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Impact of loosening and straw addition to the subsoil on crop performance and nitrogen leaching: A lysimeter study

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Abstract

Poor subsoil properties are difficult to ameliorate and detrimental to soil fertility and crop yield. The effects of loosening (L) and loosening + straw (LS) ∼60 Mg ha^{-1} into the subsoil (25–40 cm depth) on crop yield, water flow, and the nitrogen (N) balance components under bare soil conditions and a barley (*Hordeum vulgare* L.) crop were investigated in an about 21-mo lysimeter study and compared with a control treatment. Undisturbed soil columns ($n = 12$) were excavated from an agricultural field in May 2016, installed at a lysimeter station, and exposed to outdoor climatic conditions in Uppsala, Sweden, in August 2016. Spring barley ('Makof') was grown between June and September 2017. Total N leaching loads over the 21 mo were high (74–193 kg ha^{-1}). The LS treatment reduced the N load by 49% ($P = .01$) and 62% ($P = .001$) compared with the L and control treatments, respectively. Loosening reduced N load by 25% ($P < .07$) compared with the control. Emissions of N_2O were low (0.04–0.07 kg N ha^{-1}), and no differences were observed between treatments. Leaf relative chlorophyll content was lower in the LS treatment than in the L and control treatments ($P < .05$). Yield was also lowest in the LS treatment (5.8 Mg ha^{-1}) and was 7 and 8.5% lower than in the control and L treatments ($P > .05$), respectively. These results suggest that LS can reduce N leaching. The overall effects of LS on crop performance and N removal and leaching should be further scrutinized in long-term field studies.

1 | INTRODUCTION

Arable subsoils often contain low soil organic matter (SOM), are poor in nutrient availability, and may have dense structure, which restrict root growth and limit crop yield (Kautz et al., 2013; Rengasamy et al., 2003). Loosening can improve subsoil conditions to varying degrees, but its impact may only last for a few years (Botta et al., 2006; Larney & Fortune, 1986). Alternative management options that help extend the effect of loosening are thus crucial for improving soil structure and soil fertility (Hamza & Anderson, 2005). Although information remains scant, the literature cited herein indicates that treating the subsoil by loosening and addition of straw or other organic materials may increase crop yield by improving soil structure, root growth, and access to water and nutrients (e.g., Getahun

Abbreviations: BD, bulk density; L, subsoil loosening; LS, subsoil loosening with straw addition; NHI, nitrogen harvest index; PVC, polyvinyl chloride; SOC, soil organic carbon; SOM, soil organic matter.

et al., 2018; Gill et al., 2008; Jakobs et al., 2017; Leskiw et al., 2012).

Adding straw to soil may increase water-holding capacity (Van Donk et al., 2010) and reduce nitrate leaching, thereby mitigating pollution of water systems (Nicholson et al., 1997; Powlson et al., 1985; Silgram & Chambers, 2002). On the other hand, crop yield could be reduced due to temporary nitrogen (N) limitation via microbial immobilization (Elliott et al., 1981; Jenkyn et al., 2001). The impact of straw addition on N_2O emissions, however, is not consistent (Liu et al., 2019). Straw may serve as a source of soil organic carbon (SOC) and N, thus enhancing the activity of soil organisms and associated emissions of N_2O (Huang et al., 2004). Conversely, straw with a high C/N ratio may lead to net N immobilization, thus lowering the amount of mineral N in soil (Liu et al., 2011), which may reduce N_2O emissions.

Lysimeter experiments have been widely performed for monitoring water flow, solute movement, gas emissions, and transformation and translocation of nutrients (Bergström, 1990). A lysimeter set-up also offers the possibility to loosen and uniformly mix amendments across the desired subsoil depth in a precise manner, which is not possible to achieve in the field. Therefore, we conducted a lysimeter study to investigate the effect of subsoil loosening and subsoil loosening with straw addition at approximately 25–40 cm depth on (a) leachate discharge and N concentrations in leachate, (b) N_2O emissions, (c) grain yield of spring barley (*Hordeum vulgare* L.), and (d) N balance components.

Core Ideas

- Loosening + straw addition into subsoil reduced N leaching.
- There were indications of reduced N removal due to subsoil loosening with straw addition.
- An extended period without crops was followed by high N-leaching losses.

2 | MATERIALS AND METHODS

2.1 | Lysimeters and treatments

In May 2016, 12 intact soil columns were excavated from a Eutric Cambisol (FAO, 2015) in an agricultural field (Säby, 59°83′ N, 17°71′ E) close to Uppsala, Sweden, that has been under cultivation for more than a century. Selected physical and chemical characteristics of the soil are presented in Table 1. Undisturbed soil columns were extracted in polyvinyl chloride (PVC) pipes (0.295 m i.d., 1.18 m long) using a method described by Persson and Bergström (1991), where a tractor-mounted hydraulic soil auger is used to extract the soil columns. Each PVC pipe containing a soil column was lifted out of the soil pit when it reached the target depth. It was covered at both ends with lids and transported with minimum disturbance to the lysimeter station in Uppsala, about 6 km from the collection site (Figure 1). A 5-cm soil layer from the base of the soil columns was replaced with washed gravel (2–5 mm grain size), with a stainless steel mesh between soil and gravel, and a perforated PVC cap was fitted over the base. The soil columns were installed in the lysimeter station in August 2016 as described below.

The columns were randomly allocated to three experimental treatments (loosening [L], loosening with straw addition [LS], and control) in four blocks. To create similar conditions in all treatments, the topsoil was removed manually from all lysimeters to approximately 25 cm depth. The removed topsoil was pooled, loosened, and mixed thoroughly by hand, and then a similar amount of topsoil mixture was returned to all lysimeters. Before returning the topsoil, the soil columns for the two subsoil treatments were further excavated to approximately 40 cm depth and loosened. In the L treatment, the subsoil layer (25–40 cm) was returned directly to the lysimeters. In the LS treatment, the subsoil layer was mixed with dried and milled (2 mm mesh) cereal straw at a rate of about 60 Mg ha^{-1} before being returned to the lysimeters. In all cases, material was returned to lysimeters gently to avoid compaction. Due to late summer installation, soil columns were exposed to natural weather conditions and left unsown until June 2017.

In the lysimeter station, plastic pipes connected to funnels under the base of each lysimeter conducted leachate to glass collection bottles. The amount of leachate was monitored, and leachate samples were taken for chemical analysis. On a few occasions following lysimeter installation and mostly due to a moisture deficit during the cropping period, we added a total of about 157 mm of water to the lysimeters in 27 irrigation events, with 4–22 mm added on each occasion.

2.2 | Soil sampling and analysis

To determine soil properties at the beginning of the experiment, soil samples were taken at 10-cm intervals to 110 cm depth in three soil pits from which the soil columns were removed. Soil organic C and total N were analyzed in the air-dried, milled, and sieved soil samples (2-mm mesh) using dry combustion (CNS Analyzer, LECO Corp.). Bulk density (BD) was measured on 10-cm soil samples to 100 cm depth taken in the field using four soil cylinders (i.d., 7.2 cm; height, 10 cm) per layer. It was not possible to determine BD below 100 cm due to a high water table, so data for the 90-to-100-cm layer

TABLE 1 Physical and chemical properties of the field soil at the site where the soil columns were extracted

Soil depth	BD	Porosity	SOC		Total N		C/N ratio	Carbonate	pH (H_2O)	Clay	Silt	Sand
cm	Mg m^{-3}	%	g kg^{-1}	Mg-C ha^{-1}	g kg^{-1}	Mg N ha^{-1}		g kg^{-1}		%		
0–10	1.30	50.9	28.2	36.7	2.40	3.1	11.9	0.10	6.1	21.9	54.5	23.6
10–20	1.37	48.3	26.4	36.2	2.20	3.0	11.8	0.20	6.1	20.5	56.9	22.6
20–30	1.41	46.8	14.2	20.0	1.20	1.7	11.6	0.09	6.3	21.3	56.2	22.5
30–40	1.55	41.5	7.9	12.2	0.68	1.1	11.6	0.07	6.5	18.9	54.1	27.0
40–50	1.51	43.0	3.8	5.7	0.39	0.6	9.6	0.07	6.7	23.5	59.7	16.8
50–60	1.42	46.4	3.4	4.8	0.39	0.6	8.6	0.10	6.8	25.3	62.6	12.1
60–70	1.36	48.7	3.7	5.0	0.47	0.6	7.9	0.09	6.9	31.1	61.1	7.8
70–80	1.36	48.7	3.2	4.4	0.42	0.6	7.6	0.07	6.7	27.4	56.7	15.9
80–90	1.34	49.4	6.3	8.4	0.85	1.1	7.3	0.11	6.1	39.6	57.7	2.7
90–100	1.22	54.0	6.4	7.8	0.88	1.1	7.3	0.12	5.4	34.2	63.1	2.7
100–110			9.8	12.0	1.30	1.6	7.4	0.16	4.9	40.6	57.4	2.0
Total				153.2		15.1						

Note. BD, bulk density; SOC, soil organic carbon.

were used to represent the deepest layer in soil columns. The texture was determined by the pipette method, and pH was measured in a soil-water slurry at a soil/water ratio of 1:2.5 (Table 1).

2.3 | Straw characteristics

The cereal straw had a density of 0.32 Mg m^{-3}; contained 42% C, 0.47% N, 0.077% P, and 1.8% K; had a pH of 6.7; and had a C/N ratio of around 90. The water-holding capacity of the straw was approximately 5 ml g^{-1} dry matter.

2.4 | Leachate sampling and N concentrations in water

Water flow started in September 2016 after irrigation and several rain events in August and September 2016. The leachate collected in glass bottles during the study period was weighed, and subsamples were analyzed for N concentrations of nitrate (NO_3^-), nitrite (NO_2^-), and ammonium (NH_4^+), which were combined to give total mineral N. Nitrate and nitrite were determined colorimetrically by the vanadium chloride-reduction method, and ammonium concentration was determined colorimetrically using the salicylate method (ISO, 2013). The leachate was sampled for chemical analysis each time a sufficient amount for analysis was available.

2.5 | Soil and crop management

Spring barley (‘Makof’) was sown in the lysimeters on 12 June 2017. The soil in each lysimeter was hand-tilled, followed

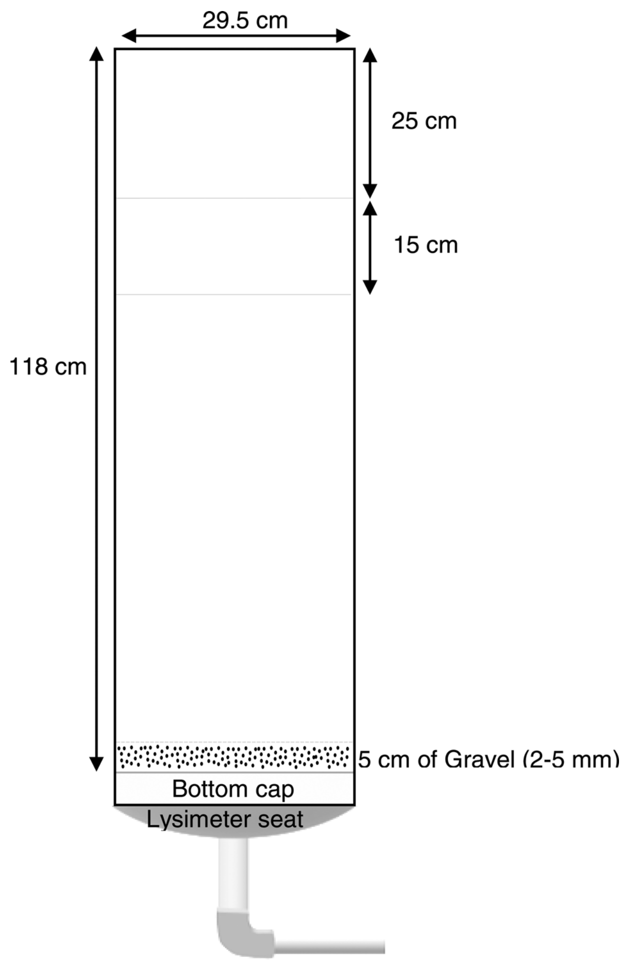

FIGURE 1 Illustration of a lysimeter. The soil column inside the lysimeter has a surface area of about 0.068 m^2. The soil column is 1.08 cm long (pipe is 1.18 m long, the soil column starts at 5 cm below the upper end of the pipe, and at the base there is a 5-cm-thick gravel layer). The upper end of the subsoil is indicated by 25 cm, and the 15 cm is the layer treated with subsoil loosening or subsoil loosening with straw addition. Adapted from Bergström and Johansson (1991).

by application of N–P–K–S equivalent to 100–20–50–15 kg ha^{-1} in the form of ammonium nitrate, potassium phosphate, and ammonium sulfate. The fertilizer solution was carefully injected at 7 cm depth in the L, LS, and control treatments. At flag leaf emergence, the barley plants were covered with netting to protect them from foraging birds. Leaf relative chlorophyll content was measured with a handheld Soil Plant Analysis Development (SPAD-502) meter (Minolta Camera Co.). Measurements were carried out around crop stages 48/49 (booting) and 58/59 (inflorescence emergence/heading) on the Zadok's growth scale (Zadoks et al., 1974). Five plant shoots per lysimeter were measured for relative chlorophyll content (three readings per selected leaf), and the heights of three shoots per lysimeter were measured. The crop was harvested by cutting close to the soil surface with scissors to determine the total aboveground biomass. After drying, plant samples were threshed to separate grains from aboveground biomass (straw). Grains and straw were separated, weighed, and ground with a mill. During the cropping season, we noticed damage to the barley plants caused by the chambers during gas measurements, foraging birds, and crop disease. We attempted to correct for damage caused by the chamber and birds based on the number of broken shoot heads. The adjusted grain yield was then calculated by adding this estimate of grain loss, which varied between 6 and 16% in the different lysimeters, to the measured grain yield (number of intact crop heads).

2.6 | Nitrous oxide emissions

Nitrous oxide fluxes from the lysimeters were measured on 19 occasions during the cropping period (13 June–29 Aug. 2017) by placing PVC chambers (0.02 m^3) on top of the lysimeters. Each chamber was equipped with a ventilation tube and a small axial fan for air mixing within the chamber. During gas collection, a loop was made between 20-ml glass septum-capped storage vials, the chamber, and the air pump. The air was circulated in this loop for 1 min during each measurement. Chamber closure time was approximately 45 min, during which five air samples were collected and air temperature inside the chamber was monitored. Gas sample vials were stored at room temperature and analyzed within a week for N_2O on a gas chromatograph (Clarus 500, Perkin Elmer). Ten gas flux measurements were performed within the first 2 wk after sowing. Thereafter, two measurements per week were made during the next 2 wk, followed by weekly measurements during the rest of the growing season. Measurements were timed to take place immediately following periods of rain or irrigation. After correcting for ambient air pressure and chamber temperature, individual N_2O fluxes were calculated with the R program *gasfluxes* (FussR, 2019) using the method "robust linear." Cumulative N_2O fluxes were calculated using the aggfluxes function from the *gasfluxes* R package.

2.7 | N balance for the soil–crop system

To obtain an N balance for the soil–crop system (kg ha^{-1}), we used a method similar to Sainju (2017). Nitrogen outputs were subtracted from N inputs to calculate the N balance. In our experiment, inorganic N fertilizer and crop seed N were inputs; N removal (grain and straw), N losses by leaching, and N_2O gas emissions were outputs. Nitrogen transformation in soil and N present in roots and belowground stem bases and changes in soil total N were not included in the N balance calculations. The amount of N present in different components of the N cycle was estimated as follows: Total N content in seeds and harvested grain and straw was determined, using clean and dust-free materials, with the Infratec NOVA grain analyzer and an elemental analysis instrument (CNS Analyzer, LECO Corp.), respectively. The output from the Infratec NOVA was protein concentration, which was divided by a conversion factor for barley to give its equivalent N concentration. Nitrogen harvest index (NHI) was determined as the ratio of grain N to total aboveground biomass N at harvest (Fageria, 2014). Biomass harvest index was determined as the ratio of grain yield to total aboveground dry matter production (Hay, 1995).

2.8 | Statistical and data analysis

The data obtained were analyzed using R software version 4.0.2. (R Core Team, 2020). Logarithmic transformation was performed on time series data of leachate, N load, and volume-weighted concentration to yield normality. For data aggregated into 3-mo meteorological seasons over the 21 mo, a mixed model considering time as a repeated factor was used to compare treatment differences in amounts of leachate (mm), volume-weighted N concentration (mg L^{-1}), and N load (kg ha^{-1}) in the ANOVA. We used an autoregressive, AR (1), correlation structure to model the error term.

One-way ANOVA was applied to data on the total amount of leachate (mm), volume-weighted concentration (mg L^{-1}) (total N load divided by total leachate amount), and total N load (kg ha^{-1}) over the 21 mo of the study. Tukey's post hoc test was used for multiple comparison tests between means.

Nitrogen load was determined by multiplying the measured N concentration by the amount of leachate on each sampling event. Seasonal (3-mo) and 21-mo mean volume-weighted concentrations (mg L^{-1}) were calculated by dividing the total N load (mg) by the total leachate amount over the period.

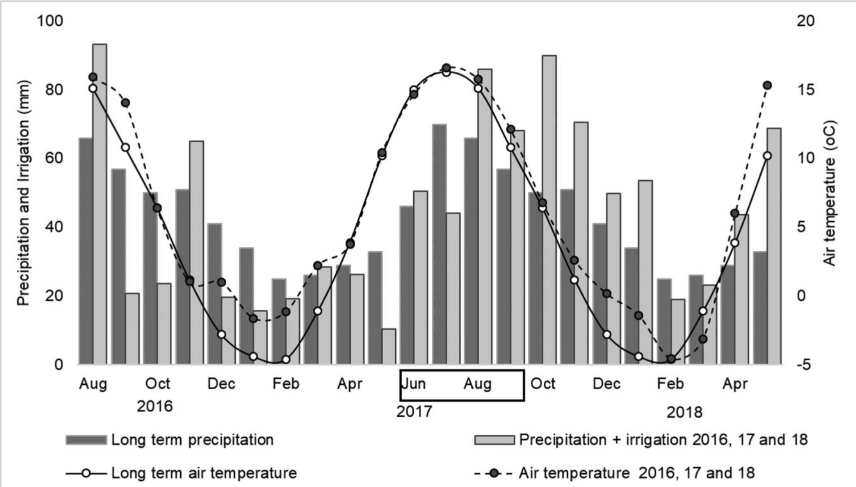

FIGURE 2 Long-term (1961–1990) and monthly air temperature and precipitation + irrigation from August 2016 to May 2018. Data from a weather station located ~300 m away from the lysimeter station. The rectangle highlighting months in the graph indicates the barley-growing period (12 June–29 Sept. 2017).

3 | RESULTS AND DISCUSSION

3.1 | Weather conditions

Total water input (precipitation and supplementary irrigation) between August 2016 and May 2018 was 990 mm, which is somewhat higher than the long-term average (1961–1990) at the lysimeter station (940 mm) for the same period (Figure 2). The total water input (precipitation and supplementary irrigation) received during the crop-growing season was about 223 mm.

3.2 | Soil properties

Analysis of soil properties at the start of the experiment indicated that SOC concentration gradually decreased to 80 cm depth in the soil profile, after which it increased with depth probably due to the postglacial sediment deposits. Total N followed the same trend as SOC. Clay content ranged from 19 to 22% between depths of 0 and 40 cm and increased with depth to around 35–40% between 80 and 110 cm. Soil pH decreased with increasing SOC at depth and was 4.9 below 100 cm depth. Bulk density was highest (1.55 Mg m^{-3}) in the 30-to-40-cm layer. Due to increasing SOC at depths >80 cm, BD decreased below 80 cm to 1.22 Mg m^{-3} at 100 cm depth. The C/N ratio in deeper soil layers was slightly lower than in the surface horizon. The relatively low C/N ratio in deeper layers suggests that the postglacial organic material was rich in N (Table 1). Total amount of SOC and N in the soil profile to 108 cm depth was around 151 Mg C and 14.7 Mg N ha^{-1}, respectively. The proportion of total N in the 25–108 cm soil layer amounted to 53% and the proportion of SOC to 45%.

3.3 | Leachate quantity

The average amount of leachate collected from the lysimeters during the 21-mo study period was 301 mm for the control, 271 mm for the LS treatment, and 260 mm for the L treatment ($P > .05$). When the data were broken into 3-mo meteorological seasons, relatively smaller leachate amounts were collected in the L ($P = .03$) and LS treatments ($P = .01$) than in the control in autumn (September–November) 2016 (Figure 3). The amount of leachate collected in relation to total precipitation and supplementary irrigation was equivalent to about 30.4% in the control, 26.3% in the L treatment, and 27.3% in the LS treatment.

Leachates were collected during autumn when evapotranspiration was low following crop harvest and during spring, after snowmelt. The leachate collected during winter reflected the mild winter conditions that occurred in 2016/2017 and 2017/2018. Similarly, Bergström and Kirchmann (1999) observed water flow over the entire winter of 1994/1995 due to relatively high temperatures. There was no water discharge during the barley-growing period (June–September 2017) (Figure 3). This was due to high evapotranspiration but also low precipitation in the month preceding June 2017, which created a moisture deficit in the soil. This has also been reported in lysimeter studies performed under the same weather conditions (Bergström, 1987; Bergström & Kirchmann, 2004).

3.4 | N volume-weighted concentrations and N loads

During the 21-mo study period, the mean volume-weighted concentration of N was considerably lower for the LS

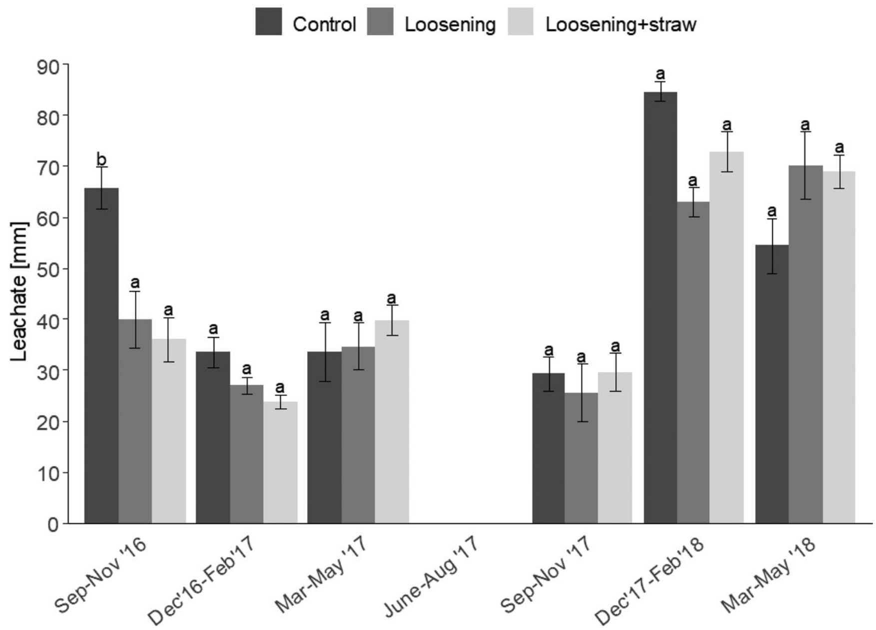

FIGURE 3 Amounts of leachate from the different treatments during the 21-mo study period. Values with different letters (each section separately) are significantly different at $P < .05$. Bars indicate the SEM of four replicates. June to August 2017 is the barley crop-growing period without leachate.

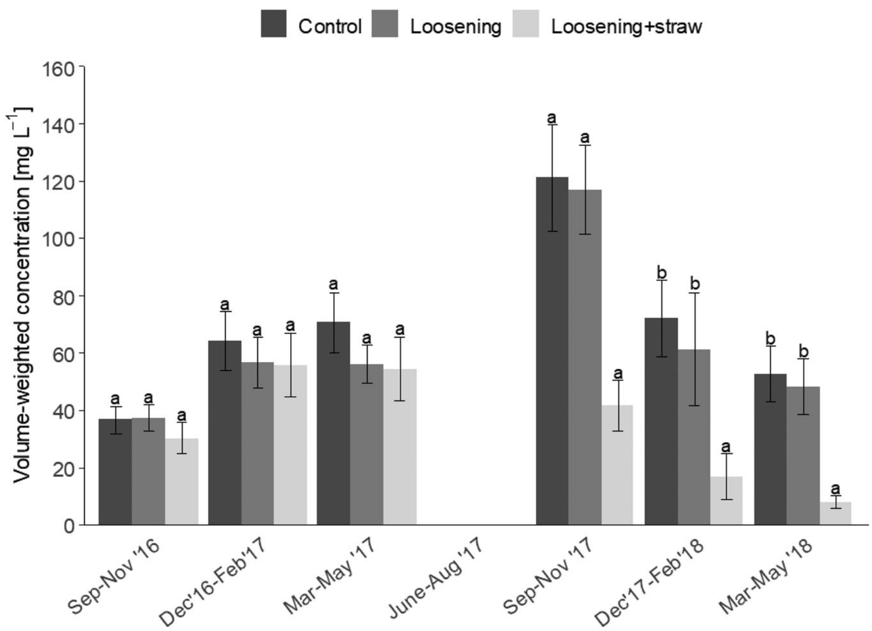

FIGURE 4 Mean (arithmetic) volume-weighted N concentration in leachate during the 21 mo in the different treatments. Values within panels with different letters are significantly different at $P < .05$. The P value for loosening + straw vs. loosening and loosening + straw vs. control (September–November 2017) was .06. Bars indicate the SEM of four replicates.

treatment (28 mg N L^{-1}) than for the L treatment (56 mg N L^{-1}; P = .002) and the control (64 mg L^{-1}; P = .0005) (Figure 4). The ammonium content of the leached N ranged between 1.2 and 2.5% (data not shown).

During the 21 mo, the largest N load (kg ha^{-1}) was observed in the control and the lowest in the LS treatment (62% lower; P = .001) (Figure 5). The total N load in the L treatment was higher than in the LS treatment (P = .01) and was around 25% lower (P = .07) than in the control. Hence, the net effect due to straw addition was about 37%. The lower N volume-weighted concentration and N leaching load in the LS treatment were likely due to immobilization, which is consistent with findings in previous leaching studies using organic materials with high C/N ratio (Jarvis et al., 1989; Machet & Mary, 1989; Nicholson et al., 1997).

Nitrogen load over the 21 mo was 74 kg N ha^{-1} in the LS treatment, 145 kg N ha^{-1} in the L treatment, and 193 kg N ha^{-1} in the control. These loads are high and are likely due to high SOM in the soil profile (Table 1) releasing N through mineralization. More importantly, the soil columns were wholly exposed to ambient air temperature for 3 mo between excavation and installation, which could have further stimulated mineralization. The N loads from mineralization of SOM prior to cropping, which was a period of about 13 mo, amounted to 69, 48, and 45 kg N ha^{-1} loss in the control, L, and LS treatments, respectively. High leaching loads during

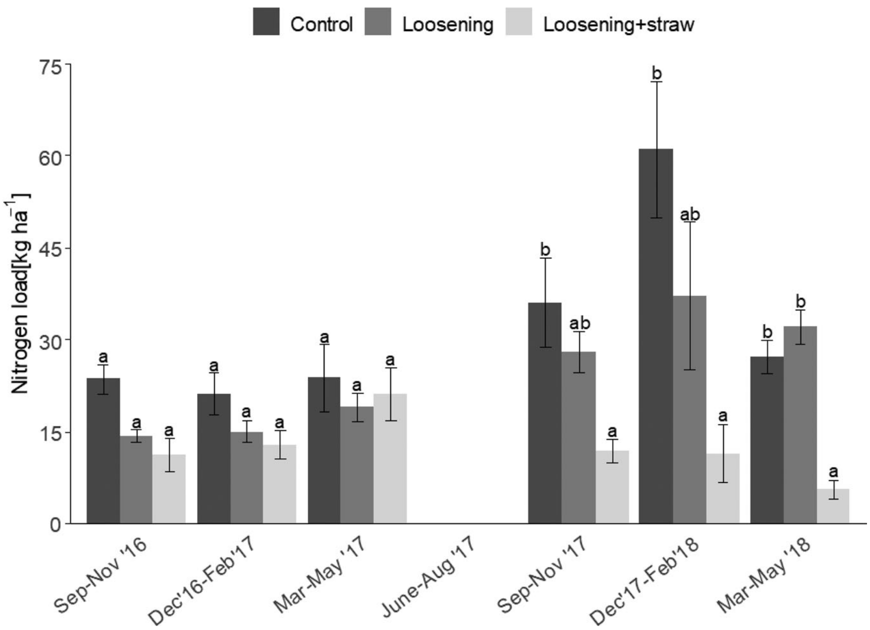

FIGURE 5 Mean (arithmetic) N loads during the 21 mo from the different treatments. Values within panels with different letters are significantly different at $P < .05$. The P value between loosening + straw and loosening (December 2017–February 2018) was .06. Bars indicate the SEM of four replicates.

TABLE 2 Treatment effects on relative leaf chlorophyll content (SPAD-index), plant height at different growth stage/Zadok's growth scale (ZGS), and yield and N content of barley straw and grain

Parameters	Control	L	LS
SPAD index at booting (ZGS 48/49)	52a	51.1a	47.1b
SPAD index at heading (ZGS 58/59)	51a	49.4a	45.1b
Plant height at booting (ZGS 48/49), cm	51.2a	54a	52.3a
Plant height at heading (ZGS 58/59), cm	65.2a	63.1ab	60b
Grain yield, Mg ha^{-1}	6.2a	6.3a	5.8a
Straw yield, Mg ha^{-1}	5.5a	5.6a	5.5a
Grain N content, %	2.3a	2.3a	2.1a
Grain protein, %	14.1a	14.2a	13.1a
Straw N content, %	0.69a	0.69a	0.58a
Biomass harvest index, %	53a	53a	51a

Note. Mean values within rows followed by different letters are significantly different at $P < .05$. L, loosening; LS, loosening + straw.

uncropped periods have also been found in previous studies (Francis et al., 1992; Meissner et al., 1998).

3.5 | Crop growth, N content, and yield

The leaf relative chlorophyll content of barley plants in the LS treatment was lower than that in the L treatment and the control at both the booting and heading growth stage ($P < .05$). Grain yield (after crop loss adjustment) in the LS treatment (5.8 Mg ha^{-1}) was 7% lower than in the control (6.2 Mg ha^{-1}) and 8.5% lower than in the L treatment (6.3 Mg ha^{-1}) (Table 2). Total N removal by the crop was moderately lower in the LS treatment than in the control and L treatments ($P > .05$). Total N concentration in grain and straw was 2.1 and 0.58%, respectively, in the LS treatment and 2.3 and 0.69%, respectively, in the L and control treatments (Table 2). The low leaf relative chlorophyll content indicated N limitation in LS probably due to N immobilization. Nitrogen immobilization following straw addition was also reported in earlier studies (e.g., Christian & Bacon, 1991; Powlson et al., 1985). In a longer time perspective, however, this immobilized N may gradually be mineralized and become available to subsequent crops (Powlson et al., 1985).

Grain protein content, an important criterion of grain quality, ranged between 13 and 14%, showing that the protein content was not considerably affected by straw addition (Table 2). Biomass harvest index value varied little, ranging from 51 (LS) to 53% (control and L), which is within the range (40–60%) reported for most grain crops (Hay, 1995). The NHI for all treatments is around 79% (data not shown), which means the crop was capable of accumulating about 79% of total plant

TABLE 3 Nitrogen balance for the soil-crop system for the 21-mo study period using the difference between inputs and outputs, where inputs are N additions (fertilizer and seeds) and outputs are N removal and losses (harvest, leaching, and N_2O emissions)

	Control	L	LS
	kg N ha^{-1} 21 mo^{-1}		
Inputs			
Seeds	8	8	8
N fertilizer	100	100	100
Straw addition	0	0	282[a]
Subtotal	108	108	108
Outputs			
Grain	141	144	122
Harvested straw	38.2	38.5	32.2
N leaching	193	145	74
N_2O–N emissions	0.04	0.07	0.04
Subtotal	372	328	228
Balance	−264	−220	−120

Note. L, loosening; LS, loosening + straw.
[a]Nitrogen input not available in the short run (initially it would not be available. However, during the latter part of the experiment, a part of straw derived N may have become available to the crop).

N in the grain at harvest. There were no observed differences due to treatments. The NHI reported for spring barley in another experiment was in the range of 71–74% (Przulj & Momcilovic, 2003).

3.6 | N balance

The N fluxes for the soil–crop system over the 21 mo are shown in Table 3 and for the 11-mo period after crop planting in Figure 6. The amount of N in grain and straw harvested in the L, control, and LS treatments corresponded to about 183, 179, and 154 kg N ha^{-1}, respectively. Differences in N removal were also reflected by grain yields (L > control > LS).

Accumulated N_2O emissions were very low (0.04–0.07 kg N ha^{-1}), and there were no differences between treatments (Table 3). These low N_2O emissions were presumably due to soil moisture conditions, which differ between lysimeters and field applications. When a lysimeter is detached from groundwater, capillary rise is hampered, which probably resulted in relatively dry subsoil conditions and, thus, low production of N_2O through denitrification.

The sum of outputs in the N balance over the 21-mo period was 328 kg N in the L treatment and around 228 kg N in the LS treatment. The N balance between input and output of the crop–soil system was negative for all treatments; it ranged from −120 kg N ha^{-1} in the LS treatment to −264 kg N ha^{-1} in the control caused by crop removal and N leaching losses over the 21 mo (Table 3). The corresponding data for the 11 mo after crop planting were −195 and −172 kg N ha^{-1} for the control and L treatments, respectively (Figure 6). Based on these data, around 100 kg N (difference between L and LS treatments) was probably immobilized over the 21 mo by straw addition, assuming that gaseous N losses did not differ between these treatments (as indicated by similar N_2O emissions) (Table 3). Immobilization for the 11 mo after crop planting was still about 97 kg N (Figure 6).

4 | CONCLUSIONS

The results obtained in this 21-mo lysimeter study showed that loosening with straw incorporation into subsoil appeared to be an environmentally friendly farming method because it has the potential to reduce N leaching. Nitrogen leaching was the dominant process of losses compared with N_2O emissions. Subsoil treatments did not affect N_2O emissions, and N balance calculations revealed that the loosening with straw treatment resulted in the lowest N losses. Hence, loosening with straw incorporation could be used to combat N leaching in the short term. However, it is not possible to draw

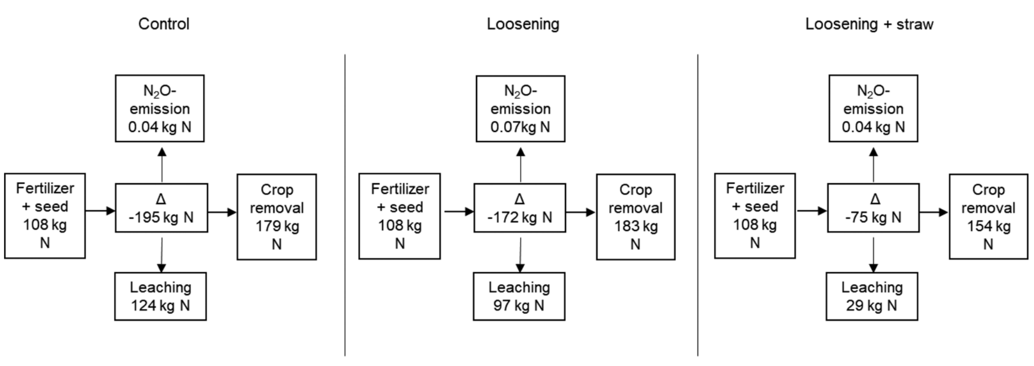

FIGURE 6 Nitrogen balance for the soil–crop system for the 11 mo after crop planting, using the difference between inputs and outputs. Inputs are N additions (fertilizer and seeds); outputs are N removal and losses (harvest, leaching, and N_2O emissions).

conclusions from this short-term study about the long-term effect of loosening with straw incorporation on crop performance and N cycling, which must be verified in long-term field studies.

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AUTHOR CONTRIBUTIONS

Gizachew Tarekegn Getahun, Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing-original draft, Writing-review & editing; Lars Bergström, Conceptualization, Formal analysis, Methodology, Supervision, Writing-review & editing; Katrin Rychel, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing-review & editing; Thomas Kätterer, Methodology, Supervision, Writing-review & editing; Holger Kirchmann, Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

Bergström, L. (1987). Nitrate leaching and drainage from annual and perennial crops in tile-drained plots and lysimeters. *Journal of Environmental Quality*, *16*, 11–18. https://doi.org/10.2134/jeq1987.00472425001600010003x

Bergström, L. (1990). Use of lysimeters to estimate leaching of pesticides in agricultural soils. *Environmental Pollution*, *67*, 325–347. https://doi.org/10.1016/0269-7491(90)90070-S

Bergström, L., & Johansson, R. (1991). Leaching of nitrate from monolith lysimeters of different types of agricultural soils. *Journal of Environmental Quality*, *20*(4), 801–807. https://doi.org/10.2134/jeq1991.00472425002000040015x

Bergström, L., & Kirchmann, H. (1999). Leaching of total nitrogen from nitrogen-15-labeled poultry manure and inorganic nitrogen fertilizer. *Journal of Environmental Quality*, *28*, 1283–1290. https://doi.org/10.2134/jeq1999.00472425002800040032x

Bergström, L., & Kirchmann, H. (2004). Leaching and crop uptake of nitrogen from nitrogen-15-labeled green manures and ammonium nitrate. *Journal of Environmental Quality*, *33*, 1786–1792. https://doi.org/10.2134/jeq2004.1786

Botta, G. F., Jorajuria, D., Balbuena, R., Ressia, M., Ferrero, C., Rosatto, H., & Tourn, M. (2006). Deep tillage and traffic effects on subsoil compaction and sunflower (*Helianthus annus* L.) yields. *Soil & Tillage Research*, *91*, 164–172. https://doi.org/10.1016/j.still.2005.12.011

Christian, D. G., & Bacon, E. T. G. (1991). The effects of straw disposal and depth of cultivation on the growth, nutrient-uptake and yield of winter-wheat on a clay and a silt soil. *Soil Use and Management*, *7*, 217–222. https://doi.org/10.1111/j.1475-2743.1991.tb00877.x

Elliott, L., Cochran, V., & Papendick, R. (1981). Wheat residue and nitrogen placement effects on wheat growth in the greenhouse. *Soil Science*, *131*(1), 48–52.

Fageria, N. K. (2014). Nitrogen harvest index and its association with crop yields. *Journal of Plant Nutrition*, *37*(6), 795–810. https://doi.org/10.1080/01904167.2014.881855

FAO. (2015). *World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps. World soil resource reports no. 106*. FAO. http://www.fao.org/publications/card/en/c/942e424c-85a9-411d-a739-22d5f8b6cc41/

Francis, G. S., Haynes, R. J., Sparling, G. P., Ross, D. J., & Williams, P. H. (1992). Nitrogen mineralization, nitrate leaching and crop growth following cultivation of a temporary leguminous pasture in autumn and winter. *Fertilizer Research*, *33*, 59–70. https://doi.org/10.1007/Bf01058010

FussR. (2019). *gasfluxes: Greenhouse gas flux calculation from chamber measurements. R package version 0.4-2*. https://CRAN.R-project.org/package=gasfluxes

Getahun, G. T., Katterer, T., Munkholm, L. J., Parvage, M. M., Keller, T., Rychel, K., & Kirchmann, H. (2018). Short-term effects of loosening and incorporation of straw slurry into the upper subsoil on soil physical properties and crop yield. *Soil & Tillage Research*, *184*, 62–67. https://doi.org/10.1016/j.still.2018.06.007

Gill, J. S., Sale, P. W. G., & Tang, C. (2008). Amelioration of dense sodic subsoil using organic amendments increases wheat yield more than using gypsum in a high rainfall zone of southern Australia. *Field Crops Research*, *107*, 265–275. https://doi.org/10.1016/j.fcr.2008.02.014

Hamza, M. A., & Anderson, W. K. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil & Tillage Research*, *82*, 121–145. https://doi.org/10.1016/j.still.2004.08.009

Hay, R. K. M. (1995). Harvest index: A review of its use in plant breeding and crop physiology. *Annals of Applied Biology*, *126*, 197–216. https://doi.org/10.1111/j.1744-7348.1995.tb05015.x

Huang, Y., Zou, J. W., Zheng, X. H., Wang, Y. S., & Xu, X. K. (2004). Nitrous oxide emissions as influenced by amendment of plant residues with different C:N ratios. *Soil Biology & Biochemistry*, *36*, 973–981. https://doi.org/10.1016/j.soilbio.2004.02.009

ISO. (2013). *Water quality—Determination of selected parameters by discrete analysis systems—Part 1: Ammonium, nitrate, nitrite, chloride, orthophosphate, sulfate and silicate with photometric detection* (ISO 15923-1:2013). https://www.iso.org/standard/55559.html

Jakobs, I., Schmittmann, O., & Schulze Lammers, P. (2017). Short-term effects of in-row subsoiling and simultaneous admixing of organic material on growth of spring barley (*H. vulgare*). *Soil Use Management*, *33*, 620–630. https://doi.org/10.1111/sum.12378

Jarvis, S., Barraclough, D., Unwin, R., & Royle, S. (1989). Nitrate leaching from grazed grassland and after straw incorporation in arable soils. In J. C. Germon (Ed.), *Management system to reduce impact of nitrates* (pp. 110–125). Elsevier Applied Science.

Jenkyn, J. F., Christian, D. G., Bacon, E. T. G., Gutteridge, R. J., & Todd, A. D. (2001). Effects of incorporating different amounts of straw on growth, diseases and yield of consecutive crops of winter wheat grown on contrasting soil types. *Journal of Agricultural Science*, *136*, 1–14. https://doi.org/10.1017/S0021859600008558

Kautz, T., Amelung, W., Ewert, F., Gaiser, T., Horn, R., Jahn, R., Javaux, M., Kemna, A., Kuzyakov, Y., Munch, J. -C., Pätzold, S., Peth, S., Scherer, H. W., Schloter, M., Schneider, H., Vanderborght, J., Vetterlein, D., Walter, A., Wiesenberg, G. L. B., & Kopke, U. (2013). Nutrient acquisition from arable subsoils in temperate climates: A review. *Soil Biology & Biochemistry*, *57*, 1003–1022. https://doi.org/10.1016/j.soilbio.2012.09.014

Larney, F., & Fortune, R. (1986). Recompaction effects of mouldboard ploughing and seedbed cultivations on four deep loosened soils. *Soil & Tillage Research*, *8*, 77–87. https://doi.org/10.1016/0167-1987(86)90324-7

Leskiw, L. A., Welsh, C. M., & Zeleke, T. B. (2012). Effect of subsoiling and injection of pelletized organic matter on soil quality and productivity. *Canadian Journal of Soil Science*, *92*, 269–276. https://doi.org/10.4141/Cjss2011-003

Liu, C., Wang, K., Meng, S., Zheng, X., Zhou, Z., Han, S., Chen, D., & Yang, Z. (2011). Effects of irrigation, fertilization and crop straw management on nitrous oxide and nitric oxide emissions from a wheat–maize rotation field in northern China. *Agriculture Ecosystem and Environment*, *140*, 226–233. https://doi.org/10.1016/j.agee.2010.12.009

Liu, P., He, J., Li, H. W., Wang, Q. J., Lu, C. Y., Zheng, K., Liu, W., Zhao, H., & Lou, S. Y. (2019). Effect of straw retention on crop yield, soil properties, water use efficiency and greenhouse gas emission in China: A meta-analysis. *International Journal of Plant Production*, *13*, 347–367. https://doi.org/10.1007/s42106-019-00060-w

Machet, J., & Mary, B. (1989). Impact of agricultural practises on residual N in soil and nitrate losses. In J. C. Germon (Ed.), *Management system to reduce impact of nitrates* (pp. 126–146). Elsevier Applied Science.

Meissner, R., Seeger, J., & Rupp, H. (1998). Measuring environmental impacts of land use changes on water quality with lysimeters. In F. Führ, R. J. Hance, J. R. Plimmer, & J. O. Nelson (Eds.), *Symposium of the 213th National Meeting of the American Chemical Society, San Francisco, California: The lysimeter concept: Environmental behavior of pesticides* (pp. 163–176). American Chemical Society.

Nicholson, F. A., Chambers, B. J., Mills, A. R., & Strachan, P. J. (1997). Effects of repeated straw incorporation on crop fertilizer nitrogen requirements, soil mineral nitrogen and nitrate leaching losses. *Soil Use Management*, *13*, 136–142. https://doi.org/10.1111/j.1475-2743.1997.tb00574.x

Persson, L., & Bergstrom, L. (1991). Drilling method for collection of undisturbed soil monoliths. *Soil Science Society of America Journal*, *55*, 285–287. https://doi.org/10.2136/sssaj1991.03615995005500010050x

Powlson, D. S., Jenkinson, D. S., Pruden, G., & Johnston, A. E. (1985). The effect of straw incorporation on the uptake of nitrogen by winter wheat. *Journal of the Science of Food and Agriculture*, *36*, 26–30. https://doi.org/10.1002/jsfa.2740360105

Przulj, N., & Momcilovic, V. (2003). Dry matter and nitrogen accumulation and use in spring barley. *Plant Soil and Environment*, *49*, 36–47. https://doi.org/10.17221/4087-Pse

R Core Team. (2020). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. https://www.R-project.org/

Rengasamy, P., Chittleborough, D., & Helyar, K. (2003). Root-zone constraints and plant-based solutions for dryland salinity. *Plant and Soil*, *257*, 249–260. https://doi.org/10.1023/A:1027326424022

Sainju, U. M. (2017). Determination of nitrogen balance in agroecosystems. *MethodsX*, *4*, 199–208. https://doi.org/10.1016/j.mex.2017.06.001

Silgram, M., & Chambers, B. J. (2002). Effects of long-term straw management and fertilizer nitrogen additions on soil nitrogen supply and crop yields at two sites in eastern England. *Journal of Agricultural Science*, *139*, 115–127. https://doi.org/10.1017/S0021859602002435

Van Donk, S., Martin, D. L., Irmak, S., Melvin, S. R., Petersen, J., & Davison, D. (2010). Crop residue cover effects on evaporation, soil water content, and yield of deficit-irrigated corn in west-central Nebraska. *Transactions of the ASABE*, *53*, 1787–1797.

Zadoks, J. C., Chang, T. T., & Konzak, C. F. (1974). A decimal code for the growth stages of cereals. *Weed Research*, *14*, 415–421. https://doi.org/10.1111/j.1365-3180.1974.tb01084.x

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