no-till malt barley-pea (NTB-P) and continuous no-till barley (NTCB). In no-till malt barley-fallow (NTB-F) and

N rate (kg N ha^{-1})	Soil organic C (Mg C ha^{-1})				
	0–10 cm	10–30 cm	30–60 cm	60–90 cm	90–120 cm
Strip-tilled soil					
0	10.1a[a]	16.0a	10.9	7.2	5.5
60–65	9.3b	14.4b	10.2	4.5	5.3
120–130	10.3a	14.7ab	9.8	7.3	5.8
Chisel-tilled soil					
0	8.9b	12.5b	10.1	7.4	5.9
60–65	9.6a	13.4b	10.1	7.3	5.3
120–130	9.3ab	14.8a	10.6	7.9	6.1

[a]*Numbers followed by the same letter within a column in a set are not significantly different at $P \le 0.05$.*

Table 3.
Effect of 3 years of N fertilization rate on soil organic C at the 0–120-cm depth in strip-tilled and chisel-tilled soils under cotton and sorghum in central Georgia, USA [39].

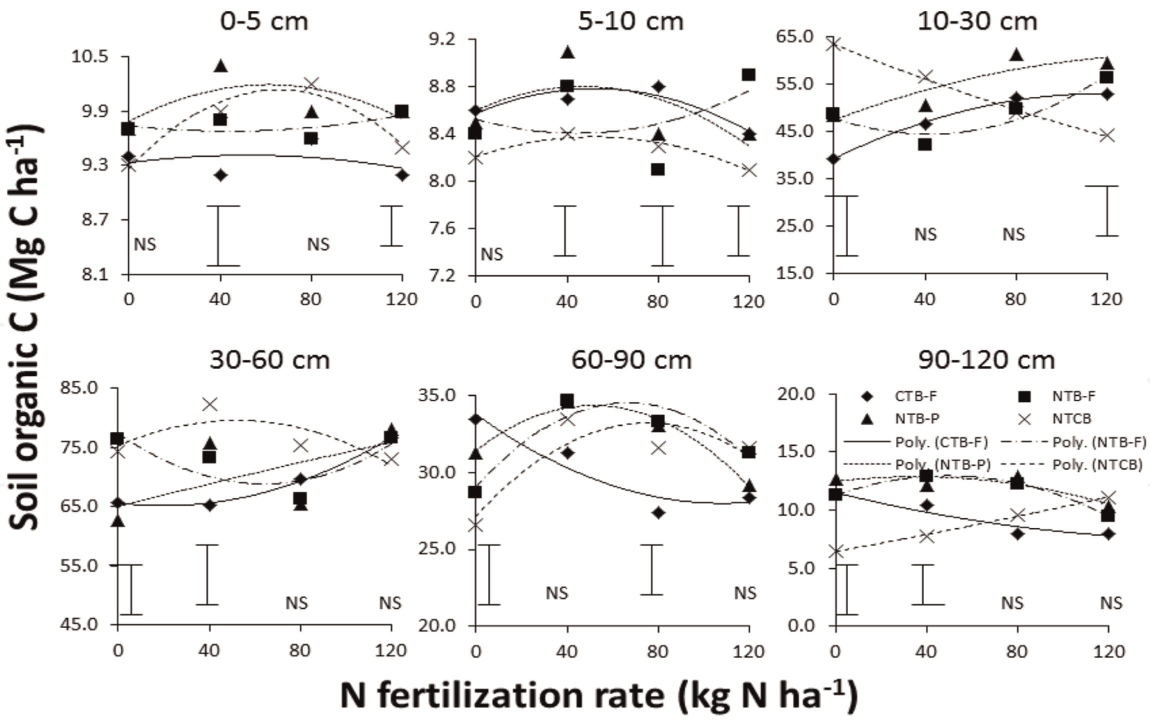

Figure 5.
Soil organic C at the 0–120 cm depth as affected by 6 years of N fertilization rates to malt barley in various cropping systems in eastern Montana, USA. CTB-F denotes conventional-till malt barley-fallow; NTB-F, no-till malt barley-fallow; NTB-P, no-till malt barley-pea; and NTCB, no-till continuous malt barley. Vertical bars denote least significant difference between tillage and cropping sequence treatments within a N rate at P = 0.05 [9].

conventional till malt barley-fallow (CTB-F), the trend of soil organic C with N rates varied at various depths. Soil organic C at these depths was greater with NTB-P and NTCB than other treatments at most N rates due to greater amount of crop residue returned to the soil. Soil organic C at 5–10, 30–60, and 60–90 cm were greater with 40 kg N ha^{-1} than other N rates. Sainju [9] also found that C sequestration rate at 0–10 cm was 83 kg C ha^{-1} $year^{-1}$ with 40 kg N ha^{-1} that was close to 94 kg C ha^{-1} $year^{-1}$ at 0–15 cm with 45 kg N ha^{-1} for dryland cropping systems in Colorado [36].

Under perennial grasses, several researchers [40, 41] did not find a significant effect of N fertilization on soil organic C at 0–30 cm after 2–5 years in Alabama and Colorado, USA. Only after 4–12 years, N fertilization increased soil organic C at 0–90 cm by 0.5–2.4 Mg C ha^{-1} $year^{-1}$ compared with no N fertilization under switchgrass in USA and Canada [42, 43]. Rice et al. [43] reported that N fertilization to cool-season grasses increased C sequestration rate at 0–30 cm by 1.6 Mg C ha^{-1} $year^{-1}$ compared with no N fertilization after 5 years in Kansas, USA. In Alberta, Canada, Bremer et al. [42] observed that N fertilization to perennial grasses increased C sequestration rate at 0–5 cm by 0.5 Mg C ha^{-1} $year^{-1}$ compared with no N fertilization after 6–12 years. In South Dakota, USA, Li et al. [44] noted C sequestration rate of 2.4 Mg C ha^{-1} $year^{-1}$ at 0–90 cm under switchgrass after 4 years. Sainju et al. [45] found increasing trend of soil total C at 30–60 cm with increased N rate under intermediate wheatgrass and smooth bromegrass and a declining trend with switchgrass after 5 years in eastern Montana (**Figure 6**). At 60–90 cm, the trend reversed with grasses. They suggested that longer than 5 years is needed to observe the effect of N fertilization on soil total C under perennial grasses.

Nitrogen fertilization has less impact on soil total N than soil organic C. Sainju and Singh [46] reported that soil total N at 0–15 cm under cotton and sorghum was greater with 60–65 than 0 kg N ha^{-1}, but not at lower depths in the

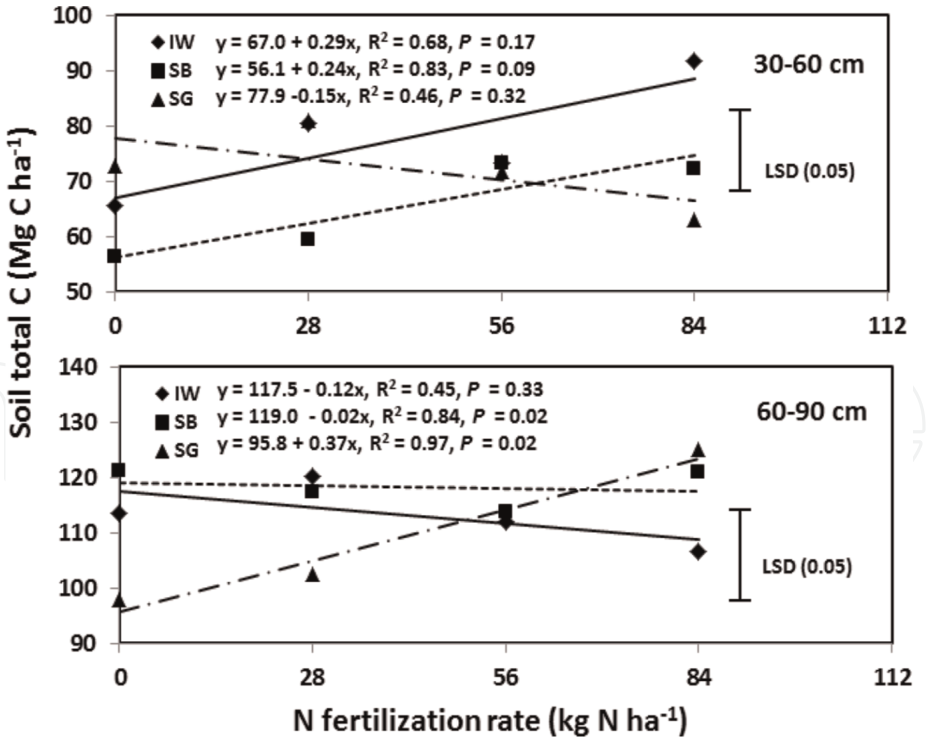

Figure 6.
Soil total C at 30–60 and 60–90 cm depths as affected by 5 years of N fertilization rates to perennial grasses in eastern Montana, USA. Perennial grasses are IW, intermediate wheatgrass; SB, smooth bromegrass, and SW, switchgrass. LSD (0.05) is least significant difference between grasses within a N rate at P = 0.05 [45].

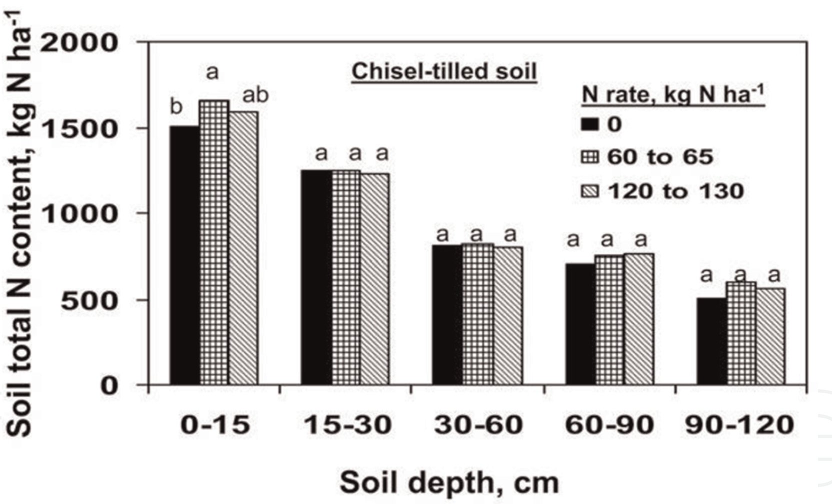

Figure 7.
Soil total N at 0–120 cm in the chisel-tilled soil as affected by 6 years of N fertilization rates to cotton and sorghum in central Georgia, USA. Bars with the same letter at the top are not significantly different among N rates at a depth at P ≤ 0.05 [46].

chisel-tilled soil in central Georgia, USA (**Figure 7**). Ghimire et al. [29] observed that soil total N at 10–20 cm increased with increased N rates after 70 years of N fertilization to winter wheat, but the trend varied with different tillage practices at higher N rates in eastern Oregon, USA (**Figure 8**). At 0–45 kg N ha^{-1}, soil total N was greater with subsurface sweep than a moldboard plow. At 90–180 kg N ha^{-1}, soil total N was lower with disc plow than other tillage practices. Increased N substrate availability due to N fertilization along with tillage may have increased microbial activity and N mineralization and therefore reduced soil total N over time.

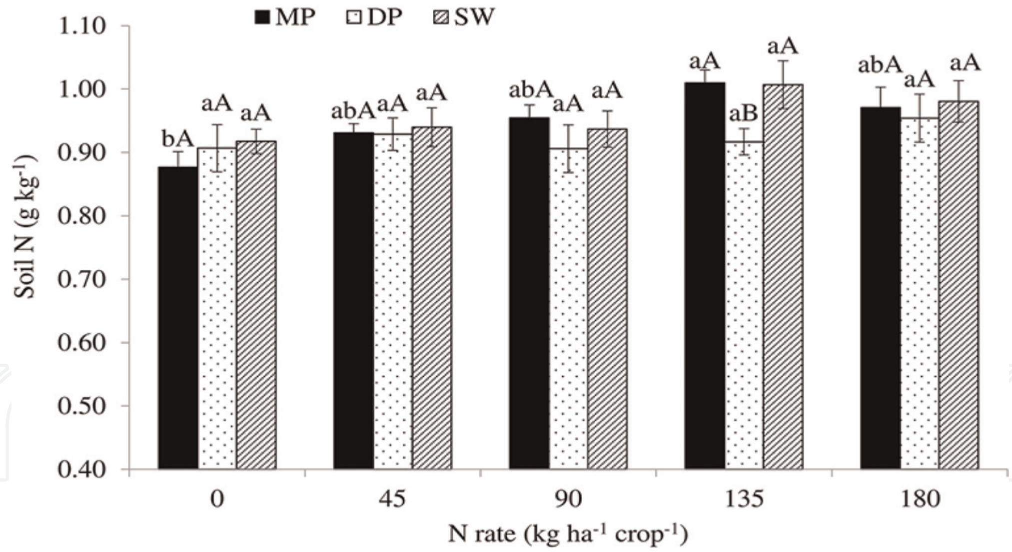

Figure 8.
Soil total N as affected by 72 years of N fertilization rates to spring wheat and tillage in eastern Oregon, USA. Tillage practices are DP, disk plow; MP, moldboard plow, and SW, subsurface sweep. Bars with different lowercase letters at the top are significantly different among tillage practices within a N rate at $P \leq 0.05$. Bars with different uppercase letters at the top are significantly different among N rates within a tillage practice at $P \leq 0.05$ [29].

5. Soil residual nitrogen and nitrogen leaching

Soil residual N refers to inorganic N (NH_4-N + NO_3-N) accumulated in the soil profile after crop harvest. This occurs because crops cannot take up all applied N fertilizer from the soil [5, 47]. Accumulation of soil NO_3-N increases with depth and is directly related to N fertilization rate [47, 48]. Deep accumulation of NO_3-N in the soil profile increases the potential for N leaching to shallow water tables [49]. Nitrogen fertilization rates that exceed crop requirement can increase NO_3-N accumulation in the soil profile and N leaching [50].

Soil inorganic N			
Treatment	**0–10 cm**	**10–30 cm**	**0–30 cm**
(kg N ha^{-1})			
Cover crop			
Winter weeds	19.6b[a]	32.9b	52.5c
Rye	19.1b	34.1b	53.2c
Hairy vetch	23.6a	38.4a	62.0a
Hairy vetch/rye	21.6a	34.8b	56.4b
N fertilization rate (kg N ha^{-1})			
0	19.6b	33.5b	53.1b
60–65	20.8b	35.3ab	56.1ab
120–130	22.5a	36.4a	59.9a

[a]*Numbers followed by the same letter within a column in a set are not significantly different at $P \leq 0.05$.*

Table 4.
Effect of cover crop and N fertilization rate on soil residual inorganic N (NH_4-N + NO_3-N) content at the 0–30 cm depth in central Georgia, USA [16].

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N fertilization rate	NH_4-N content at the soil depth										
	0–5 cm	**5–10 cm**	**10–30 cm**	**30–60 cm**	**60–90 cm**	**90–120 cm**	**0–10 cm**	**0–30 cm**	**0–60 cm**	**0–90 cm**	**0–120 cm**
kg N ha^{-1}	kg N ha^{-1}										
0	2.4b[†]	2.5a	10.4a	15.8a	19.4a	23.8a	4.9b	15.3a	31.2a	50.2a	72.0a
40	2.3b	2.3a	10.6a	15.4a	19.7a	25.0a	4.7b	15.2a	30.6a	49.7a	72.7a
80	2.5b	2.5a	10.3a	15.5a	19.7a	25.1a	5.0ab	15.4a	30.8a	49.1a	72.2a
120	2.9a	2.6a	10.8a	16.2a	19.6a	25.7a	5.5a	16.1a	32.0a	50.8a	73.6a

[†]Numbers followed by the same letters within a column are not significantly different at $P \leq 0.05$.

Table 5.
Effect of N fertilization rate on soil residual NH_4-N content at the 0–120 cm depth from 2006 to 2011 in eastern Montana, USA [55].

N fertilization rate	NO_3-N content at the soil depth										
	0–5 cm	**5–10 cm**	**10–30 cm**	**30–60 cm**	**60–90 cm**	**90–120 cm**	**0–10 cm**	**0–30 cm**	**0–60 cm**	**0–90 cm**	**0–120 cm**
kg N ha^{-1}	**kg N ha^{-1}**										
0	6.7c[†]	3.7c	13.3c	15.5c	13.7c	16.7b	10.2c	23.6d	39.0d	52.7d	68.7c
40	8.1c	4.3bc	14.6c	17.5bc	17.1b	21.4ab	12.5c	27.1c	44.6c	61.6c	82.3b
80	10.1b	5.1b	16.7b	19.8b	17.7b	21.0ab	15.2b	31.9b	51.8b	69.4b	89.6b
120	12.2a	6.2a	20.0a	23.4a	21.7a	24.7a	18.3a	38.2a	61.7a	83.3a	107.0a

[†]*Numbers followed by the same letters within a column are not significantly different at $P \leq 0.05$.*

Table 6.
Effect N fertilization rate on soil residual NO_3-N content at the 0–120 cm depth from 2006 to 2011 in eastern Montana, USA [55].

One of the ways to reduce N fertilization rates to crops while maintaining yield goals is to account for N mineralized from soil organic matter during the crop growing season and soil residual N at crop planting [6]. Since the measurement of N mineralization requires a long time, N fertilization rates to dryland crops are adjusted by deducting soil NO_3 content to a depth of 60 cm after crop harvest in the previous year or at planting of the current year from recommended N rates [51]. Producers are increasingly interested in reducing the amount of N fertilizer applied to crops because of the higher cost of N fertilization and the associated environmental degradation.

Nitrogen fertilization rates to crops can be higher in the no-till than the conventional till system due to greater accumulation of surface crop residue that can enhance N immobilization [52]. On the other hand, N rates can be reduced in crop rotations containing legumes compared to monoculture nonlegume cropping systems [53]. Nonlegume monocropping can have higher soil residual NO_3-N content than legume-based crop rotations due to increased N fertilization rate [5, 27]. Increased cropping intensity can reduce soil profile NO_3-N content due to greater N immobilization, less summer fallow, and a greater amount of N removed by crops [54]. Sainju et al. [16] and Sainju [9] found that both soil NH_4-N and NO_3-N contents increased with N rates and depths (**Tables 4–6**).

It is well known that excessive N fertilizer application can increase N leaching in the groundwater, which is a major environmental concern [50]. Nitrate-N concentration >10 mg L^{-1} in the drinking water poses a serious threat to human and animal health [56]. Nitrate-N is soluble in water and moves down the soil profile with percolating water [47, 57]. Increased application of N fertilizer to crops during the last several decades has increased NO_3-N contamination of groundwater [56]. This occurs because of excessive NO_3-N accumulation in the soil profile [57] due to N fertilization rates that exceed crop requirements, accompanied by poor soil and crop management practices [56]. Nitrate-N accumulation and movement in the soil profile depend on soil properties, climatic conditions, and management practices [58]. For example, N leaching is greater in sandy than clayey soils due to the presence of a large number of macropores and leaching is higher in the humid than arid and semiarid regions due to differences in annual precipitation [56, 58]. Nitrate-N leaching occurs mostly in the fall, winter, and spring seasons in the northern hemisphere when evapotranspiration is low, crops are absent to uptake soil N, and precipitation exceeds the water holding capacity of the soil [59].

6. Greenhouse gas emissions and global warming potential

Management practices on croplands can contribute about 10–20% of global greenhouse gases (GHGs: carbon dioxide [CO_2], nitrous oxide [N_2O], and methane [CH_4]) [60]. Quantitative estimate of the impact of the GHGs to global radiative forcing is done by calculating net global warming potential (GWP) which accounts for all sources and sinks of CO_2 equivalents from farm inputs, farm operations, soil C sequestration, and N_2O and CH_4 emissions [61, 62]. The net GWP for a crop production system is expressed as kg CO_2 eq. ha^{-1} $year^{-1}$. Net GWP is also expressed as net greenhouse gas intensity (GHGI) or yield-scaled GWP, which is calculated by dividing net GWP by crop yield [61]. These values can be affected both by net GHG emissions and crop yields. Sources of GHGs in agroecosystems include N_2O and CH_4 emissions (or CH_4 uptake) as well as CO_2 emissions associated with farm machinery used for tillage, planting, harvesting, and manufacture, transportation, and applications of chemical inputs, such as fertilizers, herbicides, and pesticides, while soil C sequestration rate can be either a sink or source of CO_2

[62, 63]. In the calculations of net GWP and GHGI, emissions of N_2O and CH_4 are converted into their CO_2 equivalents of global warming potentials which are 310 and 28, respectively, for a time horizon of 100 years [60]. The balance between soil C sequestration rate, N_2O and CH_4 emissions (or CH_4 uptake), and crop yield typically controls net GWP and GHGI [61, 62].

Nitrogen fertilization typically stimulates N_2O emissions when the amount of applied N exceeds crop N demand [51, 61]. Nitrogen fertilization, however, can have a variable effect on emissions of other GHGs, such as CO_2 and CH_4 [64, 65]. Sainju et al. [65] found that the application of 80 kg N ha^{-1} to dryland malt barley increased CO_2 emissions, but not N_2O and CH_4 emissions (**Table 7**). Because N_2O emissions has a large effect on net GWP and GHGI, practices that can reduce N fertilization rates without influencing crop yields can substantially reduce net GHG emissions [61, 62]. Other factors that can influence N_2O emissions are the type, placement, time, and method of application of N fertilizers. Applying N fertilizer in the spring compared with autumn and using split application compared with one single application at planting can reduce N_2O emissions in some cases [66]. Applying N fertilizer at various depths can have a variable effect on N_2O emissions [67]. Anhydrous ammonia can increase N_2O emissions compared with urea [67, 68]. Similarly, chemical additives to reduce nitrification from N fertilizers, such as polymer-coated urea and nitrification inhibitors, can substantially reduce N_2O emissions compared with ordinary urea and non-nitrification inhibiting fertilizers [69]. Some N fertilizers, such as urea, emit both CO_2 and N_2O. Nitrogen fertilizers also indirectly emit N_2O through NH_3 volatilization and NO_3-N leaching [68].

Increased N fertilization rate can enhance net GWP and GHGI due to increased N_2O and CO_2 emissions associated with the manufacture, transport, and application of N fertilizers, regardless of cropping systems and calculation methods [61, 70]. In a meta-analysis of 12 experiments, Sainju [71], after accounting for all sources and sinks of CO_2 emissions, reported that net GWP decreased from 0 to ≤45 kg N ha^{-1} and net GHGI from 0 to ≤145 kg N ha^{-1} and then increased with increased N fertilization rate (**Figure 9**). Using partial accounting, net GWP decreased from 0 to 88 kg N ha^{-1} and net GHGI from 0 to ≤213 kg N ha^{-1} and then increased with increased N rate. These N rates probably corresponded to crop N demand when crops used most of the soil available N. The cropping systems that left little residual N in the soil reduced N_2O emissions, and therefore net GWP and GHGI, whereas net GWP and GHGI increased linearly with increase in N application rates that exceeded crop N demand, suggesting that excessive N fertilizer applications can induce global warming. Similar results have been reported by Li et al. [44]. Therefore, N fertilizers should be applied at optimum rates to reduce net GWP and GHGI while sustaining crop yields. The optimum N rates, however, depended on net GWP measured either per unit area or per unit crop yield.

N fertilization	CO_2 flux	N_2O flux	CH_4 flux
kg N ha^{-1}	Mg C ha^{-1}	g N ha^{-1}	g C ha^{-1}
0	1.15b[†]	308a	−314a
80	1.23a	329a	−291a

[†]*Numbers followed by different letters within a column are significantly different at $P \le 0.05$ by the least square means test.*

Table 7.
Effect of N fertilization on total soil surface greenhouse gas fluxes (from March to November) averaged across years from 2008 to 2011 under rainfed malt barley in eastern Montana, USA [65].

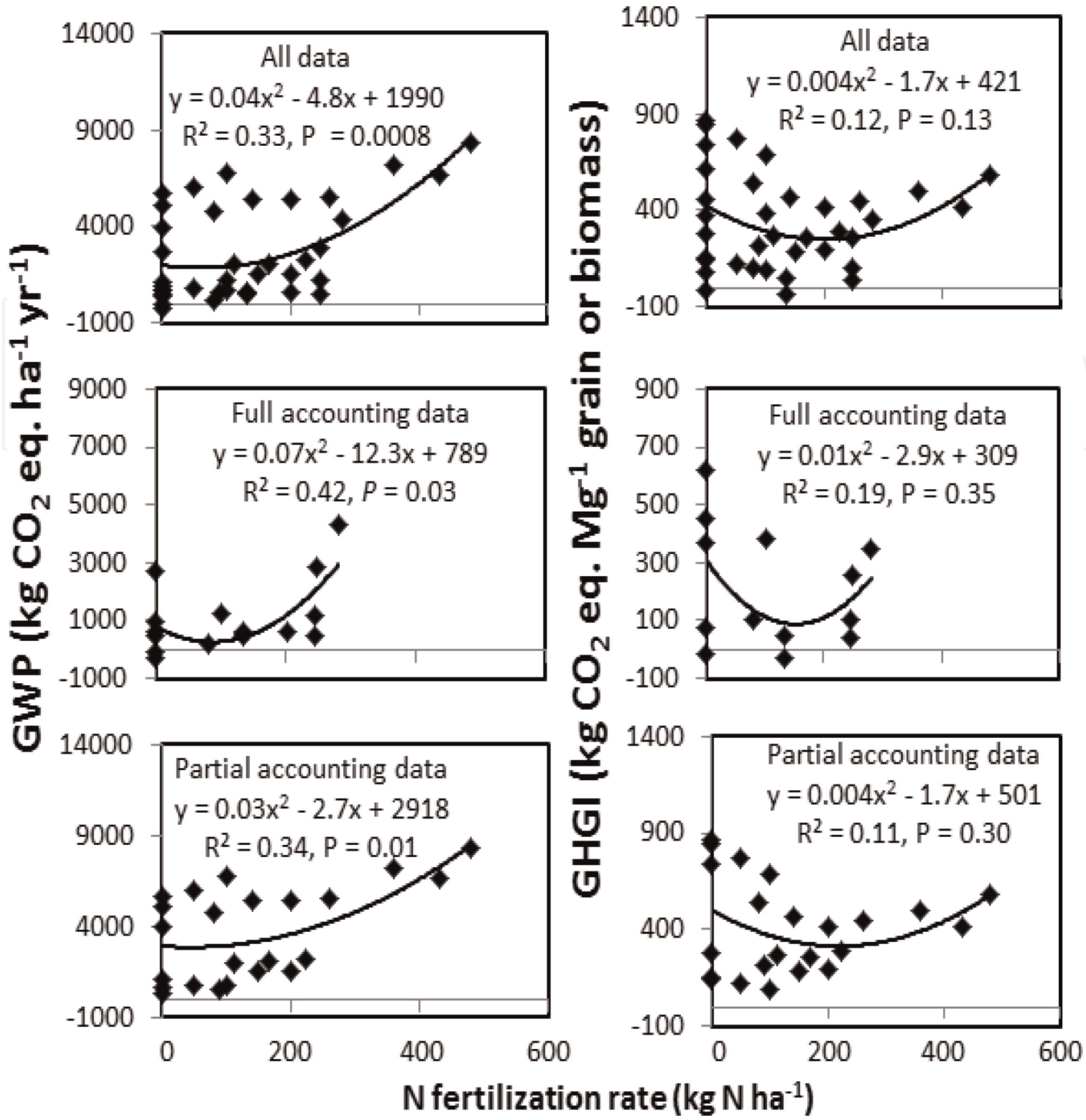

Figure 9.
The relationship between N fertilization rate and net global warming potential (GWP) and greenhouse gas intensity (GHGI). Full accounting data denote calculations of GWP and GHGI by accounting all sources and sinks of CO_2 (N_2O and CH_4 emissions, farm inputs, operations, and soil C sequestration). Partial accounting data denotes partial accounting of sources and sinks (N_2O and CH_4 emissions and/or soil C sequestration). All data denotes inclusions of full and partial accounting data [71].

Sainju [71] observed that the relationships between net GWP, net GHGI, and N rate were further improved when the duration of the experiment and soil and climatic conditions were taken into account in the multiple linear regressions. Duration of experiment and annual precipitation had positive effects, but air temperature and soil texture had negative effects on net GWP when all sources and sinks of CO_2 emissions were accounted for. With partial accounting, only air temperature had a positive effect on net GWP, but other factors had negative effects. For net GHGI, the factors having negative effects were air temperature using the complete accounting of CO_2 emissions and annual precipitation and soil texture using the partial accounting. Sainju et al. [70] reported that net GWP and GHGI calculated from soil respiration and soil C sequestration methods were lower with 80 than 0 kg N ha^{-1} (**Table 8**). They noted that, although CO_2 equivalents from N fertilization and soil respiration were higher with 80 kg N ha^{-1}, the amount of plant residue returned to the soil, soil C sequestration rate, and grain yields were greater

Cropping sequence[a]	N rate	Farm operation (A)	N fertilizer (B)[b]	Soil respiration (C)	N_2O flux (D)	CH_4 flux (E)	Annualized crop residue (F)[c]	SOC (G)[d]	GWP_R (H)[e]	GWP_C (I)[f]	Annualized grain yield (J)	$GHGI_R$ (K)[g]	$GHGI_C$ (L)[h]
	kg N ha^{-1}	kg CO_2 equivalent ha^{-1} $year^{-1}$									kg ha^{-1}	kg CO_2 kg^{-1} grain yield	
CTB-F		182	77	2722b[i]	425a	−16a	3476b	−114c	−89a	778a	1408b	−0.06a	0.55a
NTB-P		124	91	3303a	469a	−16a	5980a	554a	−2005c	115b	1649a	−1.22c	0.07b
NTCB		124	103	3547a	394a	−15a	5411a	268b	−1259b	337b	1683a	−0.75b	0.20b
	0	143	0	3093b	416a	−16a	4421b	−94b	−787a	635a	1399b	−0.56a	0.45a
	80	143	180	3288a	443a	−15a	5487a	566a	−1448b	185b	1761a	−0.82b	0.11b

[a]*Cropping sequences are CTB-F, conventional-till malt barley-fallow; NTB-P, no-till malt barley-pea; and NTCB, no-till continuous malt barley.*
[b]*Total CO_2 equivalents from direct and indirect sources of N fertilization.*
[c]*Total above- and below-ground crop residue.*
[d]*Carbon sequestration rate calculated from linear regression of change in soil organic C at the 0–10 cm depth from 2006 to 2011.*
[e]*Column (H) = Column (A) + Column (B) + Column (C) + Column (D) + Column (E) − Column (F) [61]. Negative values indicate GHG sink.*
[f]*Column (I) = Column (A) + Column (B) + Column (D) + Column (E) − Column (G) [61, 62]. Negative values indicate GHG sink.*
[g]*Column (K) = Column (H)/Column (J) [61]. Negative values indicate GHG sink.*
[h]*Column (L) = Column (I)/Column (J) [61]. Negative values indicate GHG sink.*
[i]*Numbers followed by the same letters within a column in a set are not significantly different at $P \leq 0.05$.*

Table 8.
Net global warming potential (GWP_R and GWP_C) and greenhouse gas intensity ($GHGI_R$ and $GHGI_C$) based on soil respiration and organic C (SOC) methods as influenced by cropping sequence and N fertilization rate in eastern Montana, USA [70].

with 80 than 0 kg N ha^{-1}, thereby resulting in lower net GWP and GHGI with N fertilization than without, regardless of the method used for calculation.

7. Conclusions

Nitrogen fertilization is one of the most commonly used practice to increase crop yields throughout the world because of abundant availability of N fertilizers and their great effectiveness to increase yields compared with other organic fertilizers, such as manure and compost. Excessive application of N fertilizers in the last several decades, however, has resulted in undesirable consequences of soil and environmental degradations, such as soil acidification, N leaching to the groundwater, and greenhouse gas (N_2O) emissions. Crop yields have declined in places where soil acidification is high due to unavailability of major nutrients and basic cations and toxic effect of acidic cations. Other disadvantages of excessive N fertilization include increased cost of fertilization, reduced N-use efficiency, and negative impact on human and livestock health. To reduce excessive N fertilization, composited soil sample to a depth of 60 cm should be conducted for NO_3-N test prior to crop planting and N fertilization rate be adjusted by deducting soil NO_3-N content from the desirable N rate.

Author details

Upendra M. Sainju[1*], Rajan Ghimire[2] and Gautam P. Pradhan[3]

1 Northern Plains Agricultural Research Laboratory, US Department of Agriculture, Agricultural Research Service, Sidney, Montana, USA

2 Agricultural Science Center, New Mexico State University, Clovis, New Mexico, USA

3 Williston Research and Extension Center, North Dakota State University, Williston, North Dakota, USA

*Address all correspondence to: upendra.sainju@ars.usda.gov

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