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Winter Wheat Performance Following One-time High Rates of Compost and Annual Cover Crop Planting in Wheat-fallow Rotations

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Authors' contributions

This work was carried out in collaboration among all authors. All authors contributed to the conception and design of this research. Research data collection and analyses were performed by author MBB. The first draft of the manuscript was prepared by author MBB and all authors reviewed previous versions of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Aims: One-time high rates of compost were applied at 15, 30, and 45 Mg ha^{-1} to improve soil organic matter (SOM) and fertility in dryland organic winter wheat-fallow rotations. Cover crop mixtures (oats and Austrian winter peas) were planted in fallow phases annually to suppress weeds and reduce repetitive tillage used for weed control because the latter breaks down SOM.
Study Design: The experiment was laid-out in a split-plot design with four replications. Fertilizer (compost rates, inorganic fertilizer and no amendment control) and cover crops served as main and sub-plot factors respectively.
Place and Duration of Study: The experiment was conducted at the Sustainable Agriculture Research and Extension Center, University of Wyoming, from September 2015 to August 2018.
Methodology: Soil samples, weed biomass, wheat yield and protein quality data were collected and analyzed over three years.

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Results: Results indicated that 45 Mg ha^{-1} compost increased (*P=.05*) soil total carbon (TC) and nitrogen (TN) concentrations up to 25 and 19% respectively, in the last two years. Wheat yield was not affected (p>0.05) by compost or cover crops in any growing season but 45 Mg ha^{-1} compost increased (*P=.05*) protein quality by 2-9% in the first growing season. Cover crops suppressed weeds while growing in the first growing season but had varying effects on weeds in wheat phases that followed them in rotation. It was noted that soil electrical conductivity levels affected by 45 Mg ha^{-1} compost was 5 times lower than wheat thresholds; and soil moisture loss by cover crops did not affect wheat yield.

Conclusion: 45 Mg ha^{-1} compost improves soil fertility and SOM in the short term. However, significant reflection of soil changes in wheat yield may take longer time. Further research is needed to effectively integrate cover crops as a weed control measure in dryland organic wheat-fallow rotations.

Keywords: Dryland organic farming; crop rotation; soil organic matter; soil nitrogen; wheat yield; wheat protein; weed management.

1. INTRODUCTION

An increasing number of winter wheat (*Triticum aestivum*, L.) farmers in South-eastern Wyoming are transitioning to organic certification. This transition is driven by better economic premiums on organic produce compared to convetional ones. However, sustainable dryland organic winter wheat production is threatened by the little precipitation amount received (300 mm/ year) annually and the need to control weeds with repetitive tillage (since there are limited effective organic herbicides options) [1]. These conditions cause significant soil organic matter (SOM) breakdown and loss. SOM loss is a significant pathway for the loss of soil carbon (C) and nitrogen (N) and other nutrients which have dire consequences for wheat growth, yield and protein quality.The amount of precipitation received in Wyoming dictates that farmers practice a wheat-fallow rotation (15 month long fallow) to retain soil moisture in the agroecosystem [2]. On average, the fallow phase receives 6 passes of tillage to keep weeds abated while the wheat phase could be helplessly infested with weeds. [3] have observed 3-34.4% wheat yield losses due to weeds, across the United States. This challenge is exacerbated by no/low nutrient input practiced by farmers, which support little biomass production and residue addition to the soil.

For a state like Wyoming which produces lots of cattle [4], it would be assumed that organic farmers had abundant sources of feedlot cattle manure for application. However, over the years, farmers have plied the low manure input route to avoid the anecdotal perception that frequent applications (about every 3-4 years) of 10-15 Mg ha^{-1} increases soil salinity which defeats the purpose for which manure is applied. High soil salinity (15 dS m^{-1}) has been found to cause up to about 58% wheat yield losses compared to non-saline (0.33 dS m^{-1}) soils [5]. Applying small amounts of organic amendments in such rapid C loss environment also causes rapid SOM decline.Without an active SOM management program to improve the soil conditions, farmers risk losing their organic certifications [6].

The solution(s) to these problems would be an organic amendment strategy that has the ability to rapidly build SOM, hold nutrients and moisture longer in the soil and influence large biomass production which could be recycled into the soil. The application rates of this amendment should be such that it reduces the risk of soil salinity. Also, a management strategy which reduces weed proliferation and reduces the need to frequently control weeds with tillage should be adopted. The manure available to these farmers could harbor weed seeds and worsen the problem of weed infestation if applied directly. Hence, composting the manure offers a better alternative to meet crop neesds. The heat of composting kills most weed seeds and plant pathogens [7] and makes the amendment relatively safe to apply. Moreover, compost has more stable organic nitrogen forms [8] that decreases the risk of nitrogen runoff and leaching into groundwater.

There is limited information on the amounts and frequency at which compost should be applied to meet all three soil needs: building SOM., avoiding the problem of soil salinity build-up and supplying the required nutrients to crops. In Utah, a state with soil and climatic conditions comparable to Wyoming, [9] observed significant increases in soil organic carbon (C), nitrogen (N), microbial biomass, enzyme activity (dehydrogenase, acid, and alkaline phosphatase), plant-available phosphorus (P), and potassium (K) sixteen years after a one-time application of 50 Mg ha $^{-1}$ compost (50 Mg ha^{-1} compost matched to 0.5 Mg ha^{-1} gains in wheat yield every two years). Current research suggests that a one-time high rate of compost has increased winter wheat yield and protein quality over longer periods in other locations in the Central High Plains [10,11]), but such applications have not yet been tested in Wyoming. Residual effect of compost has been attributed to the soil and wheat benefits several years after a one-time application. While data is limited for real time carry-over effects of one-time high rate compost application for soils in South-eastern Wyoming, research observations in other locations are indications that such effects may be considerably longer in drylands [10,12] showed residual benefits of a single application of biosolids to a semi-arid grassland, 14 years after application. It would be a big breakthrough if such long-term soil benefits of a one-time compost application could be replicated in Wyoming. Hence this research sought to test the benefits of applying large rates of a one-time compost application over a 3-year duration in a dryland winter wheat system in Wyoming.

For such strict organic input adherence and the potential of increasing weed infestation with high rate compost application, planting cover crops in the fallow phase following compost application could provide a better weed control measure in the wheat phases that follow them in rotation. Cover crops may out-compete weeds and break the weed cycle [13], reducing the need for frequent tillage and further SOM breakdown. Leguminous cover crops in the fallow is an excellent source of N to the subsequent wheat crops if it is ploughed back into the soil . Ploughing cover crops back into the soil may also prolong the legacy of compost in building SOM [14]. To effectively outcompete weeds, legumes could be mixed with grasses like oats or rye for fast establishement and nutrient balances [15]. However, the inclusion of deep rooted leguminous cover crops may deplete soil moisture in the spring and present moisture stresses for the subsequent wheat crops [16]. Varying cover crop mixtures of *Pisum sativum* L. (winter pea), *Trifolium alexandrinum* (berseem clover), *Melilotus officinalis* (yellow sweet clover), *Raphanus sativus* var. oleiformis (forage raddish), *Lens culinaris* (lentils), *Hordeum volgare* L. (winter barley), *Secale cereale* (winter rye), *Vicia villosa* (hairy vetch), *Brassica campestris ssp. rapifera* (winfred turnip) and *Brassica napus* (winter canola) reduced soil moisture by 10 mm per 1000 kg ha^{-1} cover crop biomass resulting in 13 to 78% wheat yield loss in the Colorado Plateau [17]. [11] also observed about 50% loss in wheat yield due to soil moisture loss influenced by cover crops. In water-limited environments like Wyoming, *Pisum sativum ssp. arvense* (Austrian winter pea), a shallow rooted and cool season legume has been proposed for fallow cover cropping [18] in order to reduce water shortage for subsequent wheat. For a faster ground cover, oats has also been recommended [19] to be mixed with Austrian winter pea. Though cover crops take up soil nutrients to build up biomass, it is expected that nutrients will be returned to the soil after their incorporation and decomposition as demonstrated by [20] and [21]. These nutrients would otherwise be taken up by weeds and/or offloaded from the site through various loss pathways.

The objective of this study was to improve soil carbon and nitrogen (organic matter) and dryland organic winter wheat yield and protein quality through compost application and to control weeds by integrating cover crops in the wheat-fallow rotations. The authors sought to identify the compost rate that best responded to the above objective.

2. MATERIALS AND METHODS

2.1 Study Site

The study was conducted from September 2015 to August 2018 at the University of Wyoming's James C. Hageman Sustainable Agriculture and Research Extension Center (SAREC) near Lingle - Wyoming (42º 7'15" N, 104º 23' 13" W; 1276 m above sea level). The site is located on a gently rolling upland with a < 3% (1.71°) slope. The soil has sandy clay loam texture (loamy, mixed, active, mesic Ustic Torriorthent) with slightly alkaline soil pH and < 1% SOM content [22]. The area experiences a semi-arid climate with a wide variation in mean monthly air temperature ranging from -11.4ºC in December to 32ºC in July with 125 average frost-free days in a year. The average precipitation amount for the past 30 years is 398 ± 0.06 mm (Western Regional Climate Center). The observed precipitation and temperature data of the research period were compared (Fig. 1) with the thirty-year averages in this study.

2.2 Experimental Design

The experiment was a split-plot design with four replications. There were a total of 10 plots in a block, each measuring 9 meters long and 5.5 meters wide and separated by 4.6 meters wide border alleys. Global positioning system (GPS) coordinates were taken after field mapping and plot designations. The system was a wheat-fallow rotation with about 15 month long fallow.

2.3.1 Treatments

The treatments included fertilizer (main plot factor):15, 30, and 45 Mg ha $^{-1}$ on dry weight basis, the full rate of inorganic fertilizer (IF) and a no amendment control. The sub-plot factor was presence or absence of cover crops in the fallow phases. A mixture of cover crops [Oats (*Avena sativa*) and Austrian winter peas (*Pisum sativum*)] was planted in one-half of the fallow, while the other half was left bare.

2.3.1.1 Treatment application

The fertilizer treatments (compost rates and inorganic fertilizer) were applied once in both wheat and fallow phases just before wheat seeding in September 2015, using a compost spreader. It was then raked in to about 5 cm depth. The IF was broadcasted once in the wheat phases in April 2016. After harvest of the 2015 yield, wheat and fallow phases flipped places in the rotation and the IF was applied in the previous fallow phase (now wheat phase) in October 2016 (because IF was not applied in the previous fallow in order not to waste it). A cover crop mixture consisting of 56 kg ha^{-1} Austrian winter pea (*Pisum sativum* subsp. arvense) and 28 kg ha^{-1} oats (*Avena sativa*) was seeded in May 2016, 2017 and 2018 when the snow cover was rapidly thawing and terminated in June 2016, 2017 and 2018, just before flowering.

Based on the N and phosphorus (P) contents of the compost (Table 1) and the assumption that only 11% of compost-derived N is mineralized during the first growing season in temperate drylands [23], compost treatments supplied 15, 30, and 45 kg N ha^{-1} and 0.06, 0.12, and 0.18 kg P ha $^{-1}$, respectively. Inorganic fertilizer (IF) consisted of a mixture of 90 kg ha^{-1} monoammonium phosphate ($NH_4H_2PO_4$; commonly called MAP) and 120 kg ha^{-1} ammonium sulfate [NH_4 $(SO_4)_2$], which supplied 34 kg N ha^{-1} and 19.7 kg P ha^{-1}. The compost was obtained from Jodie Booth's compost in Torrington.

2.3 Wheat and Cover Crop Planting and Wheat Harvest

Goodstreak winter wheat (*Triticum aestivum* L.) variety (JD 9300) was planted in September 2015, 2016 and 2017 at a rate of 62 kg ha^{-1}. A half of each fallow phase was planted to the cover crop mixture in May 2016, 2017 and 2018 when the snow cover was rapidly thawing. They were terminated in June 2016, 2017 and 2018, just before flowering. Cover crops were incorporated to about 5 cm depth in their plots with a rake. Halves of the fallow phases not planted to cover crops were subjected to tillage to control weeds when needed. A tillage operation included running a disc plough (sunflower fallow king, a blade machine that has twenty-six-inch-wide sweeps, and then one more in front of the drill) to a 12 cm soil depth. Wheat harvesting was done with a plot combine harvester of 5 feet width in July 2016, July 2016, and August 2018. Plots were demarcated with spray paint before harvest and the plot combine ran through the middle of each plot. *(The growing period from September 2015 to July 2016 is refered to as the 'first growing season', September 2016 to July 2017 as the 'second growing season' and September 2017 to August 2018 as 'third growing season').*

2.4 Soil Sampling and Analyses

Prior to compost application, compost and soil were characterized by laboratory tests. Four soil cores were collected at 0-10 cm depth from each plot, using a soil corer. Ths soil was stored in a cooler with ice, and transported to the University of Wyoming for prepping and analyses. They were composited and analyzed for gravimetric moisture content [24,25], soil texture using particle size distribution , bulk density [26], electrical conductivity, and soil pH (1:1 soil: water ratio) [27], total C and N and inorganic C (Sherrod et al., 2002) [28], Olsen P [29], potentially mineralizable nitrogen (PMN) [30] and total organic C and N (TOC/N). Total organic C and N values were obtained by subtracting inorganic C and N values from total C and N values respectively. Table 1 shows the properties of the compost and soil before application of treatments.

Table 1. Physico-chemical properties of compost and soil before compost application

Properties	Compost	Soil
Moisture (%)	1.97	3.8
Texture	Not determined	Silty clay loam
pH (1:1 soil: water ratio)	8.46	7.80
Bulk density (g cm^{-3})	0.98	1.37
Total N (%)	0.9	0.17
Total C (%)	8.57	1.84
TOC (%)	7.63	1.35
IC (g kg^{-1})	9.38	4.96
PMN (mg kg^{-1})	68.2	21.1
Olsen P (mg kg^{-1})	36.2	23.5

C:N ratio of compost = 9.6

2.4.1 Routine soil sampling and analyses

Routine soil sampling started in May 2016. Four soil samples were collected randomly from each plot every two weeks during the active growing period of a growing season (May to July) and once every month during snow cover (October to April) at 0-15 cm depth using a soil corer. The samples were analyzed for total carbon and nitrogen. Soil pH and EC measurements were made in the middle of the spring of every growing season.

2.5 Vegetation Sampling

Weed biomass data was collected using two quadrats (each measuring 30 cm square) placed randomly at the center of each plot. All the plants in the quadrat were cut at the root level, oven-dried at 60ºC for two days, and weighed. Sampling was done twice in every growing season (at two weeks interval) in June 2016, July 2017, and June 2018.

Wheat biomass was assessed during wheat harvest using the same method used in weed biomass assessment. It was assessed three times in a groing season (May, June and July).

Wheat grain yield and grain moisture for each plot were determined by an automated recorder in the plot combine harvester. A grain sub-sample from each plot was oven-dried at 60ºC for two days to determine the dry weight and protein concentration using the protein determination method developed by the American Association of Cereal Chemists (AACC) International.

2.6 Statistical Analyses

Soil moisture, electrical conductivity, total carbon and nitrogen data and weed data were averaged across growing seasons. The data were subjected to analysis of variance (ANOVA) using Statistical Analysis System (SAS, Enterprise, Cary, North Carolina, USA). For 2016 data, the model tested the effect of compost on the measured soil and plant parameters in both wheat and fallow phases separately. For 2017 and 2018 data, the model tested the effects of compost and previous fallow structure (whether fallow was palnted to cover crops or not) on the soil and plant parameters measured in the wheat phase. The same model tested for effect of compost and cover crops on the measured soil and plant parameters in the fallow phases in 2017 and 2018. Fischer's protected least significant difference (LSD) was used to separate significant means at 5% probability.

3. RESULTS AND DISCUSSION

3.1 Weather

Fig. 1 shows the average monthly precipitation and temperatures from May, 2016 to September 2018, representing a part of the first growing season (May – August 2016), the second growing season (September 2016 to August 2017) and the third growing season (September 2017 to August, 2018). Average monthly temperature during the study ranged from -2.4^{o}C to 28^{o}C with December, January and February being the coldest months and July and August being the warmest months (Fig. 1). The months with the highest rainfall reception were July in the first growing season, May in the second and June in the third seasons, while the driest months were in September, October, November and March. The average monthly precipitation (Fig. 1) depicts that of normal precipitation years in Wyoming without drought https://www.usclimatedata.com/climate/lingle/wyoming/unitedstates/uswy0245) . The temperature range was favorable for winter wheat growth.

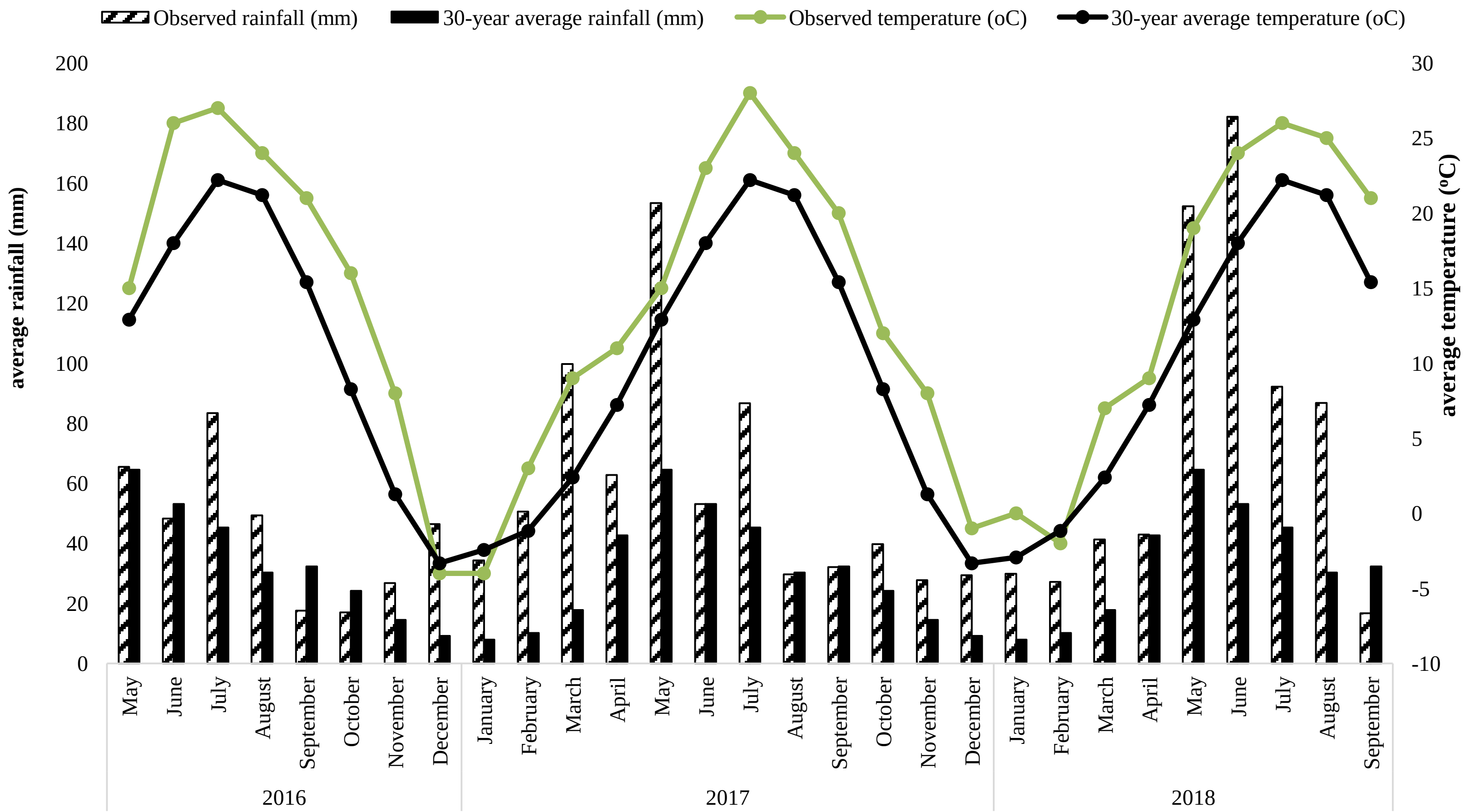

Fig. 1. Observed average monthly precipitation and average air temperatures between May 2016 and September 2018 versus 30-year averages. https://www.worldweatheronline.com/torrington-weather-averages/wyoming/us.aspx

3.2 Soil Electrical Conductivity in Wheat and Fallow Phases

Fertilizer treatments alone significantly affected (P = .03) soil EC in the wheat phase of the first growing season. In this growing season, wheat phases amended with 30 and 45 Mg ha^{-1} compost had the highest ECs of 417 and 399 µS cm^{-1},which were 16 to 21% more than ECs affected by 15 Mg ha^{-1}, the control and IF (Table 2). The 45 Mg ha^{-1} compost significantly (P < 0.010) affected the highest EC (696 µS cm^{-1}) in the fallow phases of the first growing season, between 31 to 47% more than 15 and 30 Mg ha^{-1} and the no amendment control (Table 2). The previous cover crop treatment in the fallow phase of the first growing season also significantly increased soil EC by 15% in the wheat phase of the second growing season that followed in the rotation (Table 3). These findings may have been the result of high soluble salt concentrations affected by the two largest compost rates (45 and 30 Mg ha^{-1}) in the wheat phase and the incorporated cover crops in the fallow phase. [31] demonstrated increases in soluble salt concentration of soil with high rate compost applications.

The fallow phases of the second growing season, on average, had 32% less soil EC than the wheat phases (of the first growing season) they followed. A similar decline was observed when the wheat phase of the second growing season followed the fallow of the first in rotation. Soil EC affected by the 45 and 30 Mg ha^{-1} compost generally reduced with time as the rotations continued, such that the least ECs which were comparable to each other were observed in the third growing season. This is indication that soil salinity may not persist with a one-time high rate compost application compared to frequent short interval applications.

Generally, the EC increases observed from 30 and 45 Mg ha^{-1} compost in this study were over 5 times lower than the soil EC threshold (3400 to 4300 µS cm^{-1}) that restrains winter wheat growth [32] and hence had no detrimental effect on wheat yield.

3.3 Soil Moisture in the Fallow and Wheat Phases

The amendments alone did not affect soil moisture in the fallow phase of the first growing seasons nor the wheat phases that followed the fallows in the second and third growing seasons. However, cover crops alone significantly (P = 0.005) reduced soil moisture by 16% in the fallow phase of the first growing season, compared to parts of the fallow phases where there were no cover crops (Table 4). Water is a physiological need of every plant, including cover crops [33] and as expected, cover crops used up soil moisture when they were growing in the fallow in the first growing season causing the observed reduction in soil moisture (Table 4). This finding confirms the report of [17] who observed a 10 mm loss of soil moisture per 1000 kg ha^{-1} cover crop biomass produced in a wheat-fallow rotation in the Colorado Plateau.

The wheat phase of the second growing season generally had 39% lower soil moisture compared to fallow phases. Compared to wheat phases that followed bare fallow (other half with no cover crops), wheat phases that followed cover crops had 19% (P = 0.01) less soil moisture (Table 4).

Table 2. Effect of one-time application of fertilizer (control, 15, 30, and 45 Mg ha^{-1} compost and inorganic fertilizer) and annual cover crops planting and incorporation in the fallow phase or residual cover crop effect in the wheat phase on soil electrical conductivity (µS cm^{-1}) during the first and second growing seasons. Different lower-case letters attached to treatment means represent the differences in the means

Treatments	First growing season		Second growing season	
	Wheat phase	Fallow phase	Wheat phase	Fallow phase
control	328 (b)	368 (c)	334 (b)	228 (b)
15 Mg ha^{-1}	355 (b)	480 (b)	322 (b)	239 (b)
30 Mg ha^{-1}	417 (a)	486 (b)	401 (ab)	270 (a)
45 Mg ha^{-1}	399 (a)	696 (a)	477 (a)	277 (a)
IF	351 (b)	NA	311 (c)	238 (b)

Table 3. Effect of the previous cover crops planting and incorporation in the fallow phase of the first growing season on the soil electrical conductivity (µS cm $^{-1}$) of the wheat phase of the second growing season. Different lower-case letters attached to treatment means represent the differences in the means

Treatment	Wheat phase of second growing saeson
Cover crops in preceeding fallow	399 (a)
No cover crops in preceeding fallow	339 (b)

However, previous cover crops in the fallow had no effect on the soil moisture of the wheat phase of the third growing season. The further decline in soil moisture in the wheat phase of the second growing season is an effect of water use by the growing wheat plants.It could be inferred from the study that factors other than previous cover crops, controlled soil moisture loss in the wheat phase considering the inconsistency of previous cover crop effect in the second and third growing seasons. Furthermore, the cover crops did not affect wheat yield succeeding the fallows in rotation , hence any reduction in the yield could not be attributed to the loss in soil moisture associated with cover crops. The precipitation amounts (Fig. 1) received during the wheat growing periods may have covered up for the cover crop soil moisture loss.[34] observed that two out of four experiments, cover crops did not affect corn yield but reduced yield in the other two in Iowa State, and attributed the varying cover crop effects on yield to specific cover-crop cultivar interactions and not necessarily a reduction in soil moisture linked with cover crops. [35] had similar findings and explained that the effect of a preceding cover crop on the yield of the main crop may be an artefact of cover crop effect on soil biology and not just their effect on soil moisture or nutrient concentrations.

3.4 Soil Total Carbon and Nitrogen in the Wheat Phase

Soil TC/TN was not significantly affected by the fertilizer treatments alone in the wheat phase in the first growing season. Cover crops alone in the preceding fallow also did not affect soil TC/ N in the wheat phases of all three growing seasons. The inability of the compost rates to affect soil TC and TN in the wheat phase of the first growing season confirms that compost mineralization and nutrient supply is slow as reported by [36] and may not make significant contributions to soil nutrients in the first year of application. This finding is especially true for colder regions (Fig. 1) where compost mineralization rate is slowed by the prolonged cold temperatures (Fig. 1). [37] also reported slower nutrient release rates under lower (15^{o}C) temperature than a higher one (25^{o}C). The inability of cover crops to affect soil TC and TN in both fallow and wheat phases is consistent with the findings of [38] who concluded after five years of evaluating the effect of cover cropping in a winter wheat-fallow rotation in a semiarid region, that cover crops did not affect soil profile C and N contents. However, the fact that cover crops did not reduce soil TC and TN in the succeeding wheat phases is indication that nutrients taken up to build biomass during cover crop growth were at least returned at some point during the decomposition process, after incorporation, with no net gain. As a result, cover crops had no negative effect on soil TC and TN concentrations and consequent SOM content.

However, in the second growing season, the 45 Mg ha^{-1} compost significantly increased (P = 0.004) soil TC between 10-19% more than the lower compost rates and the IF (Fig. 2A), and soil TN, 13-25% more (P =0.02) than the lower 0, 15 Mg ha^{-1} compost rates and IF (Fig. 2B). Inorganic fertilizer affected the least soil TC (1.49%) which was comparable with that of the control and 15 Mg ha^{-1} compost in the second growing season. In the third growing season, the 45 Mg ha^{-1} still recorded the highest (P = 0.003) soil TC and TN which were between 10-17% and up to 20% more than the Soil TC/TN affected by the other amendments respectively (Fig. 2A&B). By the second and third growing seasons, compost decomposition had advanced to levels where a distinction could be made between the increasing compost rates according to the amounts of carbon and nitrogen supplied by them hence the observed differences in the amendments in these growing seasons compared to the first. All the compost rates supplied some amount of organic carbon and nitrogen to the soil judging from its phisico-chemical analyses (Table 1), however, by sheer quantity, it is logical that the 45 Mg ha^{-1} compost would supply and affect the highest soil TC and TN in the second and third wheat growing seasons (Fig. 2A and B).

Table 4. Effect of one-time application of fertilizer treatments (control, 15, 30, and 45 Mg ha^{-1} compost and inorganic fertilizer) and annual cover crops planting and incorporation in the fallow phase or residual cover crop effect in the wheat phase on average soil moisture (%) during the first, second and third growing seasons. Different lower-case letters attached to treatment means represent the differences in the means. Numbers after the ± are standard errors of the means

First growing season fallow phase		Second growing season wheat phase	
Cover crops	13.28 ± 0.26$_{(b)}$	Cover crops in preceding fallow	7.94 ± 0.53 $_{(b)}$
No cover crops	15.83 ± 0.53$_{(a)}$	No cover crops in preceding fallow	9.75 ± 0.51 $_{(a)}$
Mean seasonal moisture	14.56 ± 0.39		8.84 ± 0.52

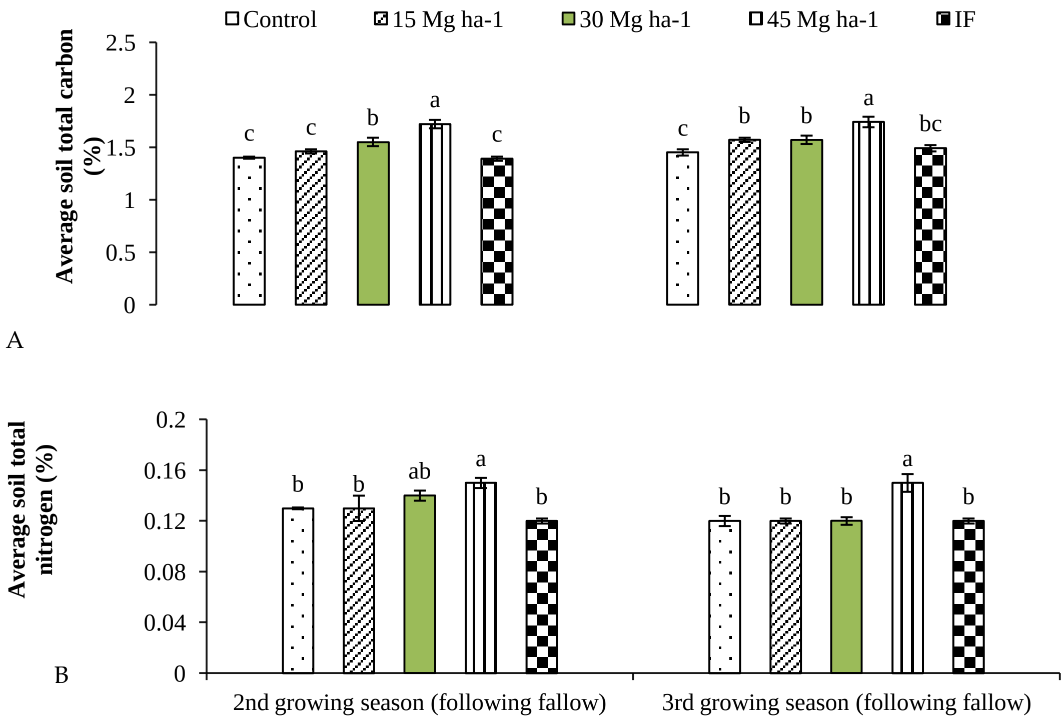

Fig. 2. Average soil total carbon, A (%) and total nitrogen, B (%) in the wheat phases of the second and third growing seasons, following fallow phases after one-time application of fertilizer treatments (control, 15, 30 and 45 Mg ha^{-1} compost and inorganic fertilizer) in the first growing season and annual cover crops planting and incorporation in the fallow phases. Error bars represent standard errors of the mean. Different lower-case letters (on top of bars) represent the differences in means

3.4.1 Wheat biomass, yield and protein quality

The applied fertilizer treatments alone significantly (P = 0.003) affected wheat biomass in the first growing season with the 45 Mg ha^{-1} compost influencing the highest (6031.7 kg ha^{-1}) between 16% to 24% more than the rest of the amendments (Fig. 3A). In the second growing season, the 45 Mg ha^{-1} significantly (P = 0.02) influenced the highest biomass (5066.04 kg ha^{-1}) between 11% and 45% more compared to other amendments (Fig. 3A). In the third growing season, the 45 Mg ha^{-1} compost significantly (p<0.01) affected the highest wheat biomass (9253.86 kg ha^{-1}) which was comparable to that of 30 kg ha^{-1} compost but between 16% and 28% more than other amendments. The highest wheat biomass affected by the 45 Mg ha^{-1} compost in all three growing seasons is the result of the higher nitrogen supply and micronutrients from it which influenced higher vegetative growth (Fig. 3A). The effect of the 45 Mg ha^{-1} compost on soil TN concentrations (Fig. 3B) confirms this. [39] observed similar effect of larger wheat biomass with increasing compost rates. They attributed their findings to increasing content and availability of nutrients and improved root activity induced by compost compared to the control. Thus, the control affected the least biomass because of nutrient limitation. These results are in agreement with findings of [40] who reported 6% increase in wheat biomass in plots treated with compost compared with the control. The readily available N supplied through IF failed to affect wheat biomass in any growing seaon because wheat plants were still young at the time of application and didn't make efficient use of most of the released nutrients which may have been lost through various pathways. Thus the quick nutrient release from inorganic fertilizer led to a lack of synchronization between crop nutrient demand and the timing of N release, and a low N-use efficiency as reported by [41]. Moreover, the N supply was not supplemented with any micronutrient supply in the IF treatment.

There was a general increase in wheat biomass in the third growing season compared to the first and second (Fig. 3A), which could be attributed to higher precipitation amounts (Fig. 1) in the third growing season during the active wheat growing period from May to July, 2018. [42] and [43] have found similar increases in plant growth and net primary productivity in arid and semi-arid systems resulting from increased rainfall amounts.

In the third growing season, the wheat plants that followed cover crop fallow realized a significant (P = 0.01) 19% reduction in wheat biomass compared to wheat plants that followed no cover crops (Table 5). This observation was the result of weeds confounding the smothering effect of cover crops in this season compared to the previous growing seasons. This is evident in the higher weed biomass (Table 6) in the third season wheat phase previously planted to cover crops in the rotation. It is documented [44]) that invasive weeds in Wyoming are extremely noxious with strong adaptation mechanisms that allow them to resurge easily after an attempt to rid them.

The effect of the different compost rates alone on the wheat yield were comparable in all three growing seasons. Whether wheat plants followed cover crops or not, did not influence wheat yield in any of the growing seasons. In general, wheat grain yield was highest in the first growing season (2721.75 kg ha^{-1}) and declined by 12 and 47% in the second and third growing seasons respectively (Fig. 3B). The continuous decline suggests that, the slight increases in soil TC/TN in second and third growing seasons (Fig. 2 A&B) were not enough for wheat yield improvements. Due to the climatic conditions of Wyoming, only 11% of nutrients applied through compost are available in the first growing season [23] and the same percentage of the remaining nutrients is available in succeeding growing seasons. Hence a one-time compost application meant that a lesser percentage of nutrients were plant available every growing seaon. This situation was worsened by a resurgence of weeds in the wheat phase of the third growing season (Table 6), causing a devastating decline in wheat yield in this growing season. Since the wheat grain filling period is heavily nutrient dependent [45], competing with weeds for nutrients at this stage caused the lack of yield correspondence to wheat biomass (Fig. 4A and B) in the third growing season. Our observation is similar to the findings of [3] who reported 3-34.4% yield losses due to weeds.

The interaction between the fertilizer treatments and annual cover crop planting had no effect on wheat protein quality in any of the three growing seasons. However, the fertilizer treatments alone significantly (P = 0.009) affected wheat protein quality in the first growing season. The 45 Mg ha^{-1} compost influenced the highest protein concentration (10.75%) between 2-9% better than the IF and other compost rates (Fig. 3C) in the first growing season, though it did not affect wheat yield in this season (Fig. 3 A&B). This common concept of a seemingly negative relationship between wheat yield and protein quality has had divergent views by different scientists [46,47,48]). The protein dilution concept [49] may have applied in our study. In this concept, protein appears to be higher in percentatge because less non-protein compounds (such as carbohydrates) that make up yield was accumulated by the wheat. A similar negative relationship between yield and protein quality is observed with the general increase in wheat.

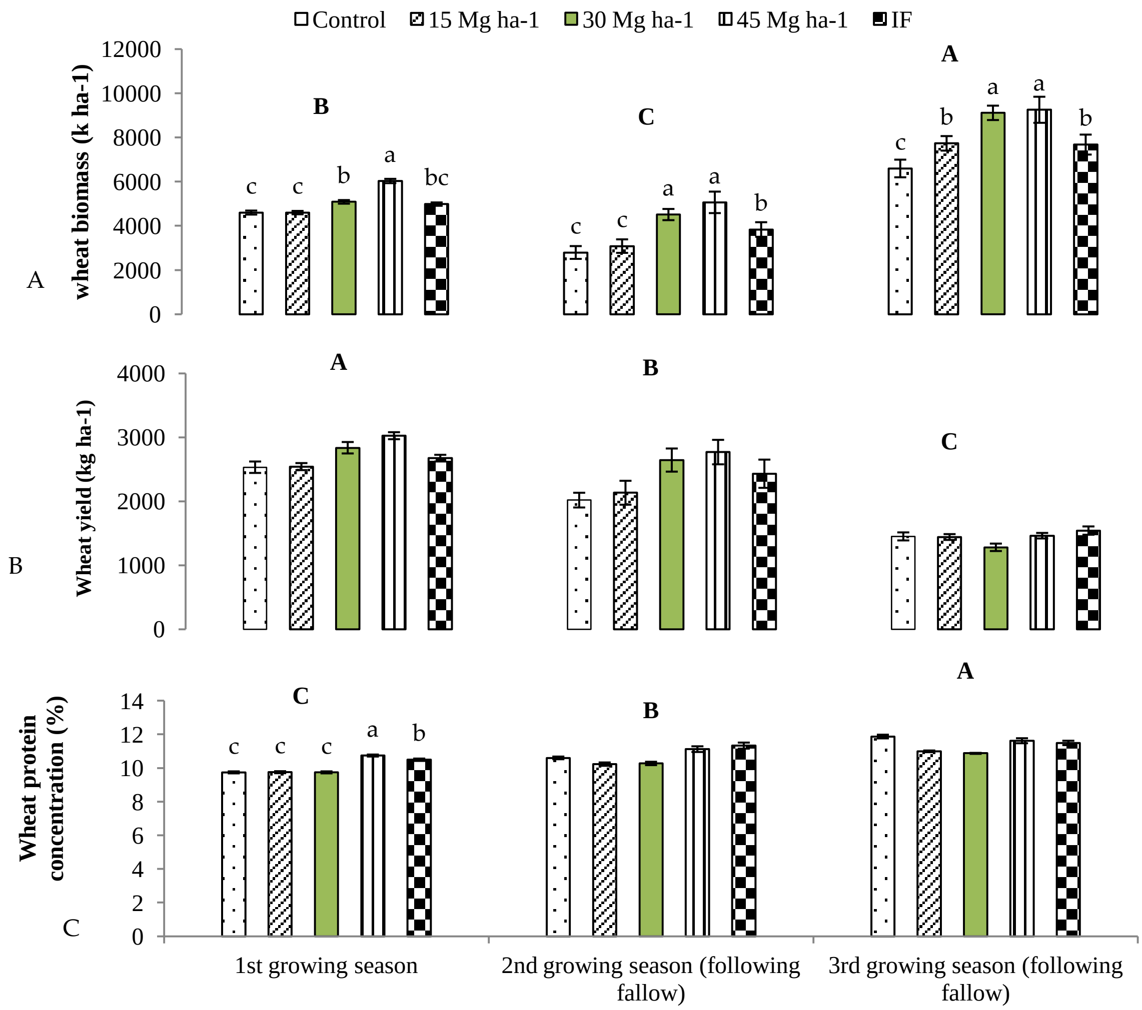

Fig. 3. Wheat biomass, A (kg ha^{-1}); wheat yield, B (kg ha^{-1}) and wheat protein concentration, C (%) in the first growing season wheat phase and the wheat phases following fallow phases in the second and third growing seasons after one-time application of fertilizer treatments (control, 15, 30 and 45 Mg ha^{-1} compost and inorganic fertilizer) and annual cover crops planting and incorporation in the fallow phase. Error bars represent standard errors of the mean. Different lower-case letters (on top of bars) represent the differences in means. Different upper case letters (on top bars) represent the differences in the measured parameters in the first, second and third growing seasons

Table 5. Effect of annual cover crops planting and incorporation in the fallow phase or residual cover crop effect in the wheat phase on average wheat biomass (kg ha^{-1}) during the third growing season. Different lower-case letters attached to treatment means represent the differences in the means. Numbers after the ± are standard erros of the means

	Third growing season
Followed cover crop fallow	7136.49 ± 236.22 $_{(b)}$
Followed no cover crops (bare) fallow	9015.85 ± 182.71 $_{(a)}$
Mean biomass	8076.17 ± 273.45$_{(a)}$

3.4.2 Weed biomass in fallow and wheat phases

In the fallow phase of the first growing season, the average weed biomass was comparable in plots receiving any of the fertilizer treatments (Fig. 4). However, cover crops alone significantly reduced (*P* = .05) weed biomass by 58% (Table 6) in the fallow. Thus cover crops suppressed weeds while growing in the fallow and broke some weed cycles leading to less weed biomass (Table 6). [50] found that adapted cool-season cover crops like those used in this study suppressed weeds during their growth in the fallow in Kentucky, United States.

In the second growing season, the previous cover crop smothering effect significantly reduced (*P=.05*) weed biomass by 53% in this wheat phase (Table 6). On average, weed biomass in this wheat phase was 62% lower than that in the fallow phases it succeeded (Table 6) because the smothering effect of the cover crops was being perpetuated by the keen competition given by wheat plants. Wheat was always planted before the emergence of weeds, hence wheat formed a soil cover which out-competed weeds. As reported by [51], wheat vegetation may have reduced red to far-red light in the UV spectrum of solar radiation reaching the weeds and might have caused a modification in weed physiology leading to reduced weed biomass.

In the third growing season, there was a general resurgence of weeds leading to 43% increase in weed biomass in this wheat phase (Table 6) compared to the wheat phase of the second growing season. The quick bounce back (though not like the first growing season) of weeds (Table 6) in the wheat phase of the third growing season is because of the highly invasive nature of the weeds that were being dealt with. Some of the weeds encountered on the field were *Chenopodium album, Amaranthus albus, Salsola tragus, Lactucaseriola, Basia scorpia* among others. They have strong and flexible adaptative mechanisms [44] that could make them very difficult to be rid of in one attempt.

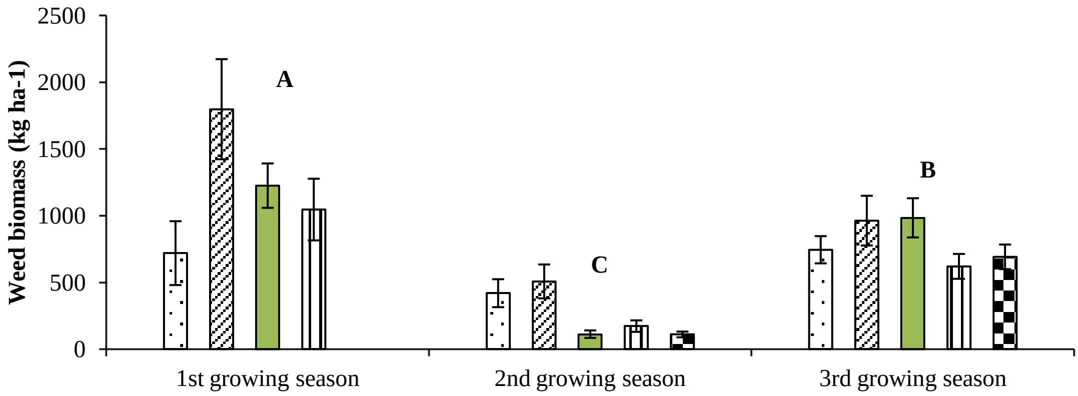

Fig. 4. Weed biomass (kg ha^{-1}) in the first growing season fallow phase and the wheat phases following fallow phases in the second and third growing seasons after one-time application of soil amendments (control, 15, 30 and 45 Mg ha^{-1} compost and inorganic fertilizer) and annual cover crops planting and incorporation in the fallow phase. Error bars represent standard errors of the mean. Different upper case letters (on top bars) represent the differences in the measured parameter in the first, second, and third growing seasons

Table 6. Effect of one-time application of fertilizer treatments (control, 15, 30, and 45 Mg ha^{-1} compost and inorganic fertilizer) and cover crops planting and incorporation in the fallow phase or residual cover crop effect in the wheat phase on weed biomass (kg ha^{-1}) during the first, second and third growing seasons. Different lower-case letters attached to treatment means represent the differences in the means. Numbers after the ± are standard erros of the means

Fallows of first growing season		Wheat phases of second and third growing seasons		
Cover crops	675.51 ± 53.28 $_{(b)}$	Followed cover crops	290.88 ± 36.20 $_{(b)}$	916.90 ± 79.14
No cover crops	1589.48 ± 182.97 $_{(a)}$	Followed no cover crops	615.50 ± 39.41 $_{(a)}$	683.11 ± 46.29
Mean weed biomass	1196.23 ± 193.50$_{(a)}$		453.19 ± 64.18$_{(c)}$	800.00 ± 78.61$_{(b)}$

4. CONCLUSIONS

Based on the findings of this study it is concluded that, application of 45 Mg ha^{-1} compost to dryland soil only increases soil EC by about 1.5% on average. Hence, if the soil EC (salinity) is not already close to the wheat threshold of 3400 to 4300 µS cm^{-1}, adding such rates of compost to the soil would not worsen soil salinity.

Applied compost takes time (after one season of application in our case) to influence soil organic matter and fertility (soil carbon and nitrogen concentrations). In our case, the 45 Mg ha^{-1} compost increased soil carbon (10-19% more) and nitrogen (13-25% more) in the second and third growing seasons.

Cover crops reduce soil moisture (by 16% in this study) while they are growing in the fallow phases but precipitation is enough to restore soil moisture for use by subsequent wheat. Therefore, precipitation is a more important factor controlling the wheat yield- soil moisture relationship than cover crops in the fallow phases. Hence in the absence of drought, including cover crops in the rotation should not pose problems.

There is evidence that cover crops controlled weeds with the 53-58% reduction in weed biomass in the fallow of the first growing season and the wheat that followed it in succession in the second growing season. However, with the notoriety of the weeds being dealt with during the study, more research is needed to effectively include cover crops as a weed control measure.

The 45 Mg ha^{-1} compost had a promising effect on wheat biomass and protein quality (though not but not yield, hence the need to continuously monitor the field to determine the timelines for maximum yield benefits for one-time compost application.

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STATEMENTS AND DECLARARTIONS

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AVAILABILITY OF DATA AND MATERIALS

The dataset generated and/or analyzed during the study are available from the corresponding author on reasonable request.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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