Original Research Article

Winter wheat performance following one-time high rates of compost and annual cover crop planting in wheat-fallow rotations

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 fallows 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

Place and duration of study: It was conducted at the Sustainable Agriculture Research and Extension Center, University of Wyoming, USA from September 2015 to August 2018.

Methodology: Soil samples, weed biomass, wheat yield and protein quality data were collected and analyzed over three years.

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 returns obtained from organic produce compared to convetional ones. However, sustainable dryland organic winter wheat production in Wyoming is threatened by the little precipitation amount received (300 mm/ year) annually and the need to control weeds with repetitive tillage (since there are no effective organic herbicides in the region) **[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 prtein 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 up to 72% wheat yield losses due to weeds in this region. This challenge is exacerbated by low nutrient input practiced by farmers, which support little biomass production and residue addition to the soil.

For a state like Wyoming that produces large quantities of feedlot manure **[4]**, it would be assumed that farmers had abundant sources of organic nutrients for their farms. 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 $10^{-1}5$ Mg ha^{-1} increases soil salinity which defeats the purpose for which manure is applied. Higher soil salinity (15 dS m^{-1}) has been found to cause about 58% wheat yield losses compared to non-saline (0.33 dS m^{-1}) soils **[5].** Applying little amounts of organic amendemnts in such nutrient dependent organic fields also cause rapid SOM decline.Without better organic soil management strategies 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 soil management strategy which reduces weed proliferation and reduces the need to frequently control weeds with tillage should be adopted. The ubiquitous amouts of 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 make the amendment safe to apply. Moreover, composted manure 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 while 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 which extrapolated 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 NHP **[10]**; **[11]**), but such applications have not yet been tested in Wyoming. Compost carry-over effect has been assigned as the reason for these soil and wheat benefits several years after a one-time compost 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.**[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 farming 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 such fallows. 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 mixes 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 produced resulting in 13 to 78% wheat yield loss in the Colorado Plateau **[17]**. **[11]** also observed about 50% loss of wheat yield due to water loss influced 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 as appropraiate 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 mix with Austrian winter pea. Though cover crops would take up soil nutrients to build up its biomass, it is expected that nutrients will be returned to the soil after its incorporation and decomposition as demonstrated by **[20]** and **[21]**. These nutrients would otherwise be taken up by weeds and offloaded from the site or lost through various pathways.

The objective of this study was to improve soil carbon (organic matter) and nitrogen 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 April 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. It 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 $^{-1}$1.4 ºC in December to 32 ºC 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 (Figure 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 30 feet long and 18 feet wide and separated by 15 feet wide border alleys. Global positioning system (GPS) coordinates were taken for the 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 a dry weight basis), the full rate of inorganic fertilizer (IF) and a no amendment control and sub-plot factor: cover crop mixture [Oats (*Avena sativa*) and Austrian winter peas (*Pisum sativum*)] planted in half of a fallow and no cover crops in the other half.

2.3.1.1 Treatment application

The compost rates 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 produce, wheat and fallow 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 consisted of 56 kg ha^{-1} Austrian winter pea (*Pisum sativum* subsp. arvense) and 28 kg ha^{-1} oats (*Avena sativa*). Cover crops were 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 and the assumption that only 11% of compost-derived N is mineralized during the first growing season **[23]**, compost treatments supplied 70, 140, and 205 kg N ha^{-1} and 0, 0.27, 0.54, and 0.81 kg P ha $^{-1}$, respectively. Inorganic fertilizer (IF) consisted of a mixture of 0.09 Mg ha^{-1} monoammonium phosphate ($NH_4H_2PO_4$; commonly called MAP) and 0.12 Mg ha^{-1} ammonium sulfate [$NH_4 (SO_4)_2$], which supplied 39 kg N ha^{-1} and 180 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 70 lbs ac^{-1}. A half of each fallow block was planted to a cover crop mixture of 56 kg ha^{-1} of Austrian winter pea (*Pisum sativum* subsp. *arvense*) and 28 kg ha^{-1} of oat (*Avena sativa*) 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 tilled 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', from September 2016 to July 2017 is the 'second growing season' and from September 2017 to August 2018 is 'third growing season').***

2.4 Soil Sampling and Analyses

Prior to compost application, compost and soil were characterized.   Four soil cores were collected at 0^{-1}0 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]**, 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.

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

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 every month during the slow plant growth season (September to November) at 0^{-1}5 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 identification and counting were done using two quadrats (each measuring 30 cm square) placed randomly at the center of each plot. All weeds were cut at the root level, oven-dried at 60ºC for two days, and weighed. This activity was carried out in both wheat and fallow phases at the physiological maturity stage of wheat in the wheat phase and just before cover crop incorporation in the fallow phase. The plant materials were milled with a miller (Willey Laboratory Mill, Model 4, Arthur H. Thomas Co.' Philadelphia, USA) and analyzed for total C and N. Weed density was calculated as follows:

Weed density = $\frac{no.of\ weeds}{area\ collected}\ (no. m^{-2})$

Weed biomass data were 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. Samplings were done twice in a month (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).

Cover crops were terminated and incorporated into the soil in June 2016, July 2017, and June 2018 respectively (6 weeks after planting).

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 a growing season. The data were subjected to analysis of variance (ANOVA) using Statistical Analysis System (SAS, Enterprise, Cary, North Carolina, USA). In 2016, the model tested the effect of compost on the measured soil and plant parameters in both wheat and fallow phases separately. In 2017 and 2018, the model tested the effects of compost, 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 pahese in 2017 and 2018. Fischer's protected least significant difference (LSD) was used to separate significant means at a 5% level of significance.

3. RESULTS AND DISCUSSION

3.1 Weather

Figure 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°C to 28°C with December, January and February being the coldest months and July and August being the warmest months (Figure 1). The wettest months were July in the first season, May in the scond season and June in the third season, while the driest months were in September, October, November and March. The average monthly precipitation (Figure 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 (Porter and Gawith, 1999).

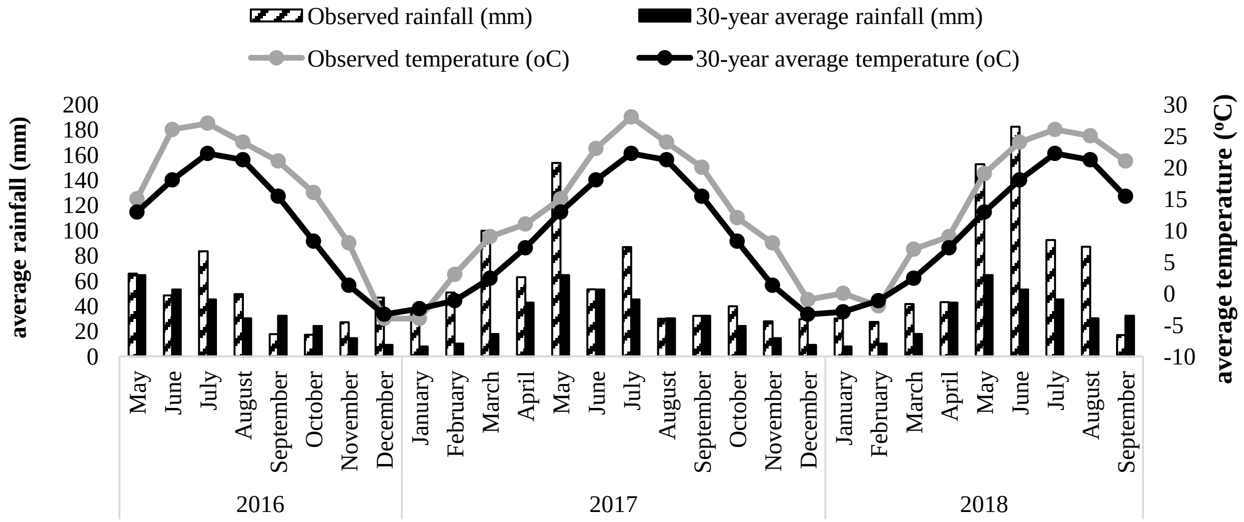

Figure 1. Observed average monthly precipitation and average air temperatures between May 2016 and September 2018 versus 30-year averages. https://www.worldweatheronline.com/torrington-weather-averages/wyoming/us.aspx

3.2 Soil electrical conductivity in wheat and fallow phases

There was no significant interaction effect of the fertilizers and cover crop treatments on soil EC in any growing season. However, in the first growing season, wheat phases amended with 30 and 45 Mg ha^{-1} compost had the highest ECs (*P* = .03) of 417 and 399 µS cm^{-1},which were 16 to 21% more compared to

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 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 salts concentrations affected by the two largest compost rates (45 and 30 Mg ha $^{-1}$) and incorporated cover crops in both wheat and fallow phases. **[31]** demonstrated increases in soluble salt concentrations of the soil with high rate compost applications.

The fallow phases of the second growing season averagely 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 were observed by the third growing season and none of the compost rates affected them. 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]** as such had no detrimental effect on wheat yield.

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)

3.3 Soil moisture in the fallow and wheat phases

There was no significant interaction between the fertilizer and cover crops on the average soil moisture in the fallow phase in the first growing season and wheat phases that followed the fallows in the second and third growing seasons. The amendments alone also 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 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 that of **[17]** who reported a 10 mm loss of soil moisture per 1000 kgha^{-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% decline in soil moisture compared to fallow phases. Compared to wheat phases that followed bare fallow, wheat phases that followed cover crops had 19% (P = 0.01) less soil water (Table 4). 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 due to cover crops. The precipitation amounts (Figure 1) received during the wheat growing periods may have covered up for the cover crop soil moisture loss.**[34]** observed that two out of their four year experiments, cover crops did not affect corn yield but reduced yield in the other two years in Iowa and attributed the varying cover crop effects on yield to specific cover-crop cultivar interactions and not necessarily a reduction in soil moisture during their growth. **[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. It could be inferred from this study that preceding cover crops had other benefits which could compensate for the loss in soil moisture from the profile during their growth.

Table 4. Effect of 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 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 erros 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$_{(a)}$		9.75 ± 0.51 $_{(a)}$
		No cover crops in preceding fallow	
Mean seasonal moisture	*14.56 ± 0.39*		*8.84 ± 0.52*

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 interaction between fertilizer and cover crops in the previous fallow did not affect total carbon and nitrogen (TC/N) in any of the wheat phases of the last two 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 (Figure 1) where compost mineralization rates is slowed by the prolonged cold temperatures (Figure 1). **[37]** also reported slower nutrient release rates under lower (18^{o}C) decomposition temperatures than a higher one (24^{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. 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 (Figure 2A), and soil TN, 13-25% more (*P* =0.02) than the lower 0, 15 Mg ha^{-1} compost rates and IF (Figure 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 (Figure 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 amount 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 (Figure 2A and B).

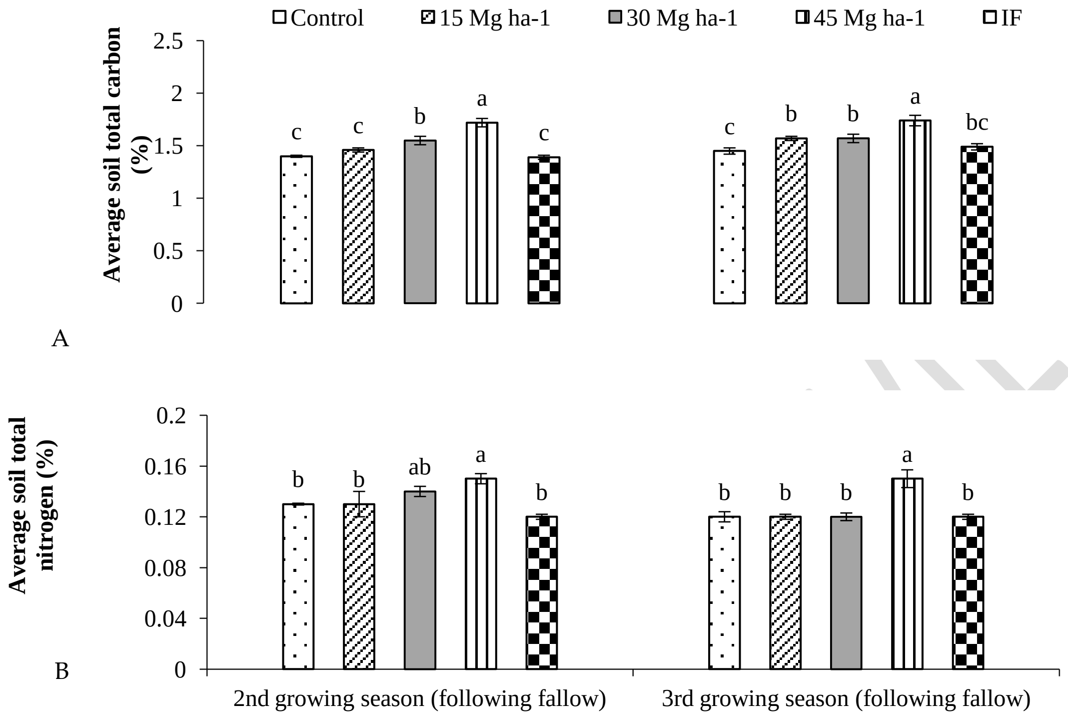

Figure 2. Average soil total carbon, A (%) and total nitrogen, B (%) in the wheat phases of the second and third growing seasons, following fallow phases after one-time application of soil amendments (control, 15, 30 and 45 Mg ha^{-1} compost and inorganic fertilizer) in the first growing season and 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.

Wheat biomass, yield and protein quality

There was no significant interaction effect between the soil amendments and the annual cover crop planting in the fallow, on wheat biomass in any growing seasons. However, the applied amendments 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 (Figure 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 (Figure 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 (Figure 3A). The effect of the 45 Mg ha^{-1} compost on soil TN concentrations (Figure 3B) confirms this. **[39]** observed similar effect of larger wheat biomass production with increasing compost rates. They attributed their findings to increasing content and availability of nutrients and improved root activity induced by compost. These results are in agreement with findings of **[40]** who reported of up to 48% increase in wheat biomass in plots treated with 40 Mg ha^{-1} compost compared with the control. Thus, the control affected the least biomass because of nutrient limitation. 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 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, anda low N-use efficieny as reported by **[41]**. Moreover, the N supply was not matched with other beneficial micronutrient supply in the IF treatment.

There was a general increase in wheat biomass observed in the third growing season compared to the first and second (Figure 3A), and it could be attributed to higher precipitation amounts (Figure 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 weeds in these semi-arid regions are extremely noxious with strong adaptation mechanisms that allow them to resurge easily after an attempt to rid them.

The interaction between fertilizers and the annual cover crop planting, had no effect on wheat yield in any growing season. 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. On average, 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 (Figure 3B). The continuous decline suggests that, the slight increases in soil TC/TN in second and third growing seasons (Figure 2 A&B) were not significant to 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 (Figure 4A and B) in the third growing season, which contrasts many studies **[46]**; **[47]**;**[48]**). However, our observation is similar to the findings of **[3]** who reported up to 72% 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 (Figure 3C) though it did not affect wheat yield in this season (Figure 3 A&B). This common concept of a seemingly negative relationship between wheat yield and protein quality has had divergent views by different scientists for a long time **[49]**; **[50]**; **[51]**). One school of thought explains from a physiological point of view where yield increase is dependent on the assimilation of carbohydrates, while protein concentration is the ratio of amino acids translocated to the grain to the assimilated carbohydrate **[52]**. In effect, the lower the carbohydrate assimilates that increase yield, the higher amino acids, and consequent protein concentration may seem. It is in this light that the increasing levels of compost and IF, though did not influence wheat yield significantly (Figure 3B), influenced wheat protein quality (Figure 3C) in the first growing season. A similar negative relationship between yield and protein quality is observed with the general increase in wheat protein every growing season while wheat yield declined seasonally (Figure 3B and C).

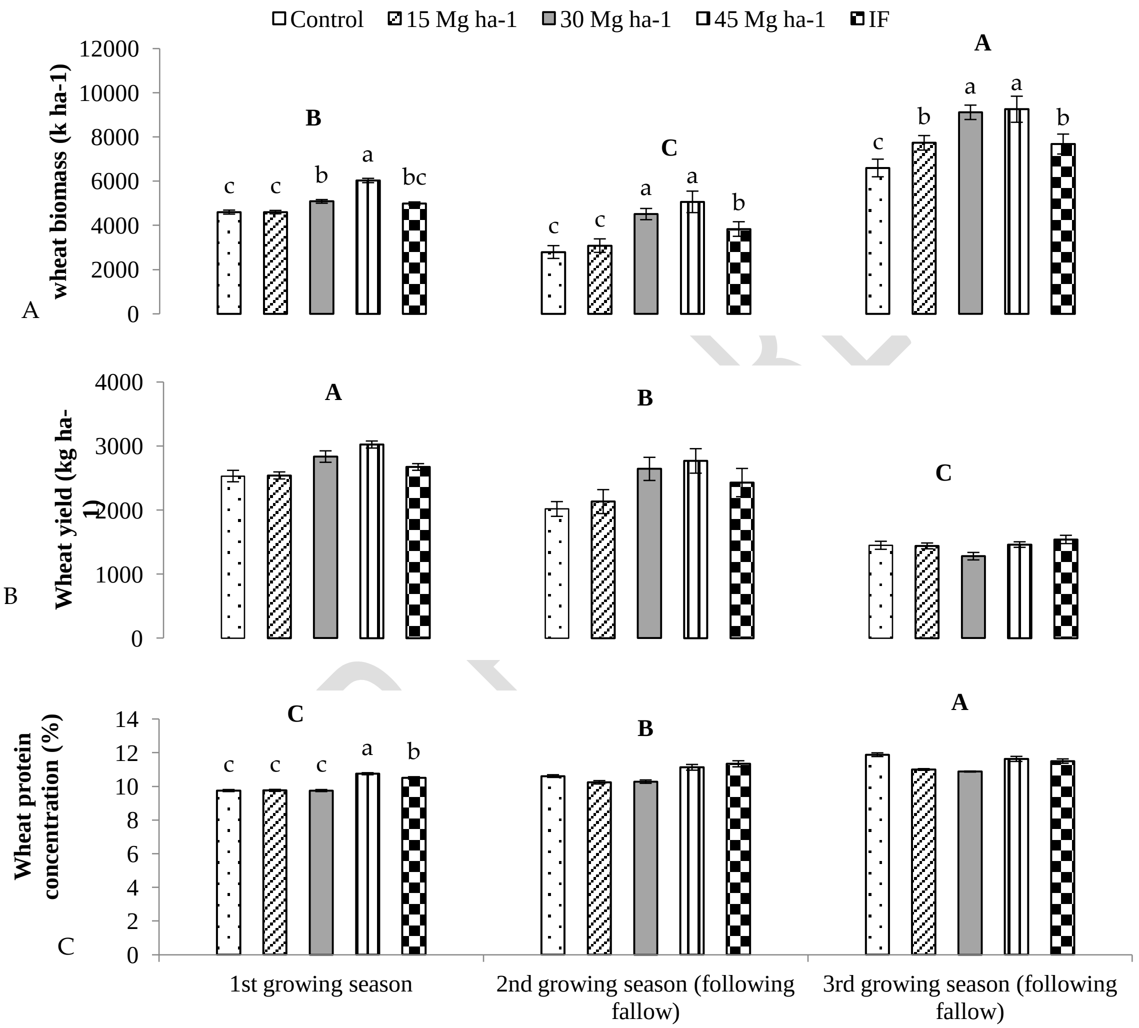

Figure 3. Wheat biomass, A (kg ha^{-1}); wheat yield, B (kg ha^{-1}) and wheat protein concentration, C (%) in the first growing season wheat phase and the wheat phases following fallow phases in the second and third growing seasons after one-time application of soil amendments (control, 15, 30 and 45 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 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 annual cover crops planting and incorporation in the fallow phase or residual cover crop effect in the wheat phase on **average wheat biomass** (kgha^{-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$_{(a)}$

Weed biomass in fallow and wheat phases

In the fallow phase of the first growing season, the average weed biomass of the season was comparable in plots receiving any of the fertilizer treatments (Figure 4), and their interaction with cover crops did not affect weed biomass. However, cover crops alone significantly reduced (P = .05) weed biomass by 58% (Table 6) in the fallow. Thus cover crops suppressed weed growth and broke some weed cycles leading to less weed biomass (Table 6). **[53]** Blackshaw et al. (2001) found that adapted cool-season cover crops like those used in this study suppressed weeds during their growth in the fallow in the semiarid Canadian great Plains.

In the second growing season, when wheat followed the fallow of the first growing season, the fertilizer treatments and their interactions with cover crops still had no effect on weed biomass. However, 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 compared to that in the fallow 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 **[54]**, the reduced red to farred light (reduced by wheat vegetation) in the UV spectrum of solar radiation, might have caused a modification in weed physiology leading to reduced weed biomass.

In the third growing season, weed biomass in the wheat phase was neither affected by fertilize treatments alone, cover crop effect alone nor their interactions. However, 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. The type of weeds encountered on the field (*Chenopodium album, Amaranthus albus, Salsola tragus, Lactucaseriola, Basia scorpia* among others) have strong and flexible adaptative mechanisms **[44]** that could make them very difficult to be rid of in one attempt.

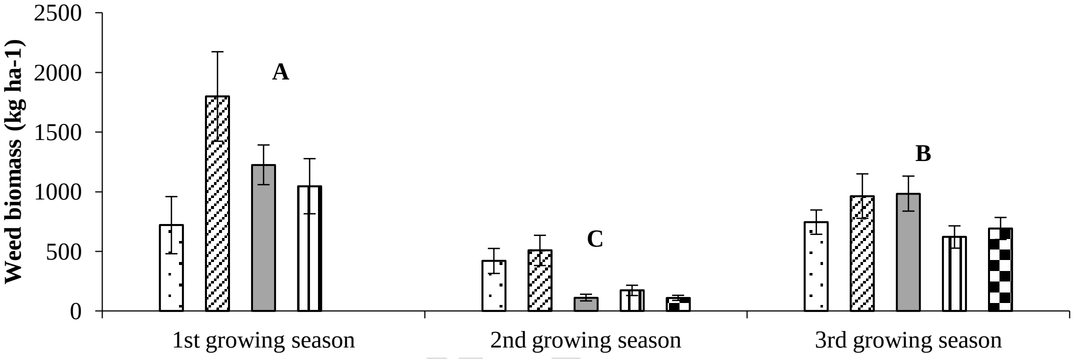

Figure 4. Weed biomass (kg ha^{-1}) in the first growing season fallow phase and the wheat phases following fallow phases in the second and third growing seasons after one-time application of soil amendments (control, 15, 30 and 45 Mg ha^{-1} compost and inorganic fertilizer) and annual cover crops planting 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 soil amendments (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

Application of 45 Mg ha^{-1} compost to the soil only increased 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. However, within the study period, an associated improvement in soil moisture was not observed from it.

The cover crops reduced soil moisture by 16% while they were growing in the fallow of the first growing season, and made 23% less water available to wheat crops when they followed them in rotation, but did not affect soil moisture in the third growing season. However, the lack of response of wheat yield and protein content in any growing seasons indicate that water supply through precipitation is a more important factor controlling the wheat yield- soil moisture relationship than cover crops in the fallow. Therefore, in the absence of drought, including cover crops in the rotation should not compromise wheat yield.

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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