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Rates of energy resource extraction in Wyoming, are among the highest in the world, and the state is a leading natural gas producer. Natural gas well-pad construction and reclamation practices cause drastic changes to soils and native plant communities. Wyoming soils are often alkaline, with low organic matter levels concentrated near the soil surface. Additionally, growing conditions are cold and dry, challenging successful reclamation of disturbed sites. Carbon additions, meant to counter invasive plant establishment and improve soil conditions, have been utilized in several rangeland studies in attempts to expedite and improve reclamation efforts, but questions remain regarding their effectiveness. The purpose of this study was to compare carbon-rich soil amendments, across nine treatments and a control, for use as a reclamation practice on southwest Wyoming natural gas well-pads. More specifically, we evaluated the cost of applying the treatments; their ability to improve soil conditions; reduce invasive plant species; and increase native plant species.

Three rates of straw, woodchips, and a woodchip/compost mixture were incorporated into soils on two reclaimed well-pad sites in southwest Wyoming. One site was on the Jonah Field, an area of dense well-pad development and accompanying high invasive plant populations. These conditions contrasted the second site located on the Pinedale Anticline, found at higher elevations and in a less dense distribution of well-pad development and invasive plants, compared to the Jonah Field site.

All treated plots on the Jonah Field and Pinedale Anticline had multiple soil properties that were significantly improved by the carbon additions, compared to the control plots. The Jonah Field had no treatments which caused significant negative treatment effects to soil or

vegetation properties compared to the control, but this did occur on the Pinedale Anticline. Carbon additions generally had positive effects on soil conditions by significantly decreasing pH and increasing labile and physically free organic carbon levels at both study sites, and decreasing calcium carbonate levels on the Pinedale Anticline. The high rates of straw and wood chips had the most significant positive soils effects, but also negative effects to seeded native plant species under the high straw, and on vegetation cover under the high WC treatments, on the Pinedale Anticline. Overall, however, the high application rate of WC had the most positive significant effects by treatments, compared to control plots, on the Jonah Field and Pinedale Anticline sties.

Treatments successfully decreased soil mineral nitrogen, with significantly lower levels measured in almost all treatments, compared to the control. Soil labile and physically free organic nitrogen levels were also generally lowered by treatments. Decreased mineral nitrogen did not cause a significant change to invasive plant species establishment, however, the lowest mineral N levels were measured under the high straw and WC treatments at both sites. These same treatments had the lowest invasive plant species densities on the Pinedale Anticline, but were not significantly different in numbers compared to the control.

The high woodchip and compost mixture on the Jonah Field had the lowest invasive plant densities and corresponding highest native seeded plant densities, but these densities were also not significantly different than those measured in the control plots. The low straw treatment significantly increased shrubs and forbs and on the Jonah Field, and shrubs on the Pinedale Anticline. The medium straw treatment also significantly increased forbs on the Jonah Field.

The wood chip treatments were about 23% more expensive than the wood chip compost mixture and about 15% more expensive than the straw treatments. Their totals costs were not excessive, however, given total reclamation cost estimates, or estimated costs of failed reclamation.

Considering the study's comprehensive findings, carbon additions seem most useful on sites with an invasive plant species problem, such as found on the Jonah Field, or where alkaline soil conditions are a primary factor hindering reclamation success. Additional time will allow better assessment of the sustained effects of the amendments' contribution to improved reclamation success.

COMPARISON OF CARBON RICH SOIL AMENDMENTS FOR RECLAMATION OF SOUTHWEST WYOMING NATURAL GAS WELL-PADS

By

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CHAPTER ONE: INTRODUCTION

Wyoming is a mineral rich state, with a long history of natural resource development. In 2010, Wyoming natural gas extraction ranked second highest nationally (Petroleum Association of Wyoming (PAW), 2010). Extraction of energy products directly increases disturbance to the state's natural ecosystems. These changes negatively affect soils; with loss of organic matter (OM) and aggregate structure (Driessen, 2012; Six et al., 2004; Stahl et al., 2003; Harris et al., 1993), and disruptions to nutrient cycling (Alpert and Maron, 2000; Zink et al., 1998) and related soil chemistry processes (Rowell and Florence, 1993; Averett et al., 2004). Vegetation is also negatively impacted by disturbances involved with natural gas extraction, through destruction of native plant species (Stylinkski and Allen,1999; Doerr et al., 1984), and increased susceptibility to invasion (Vinton and Georgen, 2006; Zink et. al, 1995). Reclamation practices executed to mitigate these disruptions share the goal of rapidly restoring important affected ecological functions including wildlife habitat, forage production, and watershed protections. Successful reclamation is difficult, however, given Wyoming's cold arid climate, combined with the interruptions to natural succession caused by drastic disturbances. Techniques employed to reach reclamation goals are numerous, variable, and often expensive.

Regardless of the method used, reestablishing stable healthy topsoil, capable of supporting native plant communities, with the least cost expenditure are primary reclamation objectives. Land managers attempt to achieve these goals on two major gas fields in southwest Wyoming, the Jonah Field and Pinedale Anticline, with recent trial applications of straw and wood chips from local resources. Carbon (C) additions have been intensively studied as a method to counter invasive plant species establishment (reviewed by Alpert, 2010), however, their more comprehensive use as a reclamation tool on southwest Wyoming's natural gas reclamation sites has not been previously assessed. Formal data from research on soil and vegetation effects of different C additions is needed for resolution regarding their appropriateness as a treatment, and the most beneficial rate of their application. The purpose of this study was to compare the efficacy and costs of woodchips, straw, and a woodchip/compost mixture, applied at three rates each, to: 1) improve soil conditions and OM properties; 2) promote seeded plant species; and 3) suppress invasive plant species through nitrogen (N) immobilization.

Drastic disturbance to soils negatively affects soil organic matter (SOM), by destroying aggregates, which leads to nutrient mineralization and loss (Norton et. al., 2009). Topsoil salvaging also causes many other disruptions to the soil environment, including compacted soils, evidenced by increased soil bulk density (BD) (McWilliams et al., 2007), and increases in calcium carbonate ($CaCO_3$) levels. Calcium carbonate and other salts are common in semi-arid Wyoming soils, and typically accumulate in shallow subsurface horizons. Salts then become mixed into salvaged topsoil, increasing salinity, measured by electrical conductivity (EC), and alkalinity, measured by pH in surface soils (Mummey et al., 2002; Driessen, 2012; Rowell and Florence, 1993). The combined effects of compacted, high pH, and saline topsoil often results in decreased native plant species establishment. Research has found organic amendments to mitigate some of these effects, however, while also increasing soil moisture (Garcia-Orenes et al., 2005; Rivenshield and Bassuk, 2007; Hemmat et al., 2010; Bot and Benites, 200; Avnimelech et al., 1994).

Soil organic matter (SOM) consists of only a relatively small proportion of the total soil composition (see Appendix F: Figure 13a for image), but is of paramount importance for soil health as it facilitates aggregate stability; water and nutrient retention; microbial driven processes, such as decomposition; and buffering of soil pH and temperature. Different pools of SOM can be investigated to help assess treatment effects. As described by Parton et. al (1987) and Sohi et. al. (2005), OM can be divided into three pools comprised of materials of varying decomposition and turnover rates (see Appendix F, Figure 13b). Active SOM is made up primarily of plant, animal, and microbial residues, which break down rapidly. Slow OM is an intermediate pool, which consists largely of gradually decomposing detritus. The remaining most recalcitrant materials belong to the passive pool of OM, also known as humus (Grubinger, 2012).

Research investigating disturbances in Wyoming gas fields has shown that removal, storing, and then re-spreading and re-contouring of topsoil during well-pad construction causes destruction of SOM and aggregate structure, and allows previously protected nutrients to be exposed and lost (Dangi et al., 2012; Wick et al., 2009). Recent research on Wyoming natural gas well-pads reports finding soil mineral N at very low levels, of about two parts per million, in pre-disturbance sagebrush-bunchgrass plant communities, where it is tied up as organic N in plants and SOM, compared to over 23 parts per million of mineral N on newly reclaimed sites (Mason et al., 2010). This disturbance-related pulse of mineral N is susceptible to loss from soil systems, and likely contributes to the prolific weed production often observed on newly seeded sites, as many invasive plant species are better able to metabolize mineral N than competing natives (Vinton and Georgen, 2006; Paschke et al., 2000; McLendon and Redente, 1992).

Soil C additions can achieve decreased establishment of invasive plant species by interfering with this soil nutrient cycling. During decomposition of high-C-content substances, mineral N in the soil is immobilized as microbial populations assimilate newly incorporated metabolic substrates, which creates competition for and uptake of the same mineral N plants require (Vasquez and Svejcar, 2008; Perry et al., 2010). Soil additions of C sources with a C to N ratio (C:N) above 20 creates microbial immobilization of mineral N, namely nitrate (NO_3^-) and ammonium (NH_4^+) (Figure 1), initially hindering plant growth.

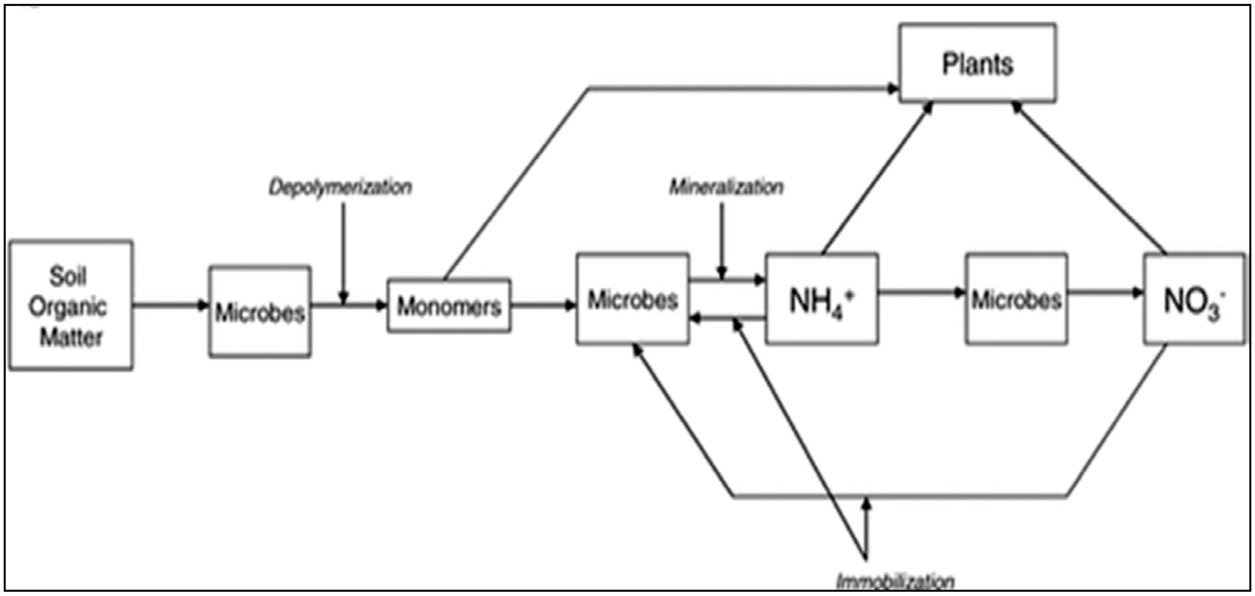


Figure 1: Image from Vasquez et al.(2008) illustrating N pathways in soils, which shows competition for N by plants and microbes.

This immobilization of mineral, plant-available forms of N, is therefore often an undesired outcome. In reclamation situations, however, addition of high C materials can facilitate capture of this available N pulse, released upon disturbances associated with well-pad development and reclamation. Previous research predicts that C additions may have the most positive vegetative effects in systems with large N release via drastic human disturbance, suggesting C additions may contribute to successful reclamation on Wyoming's oil and gas well-pads (Alpert, 2010; Eschen et al., 2006).

Wyoming land managers have also expressed interest in this work because, if effective, use of C additions can achieve multiple ecological restoration goals simultaneously. In the case of wood chips, reclamation use can help utilize biomass removed from insect and disease infestations, conifer-invaded aspen habitats, and fuel-reduction projects, while also improving reclamation success on Wyoming's difficult-to-restore sites. Research documenting effects of wood chips' use for reclamation on the Jonah Field and Pinedale Anticline gas fields is needed so managers can either utilize this practice or seek other ways to manage the excess biomass. The other treatment components, compost and straw, are also of interest for use in reclamation, as they too are locally available in southwest Wyoming, and have the potential to affect SOM to a greater or varying degree than the wood chips alone (Zvomuya et al., 2007; Larney et al., 2005).

Although findings have generally conceded on C additions' negative effects on invasive plant species establishment through mineral N immobilization (Rashid and Reshi, 2010; Alpert and Maron, 2000; Bleier and Jackson, 2007; Blumenthal et al., 2003; Tilston et al., 2009; Torok et al., 2000), research has yielded less consistent results on C additions' ability to enhance native plant species establishment (Morghan and Seastedt, 1999; Monaco et al., 2003; Corbin and D'Antonio, 2004; Perry et al., 2010; Rowe and Pascke, 2009; Miller and Seastedt, 2009; Wolk and Rocca, 2009; Eldridge, 2009), and has not converged on recommendations for application rates needed to achieve desired results (Blumenthal et al., 2003; Brunson et al., 2010; Biederman et al., 2008). We evaluated three application rates of each type of C addition utilized in this study because Wyoming reclamationists have voiced a need for advisement on successful application rates of the treatment materials.

We recognize the severe impacts drastic disturbances have on soils and native vegetation. The abilities of the different C addition treatments to increase SOM properties, and improve some of the desired soil conditions present prior to disturbance, were the foci of soils investigations in this study. We predicted C additions would provide benefits to soils by decreasing pH, EC, BD, and $CaCO_3$ levels, and by increasing soil moisture and OM pools most sensitive to management changes. We addressed these hypotheses by direct measurements and calculations. For levels of OM, we measured the C and N concentrations in a variety of OM pools, including dissolved OM; free light fraction OM; potentially mineralizable OM; and microbial biomass. We also evaluated microbial community composition with phospholipid fatty acid analyses (PLFA).

Related to the soil and vegetation effects of disturbance is nutrient cycling, especially for mineral N. The contribution this mineral N has on establishment of invasive plant species can be mitigated by addition of C to soils, and so was an additional aspect we addressed in this study. We hypothesized that the C additions would cause a decrease in mineral N, and evaluated this assumption by measuring soil NO_3^--N and NH_4^+-N levels.

Reestablishing native plant communities, while minimizing invasion by undesired species, are also common goals in reclamation, and were therefore the points of investigation for our treatment effects on vegetation. We hypothesized that C additions would decrease invasive plant species abundance, and simultaneously increase native plant species abundance. We utilized measurements of plant densities and percent ground cover, during peak growth, to address these predictions. Finally we investigated the estimated costs of the treatments, so land managers can consider the comprehensive factors involved with C addition use as a reclamation tool.

METHODS

Site Descriptions

We established two field study sites on natural gas well pads in Sublette County, Wyoming (Figure 2) (Bureau of Land Management (BLM), 2012). The location of one site was on the Jonah Field's Stud Horse Butte well-pad 60-26 (109° 41' 8.412 "W, 42° 27' 1.656" N), at an elevation of 2,211 m (Figure 3a). The second site was located approximately 32 km north, on the Pinedale Anticline's Stewart Point 14D3-32 well-pad (109°53' 34.116 " W, 42°467' 53.04"), at an elevation of 2,295 m (Figure 3b). The Jonah Field site is located along Luman Road, one of the more major roads in this gas field, and is in a more dense distribution of well-pad sites relative to the Pinedale Anticline site.

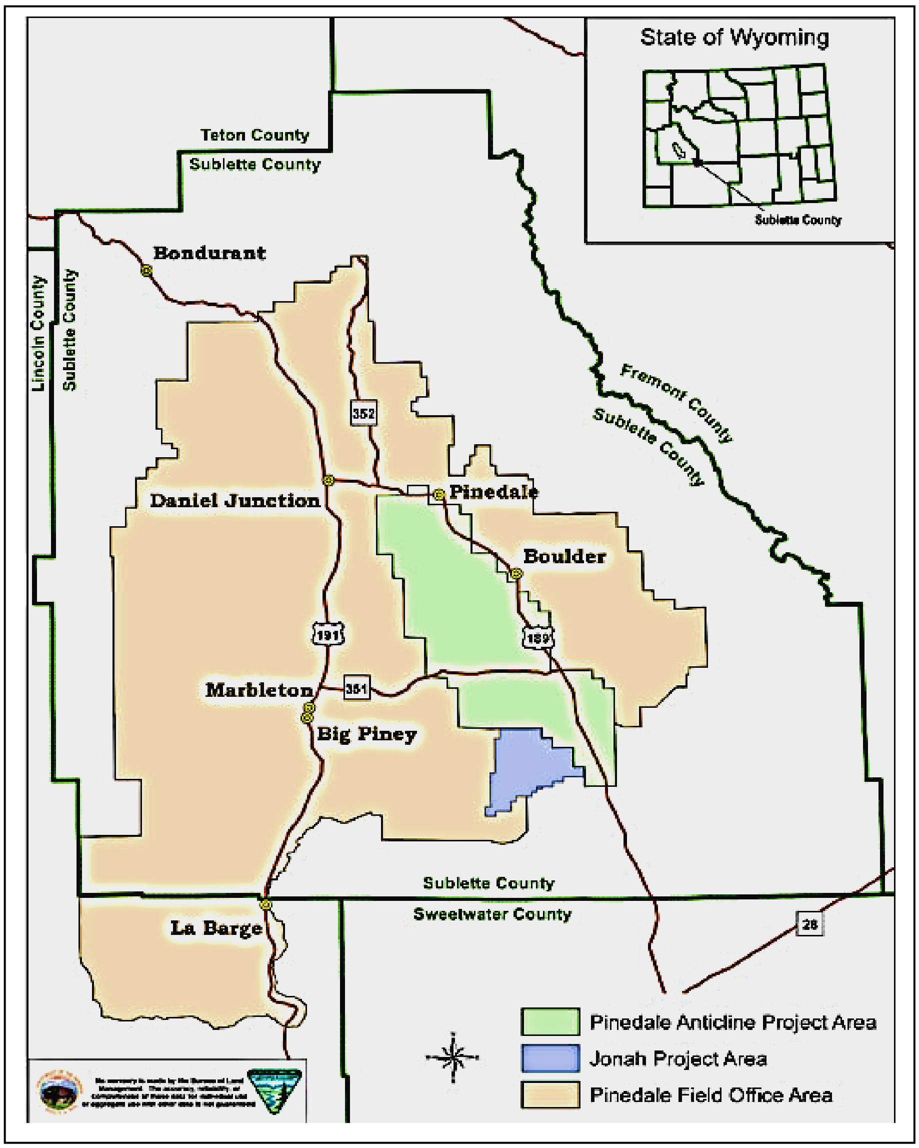
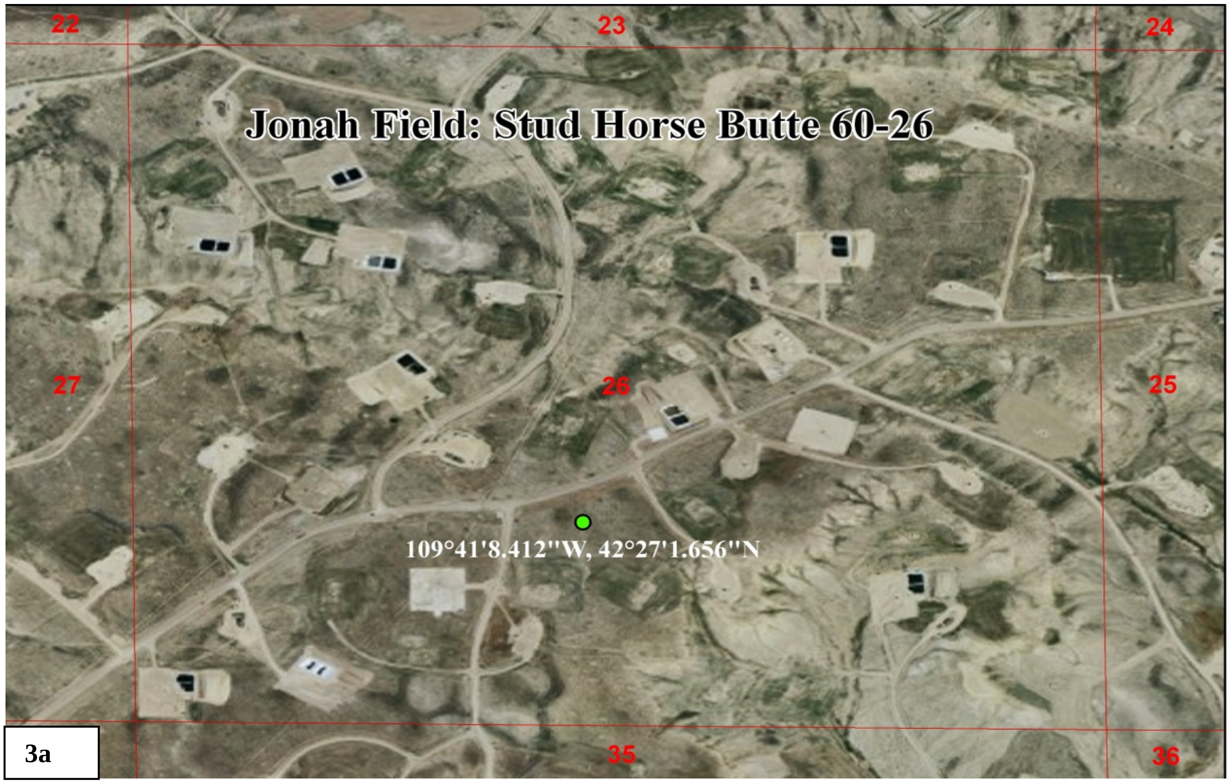


Figure 2. Sublette County, Wyoming: Location of study sites, one on the Jonah Field and the other on the Pinedale Anticline (BLM, 2012).



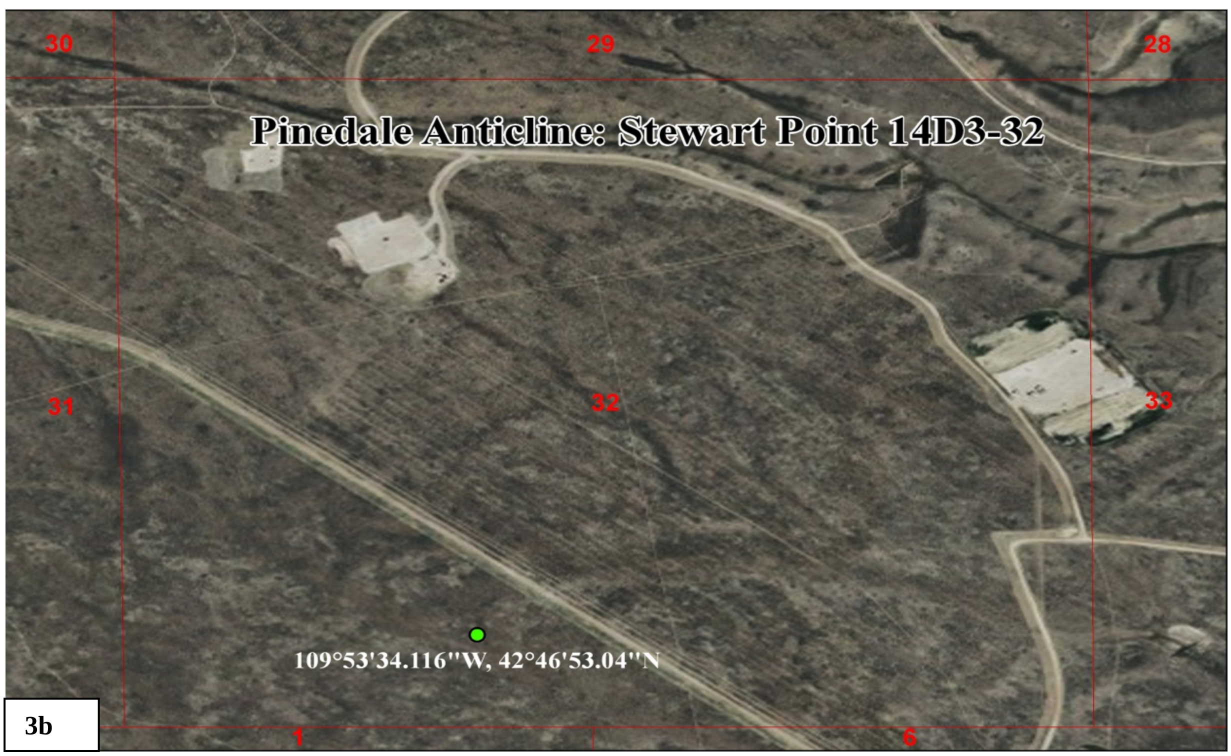
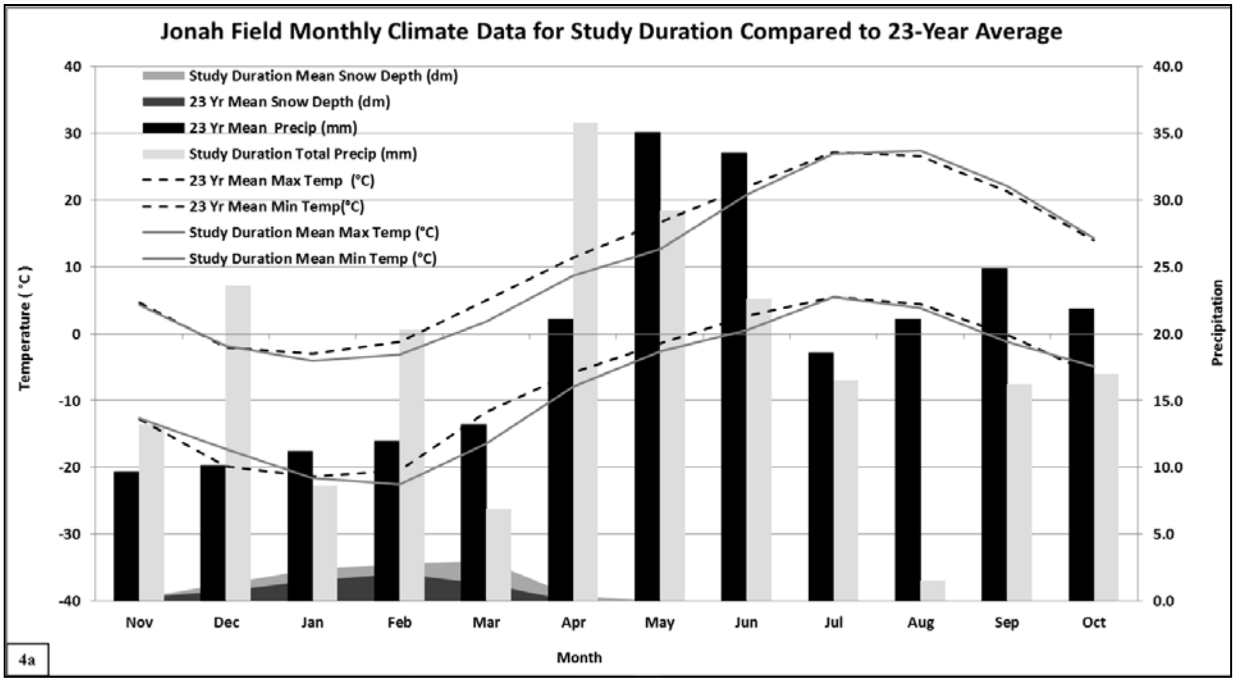


Figure 3a. Satellite imagery of study site area on the Jonah Field and **3b.** Pinedale Anticline (Environemental Systems Research Institute (ESRI), 2012). This satellite imagery does not show recent disturbances, so well-pad sites for our study are not visible.

Climate data was gathered from the Boulder Rearing Station for Jonah Field estimates and the Daniel Fish Hatchery for Pinedale Anticline estimates (Western Regional Climate Center (WRCC), 2012).



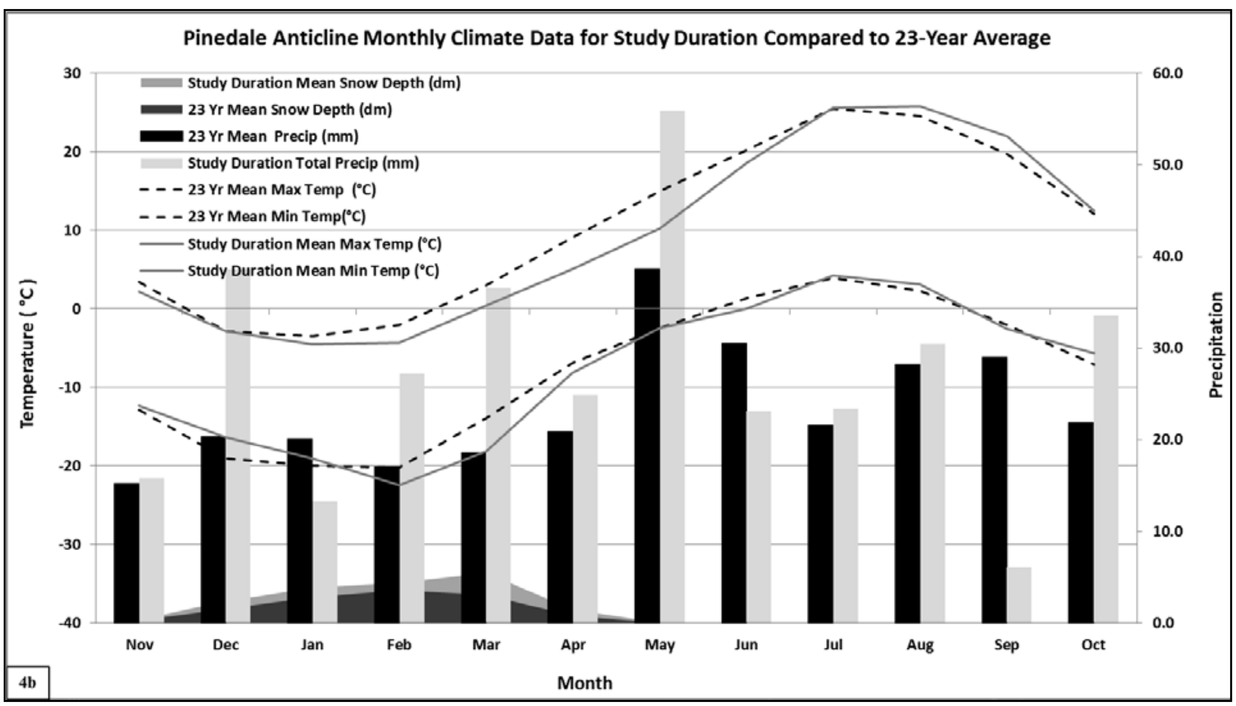


Figure 4a. Monthly climate data for study duration and 23 year average for the Jonah Field study site and 4**b.** Pinedale Anticline study site (WRCC, 2012).

Monthly averages over the period September 1989 to August 2012, a 23 year period, were gathered, in addition to corresponding values for our study duration (Figures 4a and b).The Boulder Rearing Station recorded the following annual data for the 23-year period: mean maximum temperature: 11.9 °C; mean minimum temperature: -7.22 °C; total precipitation: 232 mm; and mean snow depth: 0.487 dm. Our sampling efforts began in late October 2010 and were completed a year later for this study. Climate data annual values for the duration of our study from the Boulder Rearing Station were as follows: mean maximum temperature: 10.9 °C; mean minimum temperature: -8.09 °C; total precipitation: 212 mm; snowfall depth: 0.840 dm. The Pinedale Anticline study site is 84 m higher in elevation, and has cooler temperatures and increased precipitation, compared to the Jonah Filed study site. The Daniel Fish Hatchery recorded the following data for the 23-year period: mean maximum temperature: 10.4 °C; mean minimum temperature: -8.09 °C; total precipitation: 282 mm; mean snow depth: 0.995 dm. Corresponding climate data for the duration of our study from the Daniel Fish Hatchery were as follows: mean maximum temperature: 9.22 °C; mean minimum temperature: -8.31 °C; total precipitation: 323 mm; and snowfall depth: 1.48 dm.

Both sites saw increased snow depths and lower average temperatures, compared to the 23-year average. The temperatures were below avaerage for both study sites from February through June. The Pinedale Anticline saw increased spring precipitation, compared to the 23-year average, and the Jonah Field did during the month of April. Total precipitation on the Pinedale Anticline was much higher during the study duration compared to the 23-year average, while the Jonah Field's total precipitation was slightly lower (see Appendix A for daily climate values for the duration of our study).

The Natural Resource Conservation Service (NRCS) soil survey reports additional soil attributes (Table 1). Included here are also results from our particle size analysis (PSA) on percent sand, silt, and clay for each study site. Both sites had soils in the loam textural class.

Table 1. Soil web survey characteristics and PSA results for the two study sites, located on the Jonah Field and the Pinedale Anticline (NRCS, 2012).

Site	Map Unit	Soil Taxonomy	Parent Material	Sand	Silt	Clay
					%	
Jonah Field	5334-Sweetlette	Fine-loamy mixed,superactive, frigid Ustic Haplargids	Slope residuum weathered from sandstone	48.9	32.1	19.0
Pinedale Anticline	2106-Jemdilon gravelly loam	Fine-loamy,mixed, superactive, frigid Petronodic Ustic Calciargids	Alluvium derived from metamorphic and sedimentary rock	48.4	31.8	19.8

Driessen (2012) described soil properties at undisturbed native areas near our study sites (Table 2). Note the sampling depth here was only 0-5 cm, in contrast to our soil sampling depth of 0-15 cm. Driessen's study confirms presence of alkaline soils at both study sites, with much higher soil total organic C (TOC) and total N (TN) levels on the Pinedale Anticline compared to the Jonah Field.

Table 2. Properties of undisturbed surface soil (0- to 5-cm depth) on the Pinedale Anticline (n=3) and Jonah Field (n=3), natural gas fields. (Printed with permission Driessen, 2012)

SITE	TOC	TN	pH	EC	BD
	g kg^{-1} soil			*dS m^{-1}*	*g cm^{-3}*
Jonah Field	9.98	0.685	7.8	0.30	1.30
Pinedale Anticline	17.6	2.23	7.7	0.33	1.30

Sagebrush steppe plant species form historical climax communities, and are found in the native vegetated areas surrounding the Jonah Field and Pinedale Anticline sites. The NRCS Ecological Site Descriptions (ESD) for the study areas report both the Jonah Field, a rhizomatous wheatgrass/big sagebrush classified site, and the Pinedale Anticline, a mixed grass/big sagebrush classified site, as having *Artemisia tridentata* Nutt. ssp. *wyomingensis* Beetle & Young (Wyoming big sagebrush) as their major woody plant, and both sites also having *Krascheninnikovia lanata* [Pursh] A. Meeuse & Smit (winterfat) and *Ericameria teretifolia*

[Durand & Hilg.] Jeps. (green rabbibrush) as other woody plants. The ESD reports major grasses for both sites to include *Pascopyrum smithii* [Rydb.] Á. Löve (western wheatgrass). Additional major grasses for the Jonah Field include *Achnatherum hymenoides* [Roem. & Schult.] Barkworth (Indian Ricegrass) and *Elymus elymoides* [Raf.] Swezey (bottlebrush squirreltail). Additional major grasses listed by the ESD for the Pinedale Anticline include: *Hesperostipa comata* [Trin. & Rupr.] Barkworth (needle and threadgrass); *Pseudoroegneria spicata* [Pursh] Á. Löve (bluebunch wheatgrass); *Achnatherum lettermanii* [Vasey] Barkworth (Letterman's needlegrass); and *Poa secunda* J. Presl (Canby bluegrass) (NRCS, 2010; United States Department of Agriculture (USDA), 2012) (see Appendix B for more detailed ESD information).

Each well site hosting study plots has a producing well-head, surrounded by a road and turn-around area. During the construction phase of the well-pad, overburden and topsoil materials were removed to a depth of approximately 15-30 cm, and stored in a nearby stockpile. The Jonah Field site's topsoil was stored for approximately five months, and the Pinedale Anticline's site's topsoil was stored for approximately 12 months. Once infrastructure was in place on the well-pad, overburden and topsoil materials were replaced and re-contoured. Topsoil was re-spread on the Jonah Field site during September 2010, and re-spread on the Pinedale Anticline site during October 2010. Following re-contouring and prior to treatment application, the Jonah Field topsoil was chiseled, and the Pinedale Anticline topsoil was scarified. Both of these practices are mechanical methods of breaking up and evening out larger clods of soil with implements to help prepare the seedbed for planting.

Treatment Descriptions

Three treatments: wood chips (WC); straw; and a wood chip and compost mixture (WC+C), were disked into the soil at three rates each (Table 3). All treatment materials were obtained from local resources. Wood chips, produced from stands of primarily *Abies lasiocarpa* (Hook.) Nutt.(subalpine fir); with some *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir); *Pinus contorta* Douglas ex Loudon (lodgepole pine); *Picea pungens* (Engelm. blue spruce); and *Populus tremuloides* Michx. (quaking aspen) trees, were chipped at the Scab Creek trailhead, located approximately 48 km from the study sites and approximately 24 km northeast of Boulder, Wyoming (USDA, 2012). Certified weed-free barley straw was grown in Sublette county, and provided by Encana Oil and Gas Corporation. Compost (see Appendix C for material details) was produced and provided by Terra Firma Organics of Jackson, Wyoming, located 143 km north of Boulder.

Application rates were based on dry weights of treatment material. Treatments were weighed and manually applied to sites during the third week of October 2010. Straw treatments were applied at low: 2,242 kg/ha (2,000 lbs acre^{-1}); medium (med): 6,724 kg/ha (4,000 lbs acre $^{-1}$); and high: 11,209 kg/ha rates (10,000 lbs acre^{-1}).

Table 3. Treatment materials and application rates.

Material	C:N	N content	C Content	Moisture Content	Application Rate-Wet	Application Rate-Dry
		———	%	———	——— *Mg ha^{-1}*	———
Wood Chips	589:1	0.088	51.8	10.4	Low: 6.40	7.07
					Med: 19.2	21.2
					High: 31.9	35.2
Wood Chips	589:1	0.088	51.8	10.4	Low: 3.19	3.52
					Med: 9.60	10.6
+					High: 16.0	17.7
Compost	18:1	0.780	13.9	30.9	Low: 0.360	0.475
					Med: 1.08	1.41
					High: 1.80	2.36
Straw	188:1	0.251	47.1	7.40	Low: 2.24	2.41
					Med: 6.72	7.23
					High: 11.2	12.1

Wood chip and WC+C treatments were applied at equivalent rates to maintain the N content applied in the straw treatments. This allowed comparison of different treatment traits, including their recalcitrance and overall C:N, that might contribute to any significant effects they had. Combining the compost with wood chips ameliorated the high C:N of the wood chips (Table 4), allowing observation of effects of a wider spectrum of C:N across our treatments, as well as any possible additional benefits to soils the compost may provide in reclamation practices.

Treatment descriptions include a high (H), medium (M), or low(L) designation, indicative of the application rate, as well as of the amount of N applied (Table 4). The number following the treatment and N application designation, indicates the ranking of the treatment by the amount of C added by the treatment, one being the lowest amount of C applied, nine being the highest.

Table 4. Treatment C and N content. Wood chips (WC); wood chips/compost (WC+C); and straw followed in parentheses by application and N rate of low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Treatment	N added by treatment	C added by treatment	C:N
	kg ha-^{1}		
Straw (L1)	5.62	1,056	188:1
WC+C (L2)	5.62	1,707	304:1
WC (L4)	5.62	3,314	589:1
Straw (M3)	16.9	3,168	188:1
WC+C (M5)	16.9	5,124	303:1
WC (M8)	16.9	9,948	589:1
Straw (H6)	28.1	5,280	188:1
WC+C (H7)	28.1	8,521	303:1
WC (H9)	28.1	16,541	589:1

Sites were disked twice immediately following application of the treatments for incorporation of materials. Sites were then drill seeded with native seed mixes, developed independently for each location (Appendix D), using Truax drill seeders in early November 2010.

Experimental Design

This study utilized a randomized complete block design. Wood chips, straw, and WC+C treatments incorporated at three rates, along with a control, were randomly replicated four times for a total of 10 plots per block and four blocks per site (Figure 5). One set of blocks was established at the Jonah Field and another set was re-randomized and established at the Pinedale Anticline site in fall 2010 (see Appendix E for plot layout of each site). Test plots measured 3.05 m x 4.57 m (Figure 6), with a 6.10 m buffer surrounding each plot.

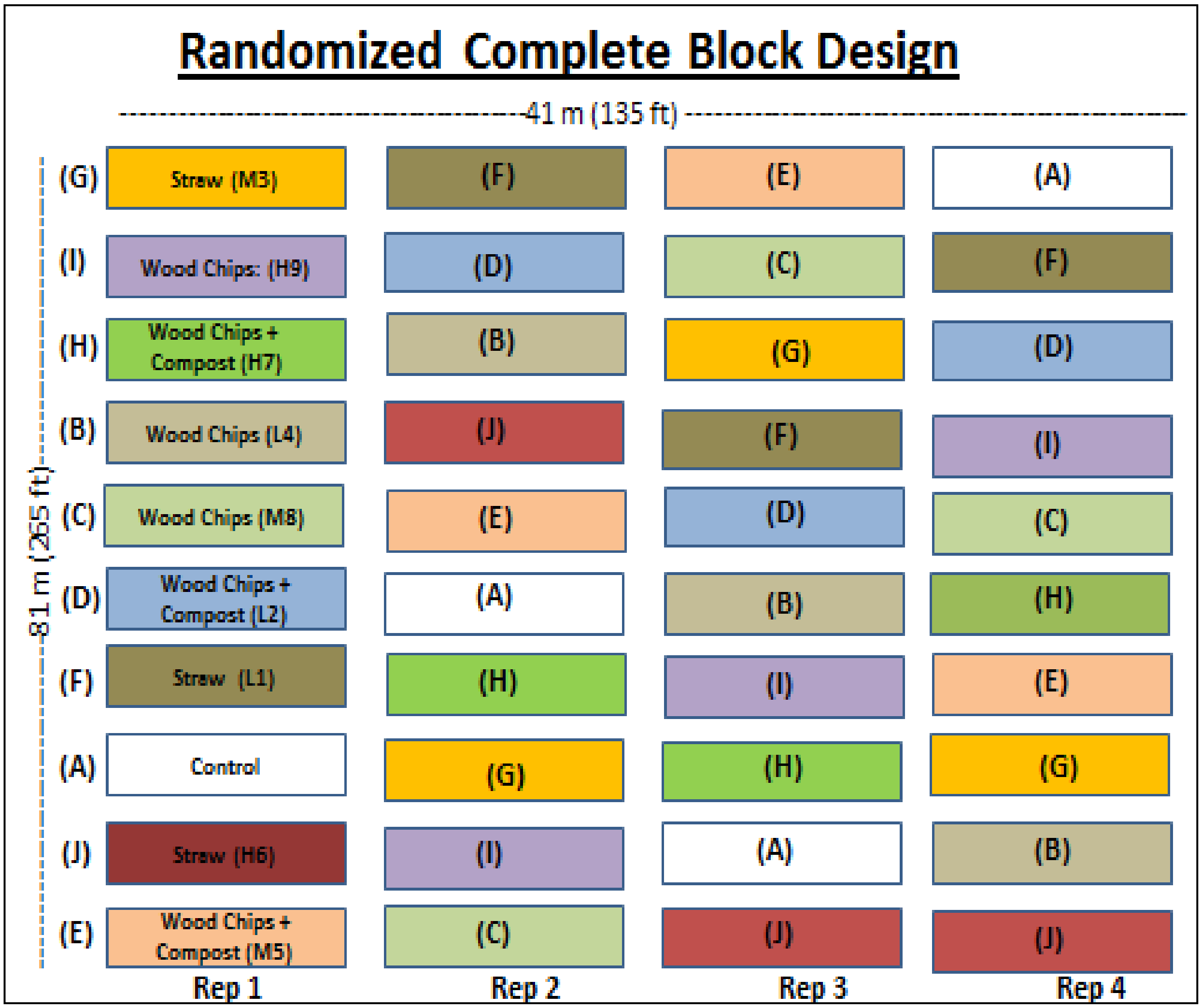


Figure 5. Field plot layout.

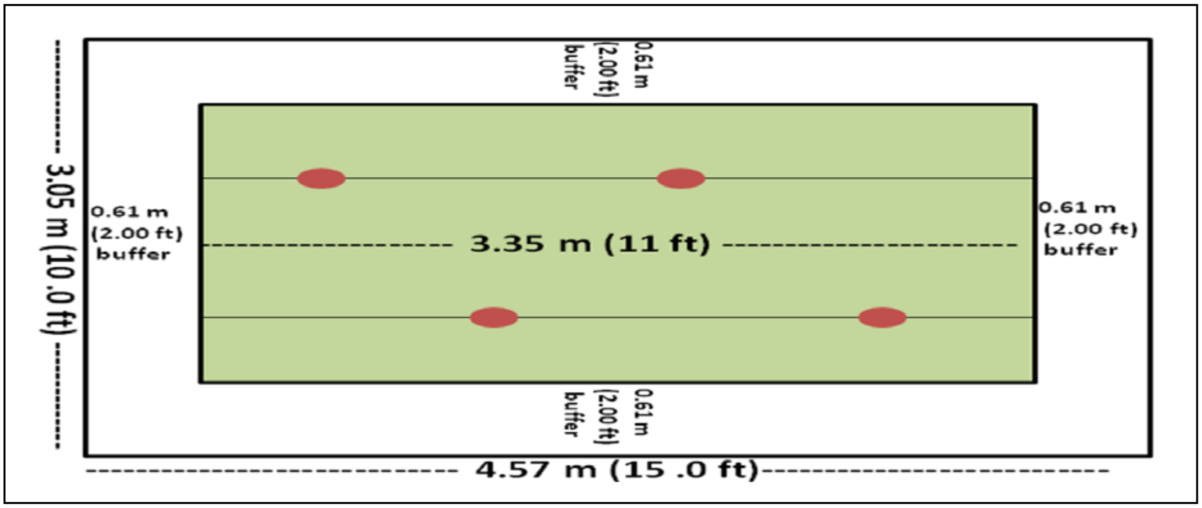


Figure 6. Study plot with vegetation sampling points and transects.

Data Collection

Soil Sampling

The objective for collecting soils data was to test for treatment effects on soil physical and chemical properties including: pH; EC; BD; $CaCO_3$ levels; moisture content; microbial biomass and diversity; and other labile and physically sensitive OM parameters. Another area of investigation pursued for the soils in this study was ascertaining the ability of treatments to induce mineral N immobilization through their C addition. Samples were collected to perform analyses that addressed these questions.

We reserved our analyses to C and N properties of OM found in active pools, as this is where we expected to measure treatment affects over the duration of this study (see Appendix F, Figure 12b for image of OM pools). We measured the C and N levels in several components of the labile OM pool including: dissolved OM, which consists of soluble organic compounds such as organic acids, sugars, and amino acids and originates from plant litter, soil humus, microbial biomass or root exudates (Kalbitz et al., 2000); free light fraction OM , which is often derived from plant and animal exudates and exists in a unique physical arrangement in the soil (Rothamsted Research Group, 2012); potentially mineralizable OM, which represents the amount of OM that would be mineralized in the soil under specific temperature, moisture, aeration, and time parameters, and is an indication of rapidly available levels in the soil (Benedetti and Sebastiani, 1996); and microbial biomass, which is a measure of the amount of total organisms in the soil excluding macrofauna and plant roots (Chu and Grogan, 2010). Additional differentiation of bacterial and fungal pools of microbes can be obtained from PLFA analyses (Frostegard and Baath, 1996), therefore one set of samples underwent these analyses to be included with microbial composition data.

Several studies have documented the negative impacts microbial communities experience when soil is removed, stockpiled, and replaced (Harris et al., 1993; Dangi et al., 2012; Mummey et al., 2002). Ample documentation of improvements organic amendments have on biota also exists and includes studies that specifically found increases in microbial biomass C (MBC) and microbial biomass N (MBN) following organic additions to degraded soils (Ros et al., 2003; Mabuhay et al., 2006; Belyaeva and Haynes 2009), and increases in microbial biomass fatty acid biomarkers through PLFA analyses (Marchner et al., 2003). Organic additions have also been shown to have positive effects on other OM pools including increases in dissolved organic C (DOC), dissolved organic N (DON) (Kalbitz et al., 2000), potentially mineralizable C (PMC), potentially mineralilzable N (PMN), total organic C (TOC), total N (TN) (Nahar et al., 2006; Zvomya et al., 2007), and FLFOM (Ryals and Silver, 2011). We expected overall increases by treatments to SOM measured through increased levels of soil TOC, TN, %FLF, FLFC, FLFN, MBC, MBN, PMC, PMN, DOC, DON and fatty acid biomarkers. We also predicted our treatments to decrease total mineral N concentrations.

Soil samples were collected three times from each plot during the study. Baseline samples were collected in fall 2010 after topsoil was re-spread, and treatments were applied. Soils were sampled again in early June 2011, to capture peak microbial activity, and during the third week of October 2011, to correspond with the baseline sampling event. Eight soil subsamples were collected by auger from the topsoil layer (0-15 cm) and mixed for one composite sample. Two samples were collected from this composite, one for non-time sensitive analyses, and another that underwent immediate analysis upon return to the laboratory. These time-sensitive samples were kept on ice in coolers as they were collected and transported. An additional sample was collected from the composites in spring 2011 for PLFA analyses. These samples were frozen until analyzed. Bulk density samples were collected from each plot during each sampling event. The NRCS method, which utilizes water density properties, was used for baseline and spring BD sampling due to the rockiness or lack of structure found in many plots. Values from these samples proved unreasonable, however, prompting use of the clod method for the final fall 2011 sampling event. Results for BD from the clod method proved more reasonable, and are therefore the sole values presented for BD.

Soil Laboratory Analysis

Physical and Chemical Properties: Electrical conductivity and then pH were obtained using an electrode submerged in a 2:1 deionized water to soil solution (Thomas, 1996). Bulk density was determined using the clod method (Blake and Hartge, 1986). Particle size analysis was performed using a hydrometer method (Gavlak et al., 2005; Gee and Bauder, 1979). Gravimetric moisture content was measured by weighing field moist samples before and after oven drying, and is reported on a dry weight basis (Gardner, 1986). Percent $CaCO_3$ was obtained by acidifying soils and measuring the resulting pressure with a pressure calcimeter (Sherrod et al., 2002).

Labile OM Properties: Potentially mineralizable C values were calculated by collecting respired C dioxide (CO_2) concentrations on days one, four, seven, and 14 of an aerobic incubation (Zibilske, 1994) and measuring infusions on a gas analyzer (Li-Cor 820 Lincoln, NE). Potentially mineralizable N was measured from potassium sulfate (K_2SO_4) extractions collected at the beginning and end of the two week incubation described above for PMC and processed as described below for mineral N.

Non-fumigated and chloroform-fumigated samples extracted with K_2SO_4 (Horwath and Paul, 1994), were run on a TOC/N analyzer and yielded values for C and N concentrations in pools of: DON, DOC, MBN, and MBC (Shimadzu TOC-VCPH with TNM-1 Scientific Instrument Inc. Columbia, MD). Additional samples were sieved, finely ground, and then analyzed for total C (TC) and TN by combustion (Nelson and Sommer, 1982) on an NC 2100 elemental analyzer (EA) (Carlo Erba Instruments, Milan, Italy). Inorganic C (IC) was calculated from the $CaCO_3$ values and TOC was calculated by subtracting the IC values from the TC values.

Although multiple OM fractions are typically collected during density fractionation, we did not expect effects on OM pools with longer turnover rates to be observed in this study, so restricted our collection to only the physical OM pool, which is most sensitive to land management changes, the FLF. Free light fraction OM is less dense than other physical fractions of the soil and can be collected by monopolizing this unique property. Fractionation through use of sodium iodide (NaI), prepared at a density of 1.80 g cm^{-3}, was utilized to collect the less dense FLF from the soil sample, leaving behind the remaining occluded and mineral fractions. This

FLF was then analyzed for free light fraction FLFC and FLFN on the EA (Sohi et al., 2001) (see Appendix F: Figure 14 for image describing OM fractionation).

Microbial Composition Properties: Measurements for PLFA levels were gathered through utilization of a 1:2:0.8 chloroform/methanol/phosphate buffer extraction solvent and underwent silica based separation of PLFA from neutral and glycolipid fatty acids followed by mild alkaline methanolysis and purification in an amino chromatography column (Frostegard and Baath, 1991; Buyer et al., 2002; Bligh and Dyer, 1959). Extracts were analyzed on an Agilent 6890 gas chromatograph (Agilent Technologies, Palo Alto, CA) with Sherlock software (Microbial ID ver. 4.5 Newark, DE). Gram positive and negative bacteria were summed for total bacteria and arbuscular mychorrhizal fungi and other fungi were summed for total fungi (see Appendix F for biomarkers used).

Mineral N Properties: Lab analyses conducted to determine the mineral N concentrations included measuring NO_3^--N and NH_4^+-N from K_2SO_4 extractions (Hart et al., 1994). These nutrients are summed for total mineral N (TMN) and PMN. Only the summed NO_3^- - N and NH_4^+ -N concentrations are presented in the results (see Appendix H: Tables 44-48 for presentation of NO_3^- and NH_4^+ concentrations separately). All N extractions were run on a microplate spectrophotometer (Biotek Inc., Winooski, VT) to capture NO_3^- (Doane and Horwath, 2003) and NH_4^+ (Weatherburn,1967) concentrations (see Appendix F for further details on all lab analyses).

Vegetative Measurements

The objectives for collecting vegetative data were to test for treatment effects on densities of seeded native versus non-seeded invasive plant species, as well as treatment effects on ground cover. Vegetation data was collected during peak growth, over the third week of July, 2011. Two transects were established in each plot, with two sampling points per transect (Figure 6). A quarter m^{-2} frame was placed at the center of each sampling point, and every plant in the frame was recorded. The four quadrats were summed for a plants m^{-2} value.

Estimated percent cover of vegetation, rock, litter/treatment, and vegetation were also recorded. A scale of 1-6 was used to estimate cover, with the following range represented by each number: 1: 0-5%; 2: 6-25; 3: 26-50%; 4: 51-75%; 5: 76-95%; 6:96-100% (Elzinga et al., 1998).

Data Analysis and Presentation

All data underwent a one way analysis of variance (ANOVA) set in a randomized complete block design with an alpha of 0.10 selected. When the ANOVA indicated differences among treatments, Fisher's Protected LSD was used for all mean separations. Statistical computations were facilitated by using the GLM procedure of the Statistical Analysis System (ver. 9.2, SAS Institute. Cary N.C.). Response variables with unequal variances were analyzed using a weighted ANOVA; weights used were the inverse of $(S^2i)^{-2}$, where S^2i was the variance of the ith treatment. Data for the Jonah Field and Pinedale Anticline is grouped when no significant site by treatment interaction occurred, but there was a significant treatment effect ($P \leq 0.10$). Data for the two sites is presented separately when there was not a significant site by treatment interaction nor any significant treatment effects (see Appendix G for ANOVA tables on all data).

Soils

Baseline data, reported to provide information regarding soil conditions for the sites at the beginning of the study, was generated from the control plots mean values for TOC, TN, pH, and EC collected during fall 2010 sampling. Values were provided for these baseline soil properties because they can be compared to the undisturbed nearby native site data (Driessen, 2012), and exemplify the effects drastic disturbances have on native soil conditions. Although Driessen's data is from soil samples collected in the top 0-5 cm, while we sampled to a depth of 0-15 cm, reclaimed topsoil is often homogenized throughout the top 15 cm when replaced, making a deeper sampling more reflective of topsoil properties. The final physical and chemical soil properties data came from the fall 2011 sampling event, and is presented following baseline soils data to provide a comparison between soil conditions that exist following reclamation disturbances, with those present at the study's commencement, after treatment effects occurred.

The baseline and final soil property data are followed by soils results OM and mineral N properties from spring 2011 and then the fall 2011 sampling events. In general, the same measurements were made in spring and fall 2011, the exception being the inclusion of PLFA values for microbial composition results in the spring data only, and the inclusion of OM fractionation values in the fall data only. Otherwise values for soil TOC, TN, MBC, MBN, DOC, DON, PMC, PMN, and TMN are provided from the spring and fall 2011 sampling events in their respective sections.

The entire fall 2010 dataset was used as a covariate term in our ANOVA models run on spring and fall 2011 soils data, with the exception of the PLFA and BD values, as these have data from only one sampling event. If the covariate term was found to be significant, it remained in the model throughout mean separations.

Vegetation

The straw-treated plots on the Jonah Field and the Pinedale Anticline experienced germination from the treatment itself, with emergence and establishment of barley. Because this was not part of the native seed mixture used for reclamation, this species was given its own grouping of volunteer barley for data analysis. Initial analyses presented include the groupings (excluding volunteer barley) of seeded grasses, forbs, and shrubs into a total-seeded species grouping to be analyzed against the volunteer barley and non-seeded invasive plant groups. The means separation for each group of seeded grasses, forbs, and shrubs is then presented separately. For the ground cover data, the midpoint percentage of the cover range was the value used for data analysis.

Treatment Costs

When comparing treatment costs, we considered the delivered material, application, and incorporation costs as these were the only expenditures, above normal reclamation practices such as topsoil replacement and seeding practices, which our treatments induced. Reclamation work is often put up for bid by outside contractors on a yearly basis, therefore gross fluctuation in cost of practices exists by contractor, location, year, and site conditions (Eldridge, 2009 reports a cost analysis for similar treatments from a Colorado study). In attempt to consider reclamation cost discrepancies, we averaged cost information from prior use of WC and straw on the Jonah Field and Pinedale Anticline, to estimate our application and incorporation costs. We combined this information with costs of materials and the application rates used in our study, to provide estimated overall treatment costs.

RESULTS

Soils

General predictions on investigated soils parameters proved significantly true for several variables, and appear to be moving toward significance for a few additional variables. Baseline soil results show normal disturbance responses by the reclaimed soils, with decreased levels of soil TOC and increases in pH at the beginning of our study. By the study’s end, there were indications that treated soils had increases in labile organic C, with subsequent positive effects to soil physical and chemical properties. Significant immobilization of labile and mineral N also resulted from most of our treatments.

Free light fraction OM was significantly increased in three treatments at both sites, and the same true for FLFC in five treatments at both sites, while FLFN was decreased in four treatments on the Pinedale Anticline. Total organic C and N results were mostly insignificant across spring and fall 2011 sampling, but did show a likely trend toward increases, especially on the Pinedale Anticline. Potentially mineralizable and dissolved organic C showed generally higher levels in soils under treatments, with this almost always the case for soils under high WC plots and often true in soils under the high straw plots. The same trend occurred for soil PMN and DON, but with a decrease in N levels in high straw and WC plots.

Microbial biomass showed indications of general increases in soil MBC and MBN, especially on the Jonah Field. Soil fungi results were not significant, but seem to be on a path toward increased numbers in treated plots, while bacteria showed decreased levels in all straw and the high WC+C treated plots. All treatments significantly lowered total mineral N and almost all treatments significantly lowered pH at both sites. The high straw treatment at both sites was the only treatment with significantly higher soil moisture by the study's end. Several treatments significantly lowered $CaCO_3$ in soils on the Pinedale Anticline site. Soil bulk density showed nearly significant differences, with means at both sites highest in the control plots.

Fall 2010 Baseline Soil Properties:TOC, TN, pH, and EC

Table 5 below presents data for baseline soil properties measured from control plots' soil samples collected, following reclamation practices at this study's initiation. These baseline data reflect typical changes soils experience upon disturbance, with notably lower soil TOC at both sites, and higher pH levels than soils of the native sites sampled in Driessen's study (Table 2). Total soil organic C levels at the beginning of our study were about half that reported for TOC in soils of nearby undisturbed sites.

We also see here site characteristic differences reflected in the higher TOC and TN levels on the Pinedale Anticline, compared to the Jonah Field. The Pinedale Anticline receives higher mean annual precipitation, which contributes to increased above and below-ground biomass and SOM. This increased SOM also likely helps buffer pH, which explains the lower pH but higher EC values measured in Pinedale Anticline soils, compared to the Jonah Field soils.

Table 5. Soil properties measured from control plots during fall 2010 baseline soil sampling on the Jonah Field and Pinedale Anticline. Values are means; (standard error).

Site	TOC	TN	pH	EC
	———g kg^{-1} soil———			dS m^{-1}
Jonah Field	4.26 (0.625)	0.688 (0.089)	7.97 (0.074)	0.278 (0.005)
Pinedale Anticline	9.01 (1.06)	1.48 (0.111)	7.94 (0.066)	0.474 (0.091)

Fall 2011 Final Physical and Chemical Soil Properties: pH, EC, GM, BD, and $CaCO_3$

Soils under most treatments had lower mean pH values compared to the control (Table 6). Both study sites showed a similar range in pH, compared to control plots by the final fall 2011 sampling event. With the exception of the low WC application, all treatments had significantly lower pH values than the control on the Jonah Field. Also on the Jonah Field, treatments with the highest N, C, and material application rates had the lowest pH values. All treatments on the Pinedale Anticline had significantly lower pH values than the control. The only treatment with significantly higher soil moisture content than the control at the final sampling event, was the high straw application at both study sites (Table 6).

Values for EC (see Appendix F: Table 49 for EC means) were not significantly different at either site by the study's end.

Table 6. Final pH and moisture values for the Jonah Field and Pinedale Anticline soils. Values are means; (standard error); different letters indicate significant differences at $P \leq 0.10$.

pH		pH		Gravimetric Moisture	
*Treatment	Jonah Field	Treatment	Pinedale Anticline	Treatment	Jonah Field & Pinedale Anticline
					%
Control	7.99 (0.042) a	Control	7.89 (0.033) a	Straw (H6)	14.5 (0.802) A
WC (L4)	7.89 (0.069) ab	WC (L4)	7.71 (0.010) b	WC (L4)	13.4 (0.871) AB
WC+C (L2)	7.84 (0.071) bc	Straw (L1)	7.71 (0.035) b	Control	12.6 (0.643) BC
Straw (L1)	7.81 (0.102) bcd	WC+C (M5)	7.68 (0.045) bc	Straw (M3)	12.5 (0.623) BC
Straw (H6)	7.80 (0.042) bcd	WC+C (H7)	7.68 (0.036) bc	Straw (L1)	12.5 (0.627) BC
Straw (M3)	7.77 (0.082) bcd	WC (H9)	7.68 (0.031) bc	WC (H9)	12.5 (0.613) BC
WC (M8)	7.75 (0.097) bcd	Straw (M3)	7.67 (0.033) bc	WC+C (L2)	12.3 (0.523) BC
WC+C (H7)	7.72 (0.087) cde	WC (M8)	7.66 (0.025) bc	WC+C (H7)	11.9 (0.565) C
WC+C (M5)	7.66 (0.115) de	Straw (H6)	7.66 (0.030) bc	WC+C (M5)	11.7 (0.591) C
WC (H9)	7.60 (0.040) e	WC+C (L2)	7.62 (0.006) c	WC (M8)	11.7 (0.666) C

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Soil BD values were nearly significant across treatments (P = 0.101), with control plots trending toward higher means than treated plots (Table 7).

Table 7. Final bulk density for the Jonah Field and Pinedale Anticline soils. Values are means; (standard error).

Bulk Density		Bulk Density	
*Treatment	Jonah Field	Treatment	Pinedale Anticline
	g cm^{-3}		g cm^{-3}
Control	1.44 (0.022)	Control	1.60 (0.059)
Straw (L1)	1.44 (0.023)	WC (M8)	1.37 (0.054)
WC+C (M5)	1.425 (0.110)	WC+C (H7)	1.35 (0.118)
WC+C (L2)	1.42 (0.109)	WC (L4)	1.29 (0.060)
Straw (M3)	1.41 (0.036)	Straw (L1)	1.28 (0.052)
WC+C (H7)	1.41 (0.072)	Straw (H6)	1.27 (0.125)
WC (M8)	1.39 (0.052)	WC (H9)	1.26 (0.047)
Straw (H6)	1.36 (0.058)	WC+C (L2)	1.26 (0.040)
WC (L4)	1.36 (0.071)	WC+C (M5)	1.21 (0.057)
WC (H9)	1.34 (0.077)	Straw (M3)	1.18 (0.062)

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Levels of $CaCO_3$ were much higher in surface soils of the Pinedale Anticline than in those of the Jonah Field (Table 8). Although no treatment had significant effects on $CaCO_3$ content on the Jonah Field, on the Pinedale Anticline, all soils treated with straw, as well as those with the low WC+C, and the high and low WC treatments, had the lowest $CaCO_3$ levels compared to the other treatments and control.

Table 8. $CaCO_3$ for the Jonah Field and Pinedale Anticline soils. Values are means; (standard error); different letters indicate significant differences at P≤ 0.10.

Calcium Carbonate

*Treatment	Jonah Field	Treatment	Pinedale Anticline
	%		%
WC (L4)	1.93 (0.47)	Control	5.10 (0.77) a
WC+C (M5)	1.92 (0.78)	WC (M8)	4.75 (0.36) a
Straw (L1)	1.84 (0.42)	WC+C (H7)	4.52 (0.69) a
Control	1.79 (0.30)	WC+C (M5)	4.49 (0.18) a
Straw (M3)	1.76 (0.39)	WC (L4)	3.86 (0.42) b
Straw (H6)	1.75 (0.26)	WC (H9)	3.73 (0.21) bc
WC (M8)	1.74 (0.79)	WC+C (L2)	3.69 (0.40) bc
WC+C (L2)	1.69 (0.49)	Straw (L1)	3.19 (0.36) bc
WC+C (H7)	1.65 (0.69)	Straw (M3)	2.83 (0.51) c
WC (H9)	1.42 (0.06)	Straw (H6)	2.51 (0.72) c

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Spring 2011 Microbial Community; Labile Organic Matter C and N; and Mineral N Properties

Data from PLFA analyses yielded values for total bacteria, gram positive and gram negative bacteria, total fungi, and arbuscular mycorrhizal fungi. No significant differences existed in the PLFA results for total fungi and arbuscular mycorrhizal fungi (see Appendix H: Tables 51-52 for means). In general, soil microbial fatty acid levels were higher on the Pinedale Anticline site than the Jonah Field. The PLFA measurements for total soil bacteria only showed significant treatment effects on the Pinedale Anticline, with all soils under the straw treatments and the high WC+C treatment having significantly lower fatty acid levels than the control plots and most other treatments (Table 9).

Table 9: Total bacteria for the Jonah Field and Pinedale Anticline soils. Values are means; (standard error); different letters indicate significant differences at P≤ 0.10.

*Treatment	Jonah Field	Treatment	Pinedale Anticline
	nmol FA g^{-1} soil		*nmol FA g^{-1} soil*
WC+C (L2)	0.600 (0.601)	WC+C (M5)	1.20 (0.182) a
Control	0.500 (0.634)	WC (L4)	1.14 (0.785) a
Straw (M3)	0.475 (0.041)	Control	1.33 (0.110) a
WC+C (H7)	0.468 (0.067)	WC+C (L2)	1.12 (0.115) a
WC (L4)	0.461 (0.109)	WC (M8)	1.04 (0.146) a
WC (M8)	0.459 (0.076)	WC (H9)	1.01 (0.092) ab
Straw (H6)	0.431 (0.073)	WC+C (H7)	0.794 (0.125) bc
WC (H9)	0.422 (0.038)	Straw (L1)	0.738 (0.097) c
WC+C (M5)	0.400 (0.065)	Straw (M3)	0.733 (0.142) c
Straw (L1)	0.368 (0.138)	Straw (H6)	0.656 (0.069) c

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Soil bacteria were further divided into G-positive and G-negative groups for PLFA analyses. No significant treatment affects occurred for G-negative bacteria (see Appendix H: Table 50 for means).

Table 10: G-positive bacteria for the Jonah Field and Pinedale Anticline soils. Values are means; (standard error); different letters indicate significant differences at P≤ 0.10.

G- Positive Bacteria		**G- Positive Bacteria**	
*Treatment	Jonah Field	Treatment	Pinedale Anticline
	nmol FA g^{-1} soil		*nmol FA g^{-1} soil*
WC+C (L2)	0.249 (0.041)	WC+C (M5)	0.606 (0.043) a
Control	0.205 (0.024)	WC+C (L2)	0.599 (0.057) a
Straw (H6)	0.184 (0.044)	WC (L4)	0.598 (0.073) a
WC (L4)	0.173 (0.054)	Control	0.598 (0.105) a
Straw (M3)	0.171 (0.030)	WC (M8)	0.575 (0.089) a
WC+C (H7)	0.167 (0.032)	WC (H9)	0.476 (0.051) ab
WC (M8)	0.165 (0.018)	WC+C (H7)	0.370 (0.068) bc
WC (H9)	0.149 (0.027)	Straw (L1)	0.325 (0.060) c
WC+C (M5)	0.136 (0.033)	Straw (M3)	0.318 (0.081) c
Straw (L1)	0.127(0.074)	Straw (H6)	0.299 (0.033) c

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

The PLFA results for total soil bacteria on the Pinedale Anticline were repeated for the G-positive group, with the straw and high WC+C treatments having significantly lower values of fatty acids per gram of soil than most other treatments and the control (Table 10).

The soil MBC and MBN values varied greatly in their trends compared to total fatty acid data. There were no significant differences in soil MBC seen across either site during the spring (see Appendix H: Table 53 for means). Microbial biomass N did show significant treatment effects, however. On the Jonah Field, the medium straw and high WC+C treatments had significantly higher MBN values than the control and low WC treatment (Table 11).We also found significantly higher MBN values on the Pinedale Anticline in the high straw treatments, as compared to the control and all of the WC+C treatments.

Table 11. Microbial biomass N for the Jonah Field and Pinedale Anticline soils from spring 2011. Values are means; (standard error); different letters indicate significant differences at $P \leq 0.10$.

Microbial Biomass N		**Microbial Biomass N**	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	mg MBN kg⁻¹soil		*mg MBN kg⁻¹soil*
Straw (M3)	8.03 (1.01) a	Straw (H6)	10.7 (1.05) a
WC+C (H7)	7.15 (0.991) ab	Straw (M3)	8.60 (0.928) ab
Straw (L1)	6.28 (0.967) abc	WC (L4)	6.97 (0.922) ab
Straw (H6)	6.03 (0.971) abc	WC (M8)	6.91 (0.939) ab
WC+C (M5)	5.74 (0.934) bc	WC (H9)	6.28 (1.03) ab
WC (H9)	5.68 (0.645) bc	Straw (L1)	6.11 (0.949) ab
WC+C (L2)	5.50 (1.03) bc	WC+C (M5)	5.72 (0.986) b
WC (M8)	5.06 (0.982) bc	WC+C (H7)	5.48 (0.986) b
WC (L4)	4.56 (0.993) c	WC+C (L2)	4.78 (0.945) b
Control	2.84 (0.936) c	Control	4.17 (0.942) b

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Additional labile SOM properties were also assessed through collection of values for soil TOC, PMC, TN, PMN, DOC, and DON. No significant differences were seen for soil TOC on the Jonah Field or Pinedale Anticline during spring 2011 sampling (see Appendix H: Table 54 for means). Several treated soils did have significantly higher PMC values than the control plots at both study sites, however (Table 12). The high straw, WC, and WC+C and the medium WC and WC+C treatments, had the highest PMC values. With exception to the low straw, treatments with the high and medium application rates had soils with more PMC.

Table 12. Potentially mineralizable C and N on the Jonah Field and Pinedale Anticline soils from spring 2011. Values are means ; (standard error); different letters indicate significant differences at $P \leq 0.10$.

Potentially Mineralizable C		**Potentially Mineralizable N**	
*** Treatment**	**Jonah Field & Pinedale Anticline**	**Treatment**	**Jonah Field & Pinedale Anticline**
	g PMC kg $^{-1}$soil		*mg PMN kg $^{-1}$soil*
Straw (H6)	5.70 (0.444) A	Control	24.0 (2.29) A
WC (H9)	5.11 (0.419) AB	WC+C (L2)	19.0 (2.19) AB
WC+C (H7)	5.05 (0.418) AB	WC (L4)	14.6 (2.20) BC
Straw (M3)	4.98 (0.436) AB	WC (M8)	10.6 (2.20) CD
WC (M8)	4.74 (0.439) ABC	WC+C (M5)	10.5 (2.17) CD
Straw (L1)	4.10 (0.419) BCD	WC+C (H7)	8.69 (2.17) DE
WC+C (M5)	3.74 (0.423) CDE	Straw (L1)	7.14 (2.17) DE
WC+C (L2)	3.37 (0.425) DE	Straw (H6)	4.96 (2.19) E
WC (L4)	3.12 (0.419) DE	WC (H9)	4.48 (2.66) E
Control	2.79 (0.433) E	Straw (M3)	3.73 (2.19) E

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Potentially mineralizable N levels were significantly higher in the control plots compared to all treatments, except the low WC+C. The high and medium straw treatments, and high WC treatments had lower PMN levels compared to all but the low straw and high WC+C treatments (Table 12).

Generally, levels of soil TN were higher and showed significant treatment effects on the Pinedale Anticline compared to the Jonah Field (Table 13). The control, medium WC, and low WC+C treatments had the least soil TN, compared to the medium straw and high WC+C.

Table 13. Total N on the Jonah Field and Pinedale Anticline soils from spring 2011. Values are means ; (standard error); different letters indicate significant differences at $P \leq 0.10$.

Total N *Treatment	Jonah Field	Total N Treatment	Pinedale Anticline
	g TN kg $^{-1}$*soil*		*g TN kg* $^{-1}$*soil*
Control	0.794 (0.090)	Straw (M3)	2.44 (0.178) a
WC (M8)	0.716 (0.116)	WC+C (H7)	2.38 (0.029)ab
WC+C (M5)	0.709 (0.081)	WC+C (M5)	2.16 (0.055) bc
WC+C (H7)	0.696 (0.047)	WC (H9)	2.15 (0.270) bc
WC+C (L2)	0.679 (0.100)	Straw (H6)	2.02 (0.193) cd
WC (H9)	0.664 (0.056)	Straw (L1)	1.95 (0.148) cde
Straw (M3)	0.631 (0.085)	WC (L4)	1.80 (0.106) de
Straw (H6)	0.591 (0.066)	WC+C (L2)	1.72 (0.039) ef
WC (L4)	0.566 (0.091)	WC (M8)	1.52 (0.078) f
Straw (L1)	0.544 (0.064)	Control	1.52 (0.224) f

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Both dissolved organic C and N showed significant differences across treated soils during spring 2011 (Table 14).

Table 14. Dissolved organic C for the Jonah Field and Pinedale Anticline soils from spring 2011. Values are means; (standard error); different letters indicate significant differences at $P \leq 0.10$.

Dissolved Organic C *Treatment	Jonah Field	Dissolved Organic C Treatment	Pinedale Anticline
	mg DOC kg $^{-1}$*soil*		*mg DOC kg* $^{-1}$*soil*
WC (H9)	32.0 (2.56) a	Straw (H6)	52.5 (2.56) a
Straw (M3)	30.8 (2.39) a	WC (H9)	41.3 (2.50) b
WC+C (H7)	29.0 (2.39) ab	WC (M8)	31.6 (2.39) c
Straw (L1)	27.3 (2.46) abc	WC+C (H7)	31.2 (2.42) c
Straw (H6)	23.7 (2.42) bcd	WC (L4)	29.4 (2.46) c
WC+C (M5)	22.5 (2.81) cd	Straw (M3)	29.3 (2.47) c
WC+C (L2)	18.9 (2.44) d	WC+C (L2)	28.9 (2.39) c
Control	18.8 (2.57) d	WC+C (M5)	27.7 (2.46) c
WC (M8)	18.3 (2.66) d	Straw (L1)	27.7 (2.41) c
WC (L4)	18.1 (2.44) d	Control	26.6 (2.40) c

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

The high WC and WC+C and medium and low straw treatments had significantly higher soil DOC than most other treatments and the control on the Jonah Field. On the Pinedale Anticline, the high straw and WC treatments had significantly higher soil DOC values than all other treatments and the control.

Dissolved organic N levels were significantly higher in the control plot soils compared to all other treatments, except the low WC+C treatments at both sites (Table 15). The control, low WC+C, and low WC had significantly more soil DON than the high WC treatment.

Table 15. Dissolved organic and total mineral N for the Jonah Field and Pinedale Anticline soils from spring 2011.Values are means; (standard error); different letters indicate significant differences at P≤ 0.10.

Dissolved Organic N		**Total Mineral N**	
Treatment	**JonahField & Pinedale Anticline**	**Treatment**	**Jonah Field & Pinedale Anticline**
	mg DON kg $^{-1}$soil		*mg TMN kg $^{-1}$soil*
Control	2.94 (0.168) A	Control	20.00 (2.01) A
WC+C (L2)	2.56 (0.163) AB	WC (L4)	15.4 (1.98) AB
WC (L4)	2.38 (0.161) BC	WC+C (L2)	14.8 (2.00) B
Straw (H6)	2.14 (0.162) CD	WC+C (M5)	8.60 91.96) C
WC+C (M5)	2.13 (0.161) CD	Straw (L1)	7.28 (2.00) CD
Straw (L1)	2.08 (0.169) CD	Straw (H6)	7.15 (1.98) CD
WC+C (H7)	2.06 (0.161) CD	WC (M8)	5.89 (1.98) CD
WC (M8)	2.01 (0.161) CD	WC+C (H7)	5.26 (2.03) CD
Straw (M3)	1.91 (0.161) CD	WC (H9)	4.24 (1.96) CD
WC (H9)	1.77 (0.161) D	Straw (M3)	3.92 (1.97) D

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

The Jonah Field and Pinedale Anticline had similar responses to treatment effects on TMN soil levels during spring 2011 sampling (Table 15). The control plots had the highest mineral N values, compared to all treatments except the low WC treatment. Also with exception of the low straw treatment, soil TMN levels were lowest in medium and high-application treated plots.

Fall 2011 Labile Organic Matter C and N and Mineral N Properties

Percent FLFOM recovered during fractionation at both sites, was significantly higher for the medium and high WC treatments and the high WC+C treatments as compared to the control and low WC and WC+C treatments (Table 16). The amount of FLFC was significantly higher in all WC and the low and medium WC+C applications, than in the control, with varying levels of significance among the other treatments.

Table 16. Free light fraction OM and free light fraction C for the Jonah Field and Pinedale Anticline soils from fall 2011. Values are means; (standard error); different letters indicate significant differences at P$\leq$0.10.

% Free Light Fraction OM		**Free Light Fraction C**	
Treatment	**Jonah Field & Pinedale Anticline**	**Treatment**	**Jonah Field & Pinedale Anticline**
	% FLFOM		*g FLFC kg^{-1}FLF*
WC (M8)	2.11 (0.185)A	WC (L4)	232 (27.6) A
WC+C (H7)	2.00 (0.179) AB	WC (H9)	228 (30.5) AB
WC (H9)	1.96 (0.183) AB	WC+C (L2)	221 (13.7) ABC
Straw (H6)	1.75 (0.182) ABC	WC+C (M5)	212 (13.6 ABCD
Straw (L1)	1.71 (0.180) ABC	WC (M8)	203 (33.4) BCD
Straw (M3)	1.71 (0.191) ABC	Straw (H6)	200 (26.7) CDE
WC+C (M5)	1.64 (0.182) BC	Straw (L1)	192 (28.7) CDE
WC (L4)	1.47 (0.180) C	WC+C (H7)	185 (24.7) CDE
WC+C (L2)	1.36 (0.205) C	Straw (M3)	177 (22.7) DE
Control	1.35 (0.181) C	Control (0)	170 (20.1) E

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Free light fraction N only showed significant treatment effects on the Pinedale Anticline. Free light fraction N was highest in low WC+C and WC and medium WC+C and control, compared to than the other treatments (Table 17).

Table 17. Free light fraction nitrogen for the Jonah Field and Pinedale Anticline soils from fall 2011. Values are means; (standard error); different letters indicate significant differences at $P \leq 0.10$.

Free Light Fraction N		Free Light Fraction N	
*Treatment	Jonah Field	Treatment	Pinedale Anticline
	g FLFN kg^{-1}FLF		*g FLFN kg^{-1}FLF*
Control	15.7 (0.432)	WC+C (L2)	14.5 (1.03) a
WC (L4)	15.6 (0.752)	WC+C (M5)	12.8 (1.25) a
WC (M8)	15.4 (0.751)	Control	12.7 (1.93) a
WC+C (L2)	15.2 (0.526)	WC (L4)	12.2 (2.00) a
WC+C (M5)	14.7 (0.559)	Straw (M3)	8.52 (1.63) b
WC+C (H7)	14.4 (1.11)	WC (M8)	8.45 (1.20) b
Straw (H6)	13.8 (1.26)	Straw (L1)	8.33 (0.589) b
Straw (L1)	13.7 (0.834)	WC+C (H7)	7.92 (0.459) b
Straw (M3)	13.0 (.714)	Straw (H6)	7.64 (0.198) b
WC (H9)	12.7 (1.24)	WC (H9)	6.73 (0.439) b

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Unlike soil MBC levels in the spring, we did find significant differences in MBC by the final fall sampling event (Table 18).

Table 18. Microbial biomass C values for the Jonah Field and Pinedale Anticline soils from fall 2011. Values are means; (standard error); different letters indicate significant differences at $P \leq 0.10$.

Microbial Biomass C		Microbial Biomass C	
*Treatment	Jonah Field	Treatment	Pinedale Anticline
	mg MBC kg^{-1} soil		*mg MBC kg^{-1} soil*
WC (H9)	100.9 (9.54) a	Straw (H6)	91.8 (9.67) a
WC+C (M5)	85.3 (9.22) ab	WC (H9)	86.9 (9.60) a
WC (M8)	83.4 (9.15) ab	Control	74.5 (9.56) abc
Straw (H6)	69.8 (9.58) bc	WC+C (M5)	74.6 (9.15) abc
Straw (L1)	69.3 (9.72) bc	WC+C (L2)	70.4 (9.27) abc
WC (L4)	67.4 (9.20) bc	Straw (L1)	70.4 (9.14) abc
WC+C (L2)	65.7 (9.19) bc	Straw (M3)	67.7 (9.12) bcd
Straw (M3)	63.9 (9.47) bc	WC (L4)	64.2 (9.18) cde
WC+C (H7)	59.4 (9.64) c	WC+C (H7)	46.2 (9.51) de
Control	55.4 (9.13) c	WC (M8)	43.4 (9.66) e

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Microbial biomass C in the Jonah Field soils was highest under the high WC, medium

WC+C, and medium WC treatments and significantly lower under the high WC+C and control plots. On the Pinedale Anticline, the high straw and WC treatments had soils with the highest MBC values, while soils in the medium straw, low and medium WC, and high WC+C had significantly lower levels of MBC.

The Jonah Field had the highest soil MBN values on the high WC and medium straw treated plots, with the control plot soils having significantly less MBN (Table 19). A different trend for MBN was seen on the Pinedale Anticline, where the high straw treatments had significantly higher MBN than the control and all other treatments. The medium WC and high WC+C had significantly lower soil MBN than most of the other treatments.

Table 19. Microbial biomass N for the Jonah Field and Pinedale Anticline soils from fall 2011. Values are means; (standard error); different letters indicate significant differences at $P \leq 0.10$.

Microbial Biomass N		**Microbial Biomass N**	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	mg MBN kg^{-1} soil		*mg MBN kg^{-1} soil*
WC (H9)	5.77 (0.802) a	Straw (H6)	13.4 (0.890) a
Straw (M3)	5.75 (0.856) a	WC (H9)	7.97 (0.788) b
WC (M8)	4.92 (0.834) ab	Straw (M3)	7.54 (0.788) bc
WC+C (H7)	4.77 (0.841) ab	Straw (L1)	6.46 (0.806) bcd
WC+C (M5)	4.51 (0.793) ab	WC+C (M5)	6.21 (0.837) bcd
Straw (L1)	4.37 (0.821) ab	Control	5.73 (0.799) cde
Straw (H6)	4.31 (0.824) ab	WC+C (L2)	5.62 (0.827) de
WC+C (L2)	4.03 (0.876) ab	WC (L4)	3.89 (0.843) ef
WC (L4)	3.96 (0.842) ab	WC+C (H7)	3.45 (0.837) f
Control	3.78 (0.794) b	WC (M8)	2.84 (0.798) f

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

No significant differences were seen across sites or treatments for levels of soil TOC by the final fall sampling event, but were for soil PMC levels (Table 20). Overall, soils treated with the higher application rates had more PMC. The soils under high straw treatments had significantly more PMC than all other treatments and the control, at both sites.

Table 20. Total organic and potentially mineralizable C for the Jonah Field and Pinedale Anticline soils from fall 2011. Values are means; (standard error); different letters indicate significant differences at P≤ 0.10.

Total Organic C		Total Organic C		Potentially Mineralizable Carbon	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**	**Treatment**	**Jonah Field & Pinedale Anticline**
	g TOC kg $^{-1}$soil		*g TOC kg $^{-1}$soil*		*g PMC kg $^{-1}$soil*
WC (H9)	13.2 (1.40)	Straw (M3)	20.9 (1.39)	Straw (H6)	12.4 (0.981) A
Straw (H6)	12.9 (1.25)	Straw (L1)	20.4 (1.30)	WC (H9)	7.68 (0.938) B
Straw (M3)	12.3 (1.45)	Straw (H6)	20.3 (1.53)	WC+C (M5)	7.05 (1.24) BC
WC (M8)	11.8 (1.33)	WC (L4)	20.3 (1.30)	Straw (M3)	6.22 (1.18) BCD
Control	11.7 (1.23)	WC+C (L2)	20.2 (1.25)	WC (M8)	6.12 (1.07) BCD
WC+C (H7)	11.6 (1.44)	WC+C (H7)	20.1 (1.25)	WC+C (H7)	5.85 (1.27) BCD
WC+C (M5)	11.2 (1.23)	WC+C (M5)	20.1 (1.38)	WC (L4)	5.24 (0.643) CD
WC+C (L2)	11.0 (1.39)	WC (H9)	18.9 (1.30)	Straw (L1)	5.19 (0.968) CD
Straw (L1)	10.8 (1.42)	WC (M8)	17.8 (1.32)	Control	4.93 (0.923) CD
WC (L4)	10.4 (1.36)	Control	16.4 (1.47)	WC+C (L2)	4.71 (0.939) D

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

There were not significant treatment effects on TN by the final fall sampling event at either site (Table 21).

Table 21. Total N for the Jonah Field and Pinedale Anticline soils from fall 2011. Values are means; (standard error).

Total N		Total N	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	g TN kg^{-1} soil		*g TN kg^{-1} soil*
Straw (M3)	1.28 (0.147)	Straw (M3)	1.60 (0.135)
WC (H9)	1.17 (0.138)	Straw (L1)	1.59 (0.134)
Control	1.17 (0.138)	Straw (H6)	1.57 (0.152)
WC+C (H7)	1.14 (0.146)	WC (L4)	1.57 (0.135)
WC+C (M5)	1.11 (0.140)	Control	1.56 (0.138)
WC (M8)	1.08 (0.143)	WC+C (H7)	1.54 (0.131)
WC+C (L2)	1.07 (0.152)	WC+C (L2)	1.52 (0.142)
WC (L4)	1.00 (0.140)	WC (H9)	1.52 (0.134)
Straw (H6)	0.976 (0.131)	WC+C (M5)	1.49 (0.164)
Straw (L1)	0.989 (0.153)	WC (M8)	1.41 (0.169)

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

By the final fall sampling event, soils under the high straw treated plots on the Jonah Field had the significantly highest means for DOC (Table 23).

Table 23. Dissolved organic C for the Jonah Field and Pinedale Anticline soils from fall 2011. Values are means; (standard error); different letters indicate significant differences at P≤ 0.10.

Dissolved Organic *Treatment	Jonah Field	Dissolved Organic C Treatment	Pinedale Anticline
	mg DOC kg^{-1} soil		*mg DOC kg^{-1} soil*
Straw (H6)	39.2 (1.81) a	Straw (H6)	38.5 (1.91) a
WC+C (H7)	30.9 (1.79) b	WC (M8)	37.9 (1.79) a
WC+C (L2)	28.2 (1.82) bc	WC+C (H7)	37.5 (1.81) a
Control	27.0 (1.92) bcd	WC (L4)	35.4 (1.84) ab
WC (H9)	25.9 (1.92) cd	Control	35.3 (1.79) ab
Straw (L1)	25.8 (1.84) cd	Straw (M3)	35.3 (1.84) ab
WC+C (M5)	25.8 (2.11) cd	WC (H9)	35.0 (1.87) ab
WC (L4)	24.9 (1.83) cd	WC+C (L2)	34.4 (1.79) ab
WC (M8)	24.3 (1.99) cd	Straw (L1)	34.4 (1.80) ab
Straw (M3)	22.9 (1.79) d	WC+C (M5)	32.6 (1.84) b

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

The high WC and medium and high WC+C and medium straw treatments had significantly lower DON than the other treatments and the control on the Jonah Field (Table 22).

Table 22. Dissolved organic N values for the Jonah Field and Pinedale Anticline from fall 2011. Values are means ; (standard error); different letters indicate significant differences at P≤ 0.10.

Dissolved Organic N *Treatment	Jonah Field	Dissolved Organic N Treatment	Pinedale Anticline
	mg DON kg^{-1}soil		*mg DON kg^{-1} soil*
Control	2.50 (0.199) a	WC+C (H7)	3.44 (0.202) a
WC+C (L2)	2.44 (0.214) ab	Straw (L1)	3.26 (0.206) ab
WC (M8)	2.31 (0.211) abc	Control	3.22 (0.215) abc
Straw (H6)	2.24 (0.207) abc	WC+C (L2)	3.17 (0.203) abc
WC (L4)	2.17 (0.207) abcd	WC (L4)	2.99 (0.211) abcd
Straw (L1)	2.08 (0.244) abcd	WC+C (M5)	2.82 (0.208) bcd
Straw (M3)	1.99 (0.211) bcd	Straw (M3)	2.78 (0.206) cd
WC+C (M5)	1.97 (0.215) cd	Straw (H6)	2.67 (0.220) de
WC+C (H7)	1.91 (0.201) cd	WC (M8)	2.49 (0.216) de
WC (H9)	1.75 (0.199) cd	WC (H9)	2.30 (0.199) e

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

The Pinedale Anticline had the lowest values of DON on the high and medium WC plots and the high straw plots. Soils in the medium WC+C treatments on the Pinedale Anticline had significantly lower levels of DON than soils in the high straw and WC+C and medium WC treatments.

Potentially mineralizable N did show significant treatment effects. The high WC and straw treatments had the lowest values for PMN at each site, with several other treatments having significantly lower PMN than the control and medium and high WC+C treatments on the Pinedale Anticline (Table 24).

Table 24. Potentially mineralizable and total mineral N for the Jonah Field and Pinedale Anticline soils from fall 2011. Values are means; (standard error); different letters indicate significant differences at $P \leq 0.10$.

Potentially Mineralizable N		**Potentially Mineralizable N**		**Total Mineral N**	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**	**Treatment**	**Jonah Field & Pinedale Anticline**
	g TOC kg $^{-1}$soil		*g TOC kg $^{-1}$soil*		*g PMC kg $^{-1}$soil*
WC (M8)	24.7 (1.09) a	WC+C (M5)	20.1 (2.77) a	Control	11.9 (0.974) A
Control	18.0 (3.69) ab	WC+C (L2)	19.0 (0.683) a	WC+C (H7)	8.69 (0.765) B
WC (L4)	15.6 (3.46) b	Control	18.2 (1.09) a	WC+C (M5)	7.86 (1.14) B
WC+C (M5)	15.2 (4.23) b	Straw (L1)	17.1 (0.893) ab	WC+C (L2)	7.77 (0.888) B
Straw (M3)	14.5 (5.29) b	WC (L4)	11.9 (1.05) bc	WC (L4)	7.75 (0.742) B
Straw (L1)	14.1 (3.18) b	Straw (M3)	11.7 (0.871) bc	Straw (M3)	7.71 (0.911) B
WC+C (L2)	12.6 (3.12) b	WC+C (H7)	9.01 (2.41) c	Straw (L1)	7.62 (1.36) B
WC+C (H7)	12.0 (4.11) b	WC (M8)	8.62 (1.46) c	WC (M8)	7.35 (1.60) B
Straw (H6)	4.22 (1.84) c	Straw (H6)	6.16 (2.19) cd	Straw (H6)	4.76 (0.710) C
WC (H9)	3.46 (0.599) c	WC (H9)	2.28 (0.339) d	WC (H9)	4.71 (0.948) C

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

The control plot soils at each site had significantly more TMN, while the high WC and straw treatment soils had significantly less than all other treatments (Table 24).

Vegetation

Treatment effects on total seeded native and non-seeded invasive plant species were largely insignificant in this study. We did see a pattern, however, of the lowest densities of total seeded species on both sites, and non-seeded invasives on the Pinedale Anticline, having the lowest levels of TMN under the high WC and straw treatments, by the study's end. Also, when the total seeded species were further partitioned into grasses, shrubs, and forbs, we did find the low straw treatment significantly increased shrub densities, consisting solely of *Artemisia Tridenta,* on both sites and the medium straw also increased forb densities on the Jonah Field. The Jonah Field showed potential effects by the high WC+C treatment to simultaneously decrease invasive and increase native plant densities. Most treatments significantly lowered percent bare ground cover.

Total Seeded Species, Volunteer Barley, and Non-Seeded Invasives

The difference in invasion on the Jonah Field by non-seeded plant species, compared to the Pinedale Anticline, is immediately evident by comparing the overall means of total seeded versus total non-seeded invasive plant densities across sites (Tables 25 and 26). These results are reflected in the images below, taken during summer 2011 vegetative data collection (Figures 7a and b). Note the visibility of seeded rows on the Pinedale Anticline in contrast to the monoculture of invasives on the Jonah Field.

The control plots on the Pinedale Anticline averaged 46.8 plants m^{-2} for total seeded species, compared to the Jonah Field's control plots' 28.0 plants m^{-2} for mean total seeded plant densities (Table 25). Conversely, the Jonah Field control plots averaged 59.8 non-seeded invasive plants m^{-2}, compared to the Pinedale Anticline's control plot's 4.00 plants m^{-2}. Treated plots did not show any significant changes to densities of non-seeded invasive plant species compared to control plots at the Pinedale Anticline or Jonah Field sites (Table 26).

Figure 7a. Image of study sites during summer 2011 vegetatiive data collection on the Jonah Field and **7b**. the Pinedale Anticline.

No significant differences between the treatment and control plots' total seeded plant densities occurred on the Jonah Field. The high straw treatment on the Pinedale Anticline was the only C addition treatment to significantly affect total seeded plant densities, with a reduction in means, compared to all other treatments and the control plots (Table 25). The Pinedale Anticline plots' high WC application and high and medium straw applications also showed significant reduced seeded plant densities compared to the high and medium WC+C and low WC treatments. The low WC+C, and the two treatments with the highest C added, the medium and high WC applications showed reduced mean seeded plant densities compared to the high WC+C treatment on the Jonah Field (Table 25).

Table 25. Total seeded native plant densities, excluding volunteer barley, for the Jonah Field and Pinedale Anticline. Values are mean densities; (standard error); different letters indicate significant differences at $P \leq 0.10$.

Total Native Seeded Species		**Total Seeded Native Species**	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	plants m⁻²		*plants m⁻²*
WC+C (H7)	43.0 (12.7) a	WC+C (M5)	57.3 (12.2) a
WC (L4)	33.5 (3.30) ab	WC+C (H7)	56.5 (6.70) a
Straw (L1)	32.0 (7.04) ab	WC (L4)	55.0 (10.2) a
Straw (H6)	30.8 (4.44) ab	Control	46.8 (6.13) ab
WC+C (M5)	29.5 (5.33) ab	WC+C (L2)	46.3 (4.15) ab
Straw (M3)	28.3 (4.97) ab	Straw (L1)	46.0 (8.38) ab
Control	28.0 (3.49) ab	WC (M8)	45.8 (5.07) ab
WC+C (L2)	26.5 (7.35) b	Straw (M3)	32.5 (7.84) b
WC (M8)	23.5 (7.33) b	WC (H9)	34.0 (4.80) b
WC (H9)	23.5 (4.41) b	Straw (H6)	2.75 (2.75) c

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Although there were not significant differences between treated and untreated plots' non-seeded invasive plant species densities on the Jonah Field or Pinedale Anticline, a few trends were observed across treatment means on each site (Table 26). The Pinedale Anticline showed nearly the same pattern of treatments with higher and lower means than the control for total seeded plants and non-seeded invasives, the exception being the low WC+C treatment. The Jonah Field did not show this pattern, but did show one treatment, the high WC+C addition, that shared the highest mean seeded plant densities and the lowest non-seeded invasive plant densities across all treatments, albeit not significantly different than the control plot measurements (Tables 25 and 26).

Table 26. Non-Seeded invasive plant densities for the Jonah Field and Pinedale Anticline. Values are mean densities; standard error); different letters indicate significant differences at P ≤ 0.10.

Non-Seeded Invasive Species		**Non-Seeded Invasive Species**	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	plants m^{-2}		*plants* m^{-2}
WC (M8)	76.0 (17.8)	WC+C (H7)	7.75 (3.77)
Straw (H6)	67.5 (14.0)	WC (L4)	7.50 (4.21)
WC (H9)	65.0 (16.2)	WC+C (M5)	5.00 (4.34)
WC+C (L2)	59.8 (23.4)	WC (M8)	4.25 (2.98)
Control	59.8 (19.2)	WC+C (L2)	4.25 (2.14)
Straw (L1)	48.0 (14.9)	Control	4.00 (1.29)
WC (L4)	44.3 (17.4)	Straw (L1)	3.50 (2.84)
WC+C (M5)	40.6 (9.45)	Straw (M3)	2.25 (0.481)
Straw (M3)	38.5 (15.3)	WC (H9)	1.75 (0.854)
WC+C (H7)	38.5 (20.6)	Straw (H6)	0.50 (0.291)

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Figure 8 below reflects a straw treatment with volunteer barley establishment.

Figure 8. Image of volunteer barley established on a high straw treatment plot, taken during summer 2011 vegetation data collection on the Pinedale Anticline.

Several plots were dominated by the volunteer barley, introducuing a confounding variable in our vegetation data. The Pinedale Anticline showed this effect more drastically with mean volunteer barley plant densities in each of the straw treatments significantly higher than all other treatments and the control (Table 27). This effect was less severe on the Jonah Field, where only the medium straw application showed significantly higher volunteer barley plant densities than the other treatments and control plots.

The Pinedale Anticline and Jonah Field both had non-straw treated plots that hosted a small number of barley plants, with seeds likely originating from the straw treatments and then dispersed by wind or animals. The high straw treatments on the Pinedale Anticline had the highest volunteer barley and invasive plant densities, and the corresponding lowest level of total seeded plant densities (Figure 8).

Table 27. Volunteer barley plant densities for the Jonah Field and Pinedale Anticline. Values are mean densities; (standard error); different letters indicate significant differences at $P \leq 0.10$

Volunteer Barley		**Volunteer Barley**	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	plants m^{-2}		*plants m*$^{-2}$
Straw (M3)	5.00 (2.22) a	Straw (H6)	30.25 (0.00) a
Straw (H6)	3.50 (3.50) ab	Straw (M3)	23.75 (6.69) b
WC+C (H7)	1.50 (1.50) bc	Straw (L1)	4.00 (1.63) c
Straw (L1)	0.75 (0.75) bc	WC+C (H7)	1.25 (0.95) d
Control	0.00 (0.00) c	WC+C (M5)	0.25 (0.25) d
WC (L4)	0.00 (0.00) c	Control	0.00 (0.00) d
WC (M8)	0.00 (0.00) c	WC (L4)	0.00 (0.00) d
WC+C (L2)	0.00 (0.00) c	WC (M8)	0.00 (0.00) d
WC+C (M5)	0.00 (0.00) c	WC+C (L2)	0.00 (0.00) d
WC (H9)	0.00 (0.00) c	WC (H9)	0.00 (0.00) d

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Figure 9 below reflects the general trends in vegetative competition for each site's total seeded natives, non-seeded invasives, and volunteer barley at each site. Plant densities for the Jonah Field's non-seeded invasives somewhat mirror its total seeded species line for all treatments, except for the high WC+C treatment, indicating a mutually exclusive effect, with little interaction from the volunteer barley on the straw treated plots. On the Pinedale Anticline, however, the densities of seeded native species and the volunteer barley show this effect, with little interaction from the non-seeded invasives.

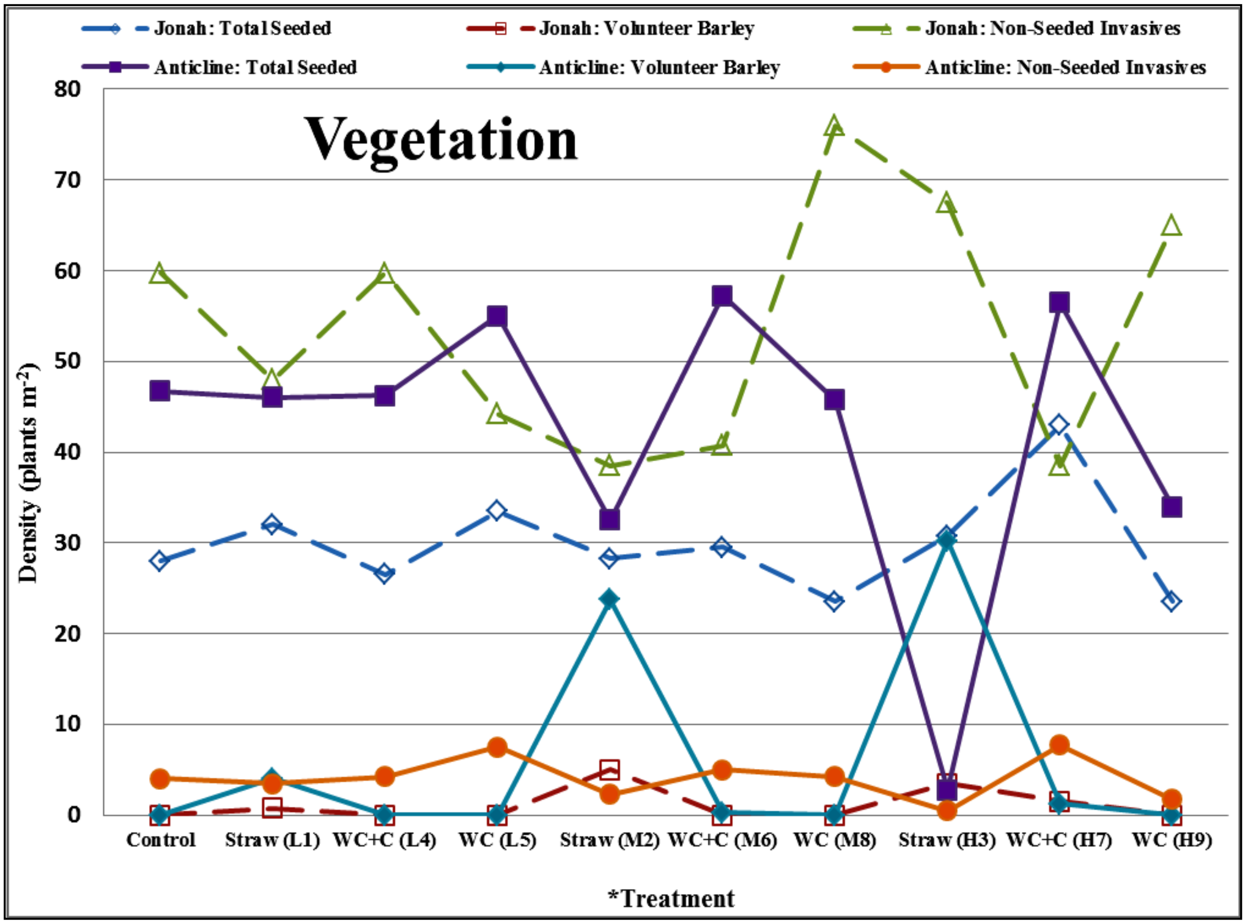


Figure 9. Total seeded, non-seeded invasive, and volunteer barley plant densities for the Jonah Field and Pinedale Anticline. * Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

The high WC+C treatment on the Jonah Field had the lowest observed mean density of non-seeded invasive plant speces, and the highest of total seeded species, and was the only treatment where seeded species means were higher than the corresponding means for invasives on this site, though these densities were not significantly different than those in control plots.

Seeded Grasses, Seeded Forbs, and Seeded Shrubs

The high WC+C treatment on the Jonah Field had significantly higher seeded grass densities than the high WC application. Seeded grass densities were significantly higher for the medium and high WC+C treatments compared to the medium and high straw and high WC treatments on the Pinedale Anticline (Table 28).

Table 28. Seeded grass densities, excluding volunteer barley, for the Jonah Field and Pinedale Anticline.Values are mean densities; (standard error); different letters indicate significant differences at P $\leq$ 0.10

Seeded Grass *Treatment	**Jonah Field**	**Seeded Grass Treatment**	**Pinedale Anticline**
	plants m^{-2}		*plants m^{-2}*
WC+C (H7)	37.00 (12.63) a	WC+C (M5)	38.00 (6.99) a
WC (L4)	30.25 (2.25) ab	WC+C (H7)	34.75 (1.11) a
Straw (H6)	27.5 (4.44) ab	Control	31.75 (3.57) ab
WC+C (M5)	26.50 (5.87) ab	WC+C (L2)	31.75 (4.44) ab
Control	25.50 (3.07) ab	WC (L4)	30.75 (2.46) ab
Straw (L1)	23.75 (5.85) ab	WC (M8)	28.25 (4.95) ab
Straw (M3)	21.5 (4.17) ab	Straw (L1)	27.00 (4.24) ab
WC (M8)	20.75 (5.96) ab	WC (H9)	24.25 (3.25) bc
WC+C (L2)	20.75 (6.41) ab	Straw (M3)	18.50 (2.60) c
WC (H9)	20.00 (4.49) b	Straw (H6)	0.00 (0.00) d

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

The high straw treatments on the Pinedale Anticline had significantly less seeded grass densities than all other treatments and the control. The medium straw treatment also had significantly lower seeded grass densities than the control plots and most treatments on the Pinedale Anticline. The high straw treatment on the Pinedale Anticline completely suppressed seeded grass establishment.

On the Jonah Field, seeded forb densities were significantly higher in the low and medium straw treated plots compared to the control plots (Table 29). As was the case for seeded grasses on the Pinedale Anticline, the high straw treatment had significantly lower seeded forb densities than all other treatments and the control, with no seeded forbs observed. The high WC+C and low WC treatments on the Pinedale Anticline had the highest seeded forbs, with significantly higher means than several of the other treatments. The Jonah Field and Pinedale Anticline saw significantly similar treatment effects for seeded shrub densities, with the low straw treatment yielding over twice as many seedlings as the control plots (Table 29). The high straw and WC treatments had the lowest seeded shrub densities, with significantly lower densities than several other treatments.

Table 29. Seeded forb and shrub densities for the Jonah Field and Pinedale Anticline. Values are mean densities; (standard error); different letters indicate significant differences at P $\leq$ 0.10.

Seeded Forbs		**Seeded Forbs**		**Seeded Shrubs**	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**	**Treatment**	**Jonah Field & Pinedale Anticline**
	plants m^{-2}		*plants m^{-2}*		*plants m^{-2}*
Straw (L1)	5.25 (1.65) a	WC+C (H7)	13.75 (2.50) a	Straw (L1)	6.75 (1.29) A
Straw (M3)	4.75 (1.93) a	WC (L4)	13.75 (1.49) a	WC (L4)	5.63 (1.45) AB
WC+C (H7)	3.75 (1.49) ab	WC+C (M5)	11.5 (2.90) ab	WC+C (H7)	5.13 (1.43) AB
WC+C (L2)	3.50 (0.87) ab	WC (M8)	11.00 (1.47) ab	WC+C (M5)	4.13 (1.20) ABC
WC (H9)	2.75 (0.25) ab	Control	10.50 (3.28) ab	WC+C (L2)	3.75 (0.99) BC
WC (L4)	2.50 (1.04) ab	WC+C (L2)	9.25 (2.10) b	WC (M8)	3.63 (1.13) BCD
WC+C (M5)	2.50 (0.65) ab	Straw (M3)	9.25 (4.09) b	Straw (M3)	3.38 (0.93) BCD
Straw (H6)	2.25 (1.03) ab	Straw (L1)	8.50 (0.96) b	Control	3.00 (0.88) BCD
WC (M8)	2.00 (0.91) ab	WC (H9)	7.75 (2.50) b	Straw (H6)	1.88 (1.03) CD
Control	1.00 (0.58) b	Straw (H6)	0.00 (0.00) c	WC (H9)	1.38 (0.73) D

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Percent Cover

Percent vegetation cover for the Jonah Field was significantly lower in the medium WC+C treatment compared to the high straw and WC+C and medium WC treatments (Table 30). The high and medium straw applications had significantly higher vegetation cover than all other treatments, with the opposite true for the high WC application on the Pinedale Anticline.

Table 30. Percent vegetation cover for the Jonah Field and Pinedale Anticline. Values are mean estimated percent; (standard error); different letters indicate significant differences at P≤ 0.10.

Vegetative Cover		Vegetative Cover	
*Treatment	Jonah Field	Treatment	Pinedale Anticline
	%		%
Straw (H6)	22.3 (3.46) a	Straw (H6)	27.2 (3.89) a
WC (M8)	21.3 (4.70) a	Straw (M3)	25.1 (3.84) a
WC+C (H7)	19.1 (4.63) a	WC+C (M5)	15.8 (2.45) b
Control	17.9 (2.16) ab	Straw (L1)	14.9 (1.34) b
WC (L4)	17.1 (3.63) ab	WC+C (H7)	14.4 (0.94) b
WC+C (L2)	16.3(4.24) ab	WC (L4)	13.6 (0.81) b
WC (H9)	16.3(2.16) ab	WC (M8)	10.3 (2.78) b
Straw (L1)	15.8 (2.45) ab	Control	9.50 (2.30) b
Straw (M3)	15.5 (4.91) ab	WC+C (L2)	9.50 (1.88) b
WC+C (M5)	12.8 (3.25) b	WC (H9)	9.50 (1.33) c

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

The Jonah Field and Pinedale Anticline had similar treatment effects across sites for cover by litter/treatment, bare, and rock covered ground (Table 31).

Table 31. Percent litter/treatment, bare, and rock cover for the Jonah Field and Pinedale Anticline. Values are mean estimated percent; (standard error); different letters indicate significant differences at P ≤ 0.10.

Litter/Treatment Cover		Bare Cover		Rock Cover	
*Treatment	Jonah Field & Pinedale Anticline	Treatment	Jonah Field & Pinedale Anticline	Treatment	Jonah Field & Pinedale Anticline
	%		%		%
Straw (M3)	75.5 (4.92) A	Control	58.9 (6.81) A	WC+C (L2)	19.9 (8.02)
Straw (H6)	71.9 (5.44) AB	WC+C (L2)	51.1 (8.03) AB	WC (L4)	15.9 (0.53)
WC (H9)	62.8 (5.22) B	WC (L4)	45.4 (7.38) ABC	Control	14.3 (5.41)
WC (M8)	44.8 (4.07) C	WC+C (M5)	38.3 (9.48) BCD	WC+C (M5)	13.8 (1.30)
Straw (L1)	36.2 (4.52) C	Straw (L1)	31.2 (9.78) BCDE	WC+C (H7)	11.7 (2.65)
WC+C (H7)	31.4 (5.02) CD	WC+C (H7)	28.3 (10.5) CDEF	WC (M8)	11.1 (1.74)
WC+C (M5)	20.3 (4.43) D	WC (M8)	25.9 (7.73) DEF	Straw (L1)	10.3 (1.47)
WC (L4)	15.1 (3.90) E	WC (H9)	13.8)11.0) EF	WC (H9)	9.66 (2.60)
WC+C (L2)	10.8 (4.34) EF	Straw (M3)	5.84 (10.2) F	Straw (H6)	6.41 (2.60)
Control	6.25 (3.34) F	Straw (H6)	5.72 (11.0) F	Straw (M3)	5.03 (0.85)

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

All treatments except the low WC+C treatment had significantly higher cover by litter/treatment than the control at both sites. This trend was understandably reversed for percent cover of bare ground, with the control and low WC+C and WC treatments having the most bare ground, and all other treatments significantly less bare ground. There was not a significant treatment effect on percent rock cover at either site (Table 31).

Summary of Significant Treatment Effects and Costs

Variables Significantly Affected by Treatments

We summarized the variables that showed differences compared to the control, throughout spring soil sampling and the combined fall soil sampling and summer vegetation data collection (Figure 10). Only variables where the treatments had significantly higher or lower means than the control were included. A few variables were not included if they were considered a redundant representation. For example, percent vegetative cover was included, but not percent bare cover. The greater or less-than symbol preceding the variable indicates the direction of influence caused by the treatment. For example, treatments that significantly lowered pH have a less-than assignment, as do treatments that increased MBC, both considered desired outcomes in this study. Variables that were clearly positively or negatively affected by treatments were assigned a (+) or (-) symbol respectively. We evaluated the ability of our treatments to cause N immobilization, so give a decrease in TMN a (+) assignment. We did not assign a positive or negative designation, to the labile and physical N pools that were significantly decreased in many treatments because, although we wanted our treatments to induce mineral N immobilization, we cannot say a decrease in organic N is a desirable effect.

We see in Figure 10 that both sites had many more variables that had significantly positive over significantly negative treatment effects compared to the control plots.

JONAH FIELD

WC (H9)	Straw (H6)	WC+C (H7)	WC (M8)	Straw (M3)	WC+C (M5)	WC (L4)	Straw (L1)	WC+C (L2)
< DON								
< PMN								
< DON								
< PMN		< DON						
> PMC (+)	< PMN	< DON		< DON				
> DOC (+)	< DON	< PMN	< PMN	< DON			< PMN	
< TMN (+)	< PMN	< DON	< DON	< PMN	< DON		< DON	
> FLF (+)	> PMC (+)	> FLF (+)	> PMC (+)	> MBN (+)	< PMN		> PMC (+)	
< TMN (+)	< TMN (+)	> MBN (+)	< TMN (+)	> PMC (+)	< DON		> DOC (+)	
< pH (+)	< TMN (+)	> PMC (+)	< TMN (+)	> DOC (+)	< TMN (+)		< TMN (+)	
> FLFC (+)	< pH (+)	> DOC (+)	< pH (+)	< TMN (+)	< pH (+)	< PMN	< pH (+)	< TMN (+)
> PMC (+)	> GM (+)	< TMN (+)	> FLF (+)	< pH (+)	> FLFC (+)	< DON	< TMN (+)	< pH (+)
> MBC (+)	> PMC (+)	< pH (+)	> FLFC (+)	< TMN (+)	> MBC (+)	> FLFC (+)	> Forbs (+)	> FLFC (+)
> MBN (+)	> DOC (+)	< TMN (+)	> MBC (+)	> Forbs (+)	< TMN (+)	< TMN (+)	> Shrubs (+)	< TMN (+)

PINEDALE ANTICLINE

WC (H9)	Straw (H6)	WC+C (H7)	WC (M8)	Straw (M3)	WC+C (M5)	WC (L4)	Straw (L1)	WC+C (L2)
	< PMN							
	< DON							
	< DON							
< PMN	< PMN							
< DON	< FLFN							
< DON	< Grass (-)							
< FLFN	< Forbs (-)							
< PMN	< Bacteria (-)	< PMN						
< Veg Cvr (-)	> MBN (+)	< DON	< PMN	< PMN				
> PMC (+)	> PMC (+)	< PMN	< DON	< DON				
> TN (+)	> TN (+)	< FLFN	< PMN	< PMN			< PMN	
> DOC (+)	> DOC (+)	< MBC (-)	< FLFN	< FLFN			< DON	
< TMN (+)	< TMN (+)	< MBN (-)	< MBC (-)	< Bacteria (-)		< PMN	< Bacteria (-)	
< pH (+)	> MBN (+)	< Bacteria (-)	< MBN (-)	> PMC (+)	< PMN	< DON	> PMC (+)	
< CaCO3 (+)	> PMC (+)	> PMC (+)	> PMC (+)	> TN (+)	< DON	< PMN	> TN (+)	
> FLF (+)	< pH (+)	> TN (+)	< TMN (+)	< TMN (+)	> TN (+)	> TN (+)	< TMN (+)	< TMN (+)
> FLFC (+)	> GM (+)	< TMN (+)	< pH (+)	> Veg Cvr (+)	< TMN (+)	< pH (+)	> Shrubs (+)	< TMN (+)
> PMC (+)	< CaCO3 (+)	< pH (+)	> FLF (+)	< pH (+)	< pH (+)	< CaCO3 (+)	< pH (+)	< pH (+)
> MBN (+)	< TMN (+)	> FLF (+)	> FLFC (+)	< CaCO3 (+)	> FLFC (+)	> FLFC (+)	< CaCO3 (+)	< CaCO3 (+)
< TMN (+)	> Veg Cvr (+)	< TMN (+)	< TMN (+)	< TMN (+)	< TMN (+)	< TMN (+)	< TMN (+)	> FLFC (+)

Spring Soils (shaded) — Fall Soils & Summer Vegetation (unshaded)

< significant treatment effect with lower value than the control
> significant treatment effect with higher value than the control

Negative Effect = (-)
Positive Effect = (+)

Figure 10. List of variables for the Jonah Field and Pinedale Anticline that were significantly affected by treatments compared to the control. Positive effects have a (+) and negative effects have a (-) sign. . Greater than or less than signs indicate direction of influence on the Jonah

The Jonah Field only had positive significant treatment effects compared to control plots. The majority of these variables were soils conditions, however. We also see in Figure 10 that, the high WC on the Jonah Field and the high straw and WC on the Pinedale Anticline had the most overall positive significant treatment effects as compared to the control on both sites. The low WC and low WC+C treatments on the Jonah Field, and the medium WC+C and low WC and WC+C on the Pinedale Anticline had the least significant effects throughout the soils and vegetation data. These treatments on the Pinedale Anticline were also the only treatments to have no variable with significant negative treatment effects compared to the control.

The only significantly improved treatment effect on a vegetative functional group on the Pinedale Anticline was by the low straw treatment's significant increase in shrub densities. This treatment had the same effect for shrub and forb densities on the Jonah Field, and the medium straw treatment also significantly improved forb densities on the Jonah Field compared to plant densities in control plots. We also observe here that seeded forb and grass densities are variables with negative effects by treatments compared to the control on the Pinedale Anticline, whereas on the Jonah Field, no vegetative functional group had significantly lower densities in treated plots compared to the control. Finally we can quickly gain from this figure, that immobilization of N occurred in multiple variables, by all treatments.

Treatment Costs

Table 32 reports costs from the historical use of WC and straw on the Jonah Field, provided by Encana Oil and Gas Corporation, and for the Pinedale Anticline, provided by QEP Energy. These averaged values were used to estimate the costs of incorporation and application of these treatments and the WC+C treatments used in our study (Table 32). We also used cost quotes for WC, provided by the Rocky Mountain Elk Foundation, and for compost, provided by

Terra Firma Organics, who collaboratively thinned local forests and chipped the wood chips. Material costs for straw are based on price quotes from a local reclamation contracting company, Hindsite Reclamation, at the time our treatments were applied.

Table 32 . Costs per hectare of prior use of wood chips (WC) and straw on the Jonah Field and Pinedale Anticline.

SITE & MATERIAL	Delivered Material	Application Rate	Application/Incorporation	Total Cost
	$ Mg $^{-1}$	*Mg ha* $^{-1}$	*$ ha* $^{-1}$	
Pinedale Anticline WC	165	8.85	556	2,016
Jonah Field WC	165	8.85	988	2,448
Pinedale Anticline Straw	215	2.24	501	981
Jonah Field Straw	138	3.36	865	1,327

We combined these values with our actual application rates to arrive at total estimated treatment costs per hectare (ha). Assuming an average well-pad size of 2.02 ha, we provide the estimated cost of our treatment use for an entire well-pad (see Appendix I for cost data in English units).

Table 33. Estimated **c**osts of treatments used in this study with averaged application (App) and incorporation (Inc) costs estimated from those used on Jonah Field and Pinedale Anticline.

*Treatment	Application Rate	Delivered Material Cost	App/Inc Costs	Total Treatment Cost	Total Cost for Average Size Well-Pad (2.2 ha)
	Mg ha $^{-1}$	*$ Mg* $^{-1}$	*$ ha* $^{-1}$	*$ ha* $^{-1}$	*$*
Straw (L1)	2.24	165	683	1,053	2,127
WC+C (L2)	3.55	101	772	1,131	2,285
WC (L4)	6.40	82.5	772	1,300	2,626
Straw (M3)	6.72	165	683	1,792	3,620
WC+C (M5)	10.7	101	772	1,853	3,743
WC (M8)	19.2	82.5	772	2,356	4,759
Straw (H6)	11.2	165	683	2,531	5,113
WC+C (H7)	17.8	101	772	2,572	5,195
WC (H9)	31.9	82.5	772	3,404	6,876

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Wood chips proved to be the most expensive treatment, followed by the WC+C, then the straw treatments (Table 33). The WC treatments were about 23% more expensive than the straw, and about 15% more expensive than the WC+C treatments. The high rates of treatments were about 2.5 times more expensive than the low applications of the same material type, because application and incorporation costs are on a per ha basis, not material amount.

DISCUSSION

Soils

Soil OM originates from plant, animal, and microbial detritus, which vary in composition and break-down time. Through decay processes, these substrates serve as metabolic resources to plants and microbes, which eventually become decomposing matter as well. This cycling of organic matter in soils can lead to SOM accumulation, but it can take decades and longer to build topsoil, depending on environmental conditions. Proper management of SOM is vital, as it plays a leading role in facilitating and maintaining healthy soils and plant communities.

Soil microbial and microfauna populations respond positively to increased SOM, as it provides a metabolic resource and habitats with high surface areas per unit volume. Increased and diversified microbial and soil animal communities facilitate decomposition and its by-products, such as worm casts and organic acids which, in addition to other OM constituents such as polysaccharides, act as binding agents between soil particles and colloids. Improved soil structure leads to better porosity and subsequent water and gas retention, which are important for plant nutrient and water uptake (see Appendix F, Figure 15 for image of stable soil aggregate).

Soil OM has a net negative charge due to dissociation of organic acids, and this property allows SOM to retain cations on exchange complexes, also making SOM a nutrient bank for plants and microbes. Over time, if soils are not disturbed and receive continuous inputs, a positive feedback system develops, with eventual increases or homeostasis by C and other nutrient pools available to microbes and plants. Typically, stable soils are N-limited and C-rich relative to disturbed soils, which are often N-rich and C-limited.

Well-pad development and reclamation practices disrupt normal soil nutrient cycling because they destroy stable soil aggregates. We know that mixing of topsoil and subsoil horizons reduces SOM through dilution and exposure of oxygen to previously protected C and N pools (reviewed by Norton et al., 2009; Mummey et al., 2002). Upon disturbance, these nutrients are lost from the soil system through assimilation, volatilization, leaching, and erosion. Mason et. al. (2010) showed a pulse of N mineralization, following stockpiled soil replacement on reclaimed Wyoming well-pads, contributing as much as 50 kg ha^{-1} from the decomposing SOM. Disturbed soils rich in newly available mineral N are often rapidly invaded by exotic plants, as they outcompete natives in high resource environments (Vasquez et al., 2008). Soils are also often compacted when replaced during reclamation. Compacted, structureless soils are poor growing mediums, as root penetration; water and oxygen infiltration; and water and nutrient retention are negatively affected by this decreased porosity. We saw evidence of these effects from our baseline data, which showed increased soil BD values and about half as much soil TOC on our research sites compared to values reported for nearby native undisturbed areas (Driessen, 2012).

Wyoming has a windy, arid climate and calcareous parent materials. The lack of precipitation to leach salts from surface horizons and the presence of high winds carrying dust, create soil layers rich in $CaCO_3$. When the little moisture that accumulates here evaporates, salts are carried to the soil surface horizons, leading to increased pH, salinity, and crusting. Salinity can increase osmotic potential and decrease soil moisture, and soil crusting can impede seedling emergence and plant root growth. High pH can also decrease nutrient availability, such as with phosphorous, leading to deficiencies in plants. Already alkaline soils see additional increases in pH upon disturbance because the $CaCO_3$ from subsoil layers becomes mixed and pulverized into topsoil layers during topsoil salvage and replacement. In addition to the increased soil compaction from reclamation practices found from baseline sampling results, we also saw an increase in soil pH at the initiation of our study, compared to data from the native undisturbed soils (Driessen, 2012).

Overall, the effects of disturbance cause destruction of SOM, which leads to changes in soil nutrient cycling, and have negative effects on physical and chemical soil processes. We saw evidence of these negative effects on the reclaimed soils at the beginning of this study. We investigated the ability of the C additions to restore a positive feedback system in the disturbed soils while also securing the mineralized N from invasive plant species or other environmental losses.

We did not generally see significant increases in TOC in spring or final fall sampling or in TN during final fall sampling in this study, but we know that accumulation and measured increases in SOM takes time. We did see, however, indications of increased soil organic C, through increases in the amounts of FLFOM and FLFC. Research investigating light and heavy fractions of soil organic C and tillage practices found that increased disturbances caused losses to both fractions and that soil TOC gains, following non-tillage, were primarily attributed to increases in C found in the light fraction (Tan et al., 2007)(see Appendix F: Figure 14 for schematic of physical soil fractions). We also measured increased levels of labile organic C in DOC, MBC, and PMC, with the most combined increases in these pools seen under the high straw and WC treatments.

Levels of TN were significantly increased by most treatments during spring sampling, a time of peak microbial activity. Most significant effects on soil MBN, compared to the control, were positive and were experienced by several treatments throughout the study. Additionally, overall levels of DON, FLFN, PMN, and total mineral N were significantly decreased by all treatments for at least one of these variables during spring and fall sampling. The high rates of treatments had the most total number of significant affects on the different N pools throughout the study. Results of measured N concentrations for soil TMN were highly significant, with all treatments having lower mineral N than the control by the study's end. Also at this time, levels of mineral N were lowest in soils under high straw and WC treatments.

We expected levels of total mineral N to be immobilized by the C treatments, and we also predicted overall increases in organic N pools, but we saw instead overall decreases in DON, PMN, and FLFN. These results are understandable, however, especially given the consistent and highly significant effects of immobilization of TMN, which likely extended to these more labile and physically free pools of N. We assume we saw a priming effect to the soils by the most PMC in our treatments, especially by the high WC and straw. We presume that the increased available C, as evidenced by our heighted PMC measurements, allowed conversion of the most PMN in the soil environment, including labile N in the FLF and dissolved organic pool, to mineral N, which was either assimilated, nitrified, or lost in some other form.

The assimilation of N by microbes is supported by the data showing increases in soil MBN and MBC that we saw under several of our treatments, and although not significant, potential increases by treatments on fungi levels seen from our PLFA analyses. Phospholipid fatty acid results did show decreased bacteria levels in several treatments, but we know that fungi are the main decomposers of high-C content materials, and we assume that over time the differences in increased fungi will be significantly higher in treated plots, supporting the results of overall increases in soil MBC and MBN that we measured.

Early indicators of increased TOC and TN in this study show potential for increased SOM in the future. These findings are supported by the results we had for positive significant treatment effects on soil physical and chemical properties. Organic matter provides chelating agents in soils, which can bind Ca^{2+}, and also releases acids during decomposition, solubilizing carbonates and lowering pH. Almost all treated soils at both sites saw significant decreases in pH levels, and soils under most treatments on the Pinedale Anticline had decreased $CaCO_3$ levels. Both of our sites also saw a significant increase in soil moisture in high straw treated plots. This was likely due to the ability of straw to capture some of the heavy snowfall experienced during the 2010-2011 winter season (Figures 3a and b), as this treatment was observed to provide the most ground cover at the initiation of the study. This treatment effect may have been associated with the most decrease in $CaCO_3$ levels that we saw on the Pinedale Anticline under the high straw, through increased leaching and dilution. Our differences in BD were nearly significant. Root growth by plants can be restricted by a BD of 1.52 g cm^{-3}, which was found in our control plots by the final sampling event. Bulk density levels of the treated plots were much closer to those observed in undisturbed native sites listed by Driessen (Table 2). Should treated plots' materials continue decomposing along the same trajectory, BD values will likely be reduced by the treatments, which will improve growing conditions through increased porosity.

Overall, we saw the most benefits to improved soil conditions, labile and physical OMC properties, and immobilization of N from our high straw and WC applications. These findings are in accordance with a study by Blumenthal et al. (2003), which specifically investigated 14 levels of C additions. Their research was most directed at decreases in mineral N and an associated increase in plant biomass, and they upheld this would only be achieved through addition of high-C-content OM. They cited several studies, in addition to their own findings, which found strong vegetation and N immobilization responses, resulting from organic materials applied at rates of 15.0 - 72.5 Mg ha^{-1} but the opposite for low application rates of 0.720 - .800 Mg ha^{-1}. As we saw significant positive effects by all treatments in our first-year results, it is reasonable to expect that C additions will expedite soil reclamation processes on disturbed sites, especially under the high straw and WC applications.

Vegetation

Disturbance to landscapes is known to promote invasive plant species establishment through several mechanisms. Resource use is declined from plants and microbes killed from disturbance, while resource availability is increased through decomposition of these substrates, as well as from the release of nutrients from disturbed soil aggregates (Mason et al., 2010; Six et al, 2004). The higher disturbance and activity levels on the Jonah Field are likely primary causes of the higher infestation of invasive plants observed in this area compared to the Pinedale Anticline (Ehrenfeld, 2003). The initial surrounding presence of these invasive plants provided a stronger seed source on the Jonah Field, and led to the their propagation on this study site, much more so than the Pinedale Anticline site. This created an opportunity to compare C addition treatment effectiveness for a highly invaded versus non-highly invaded well-pad site.

Alpert's (2010) review of C additions found that these treatments may be most successful under the following conditions: 1) competition from introduced species is intense; 2) application sites have been previously cleared and enriched in N by human disturbances; and 3) introduced species are mostly annuals and natives are mostly perennials. These qualifications were most comprehensively met on the Jonah Field site. We therefore expected this site to experience the greatest treatment effects as compared to the Pinedale Anticline site. We also expected the C additions to have a negative effect on invasive plant species densities at both sites, as was the case in the majority of studies utilizing C additions (Alpert, 2010; Alpert and Maron, 2000; Averett et al., 2004; Blumentahl et al., 2003; Brunson et al., 2010; Eshen et al., 2006; Morghan and Seastedt, 1999; Rashid and Reshi, 2010), and because we saw from our soils results that some additions had affectively immobilized mineral N. No significant treatment effect on invasive plant species was seen from the vegeatation data in our study, however. On the Pinedale Anticline, though, the high WC and straw treatments had the lowest TMN by the final sampling event, and the corresponding lowest numbers of invasive and total seeded plant densities. This suggests that the mineral N immobilization caused by these treatments is affecting both native and invasive plants. We suspect these effects will become significant provided additional time for decomposition of the treatments.

Establishment of barley, which we unintentionally introduced with our straw treatments, created a confounding varibable in our vegetation results. The Pinedale Anticline site experienced much higher rates of this barley establishment, with dominance over seeded native and non-seeded invasive plant establishment in the high straw treatments. This may have been because the volunteer barley did not undergo as much competition for resources on the less-invaded Pinedale Anticline site, as it did on the highly invaded Jonah Field site, and so was better able to establish and dominate the straw treated plots on the Pinedale Anticline.

Densities of invasive non-seeded species were highly variable in our study. We did see a pattern in the treatments with the three lowest means of non-seeded invasives on the Pinedale Anticline also appearing in the same order for the densities of total seeded plant densities. The same pattern was not measured on the Jonah Field, however, as the treatment with the most total seeded plants, the high WC+C, also had the least total non-seeded invasive plant densities, both densities insignificantly different than the control, however. Also on the Jonah Field, the treatments with the least significant total seeded species, the high and medium WC and low WC+C, all had insignificant but higher measured densities of non-seeded invasives, suggesting resource competition between seeded native and non-seeded invasives on the Jonah Field.

Disregarding significant treatment differences, review of total seeded species, non-invasive species, and volunteer barley means in Figure 9 yields some confirmation of the prediction that the more invaded Jonah Field would be most benefitted from C additions, especially given more time for decomposition of treatments than the length this study provided. Comparison of the two tend lines of the total seeded versus non-seeded invasives for the Jonah Field, reveals that for the control plots and several other treatments there is a fairly wide spread between densities of seeded natives and non-seeded invasives, suggesting here that the invasive species are outcompeting seeded species for resources, as the peak of the non-seeded invasive line corresponds to a correspondingly low point for the total seeded species. The fact that the highest spread was maintained in the medium and high WC treatments suggests that the recalcitrance of this material prevented significant N immobilization effects from taking place in the first growing season on the Jonah Field, which has drier conditions than the Pinedale Anticline. The low and medium straw, the low WC, and the medium and high WC+C treatments all had a narrowing of this spread on the Jonah Field, however, especially in the case of the high WC+C treatment, which actually showed dominance of densities by total seeded species over the non-seeded species. So, although the treatment effects did not show the significant differences we expected, especially for non-seeded invasives, these treatments do show promise as a tool to narrow the abilities of non-seeded invasives to outcompete the seeded species on a highy invaded area such as the Jonah Field.

On the Pinedale Anticline, an area not invaded by undesireable plant species, the competition for resources was between the volunteer barley and the seeded native plant species. We see this reflected in Figure nine's trend lines for volunteer barley and total seeded species in the medium and high straw treatments.

Additional site characteristic differences exist between the Pinedale Anticline's reduced invasion by exotics, compared with the more highly invaded Jonah Field. The Pindale Anticline is at higher elevations and had corresponding higher mean annual precipitation and above and below-ground biomass than the Jonah Field. This leads to higher levels of TOC and N measured at the Pinedale Anticline, compared to the Jonah Field. If we consider that the Pinedale Anticline site represents the more typical native site that is N-limited, and the Jonah Field the more typical disturbed site, that is N-rich, it proves reasonable that the Pinedale Anticline site's soils and vegetation were more sensitive to additions of high C and experienced some negative treatment effects, while the Jonah Field only saw positive effects to vegetation compared to the control plots. This idea is supported in Figure 10, where we see the Pinedale Anticline experiencing the most significant treatment effects, some of them negative effects on soils and vegetation variables, with no negative effects on any soil or vegetation parameters, compared to the control on the Jonah Field.

Although areas such as the Jonah Field site seem more likely to benefit from C additons, reclaimed well-pads on both the Jonah Field and Pinedale Anticline are under reclamation requirements administered by the BLM, with specific criteria for vegetation conditions, which must be met for a site to be deemed successfully reclaimed. Some of these requirements begin as early as the first growing season, with more stringent requirements evaluated five years post-seeding (see Appendix J for additional Full Site Final Reclamation Criteria). The following stipulations are included in the vegetation monitoring criteria:

4.1.1. Starting the first growing season post seeding, qualitative monitoring shall be conducted annually on all reclamation sites (all pads and ROW) until the locations have met the interim reclamation criteria, usually at the eighth year, set forth in Appendix C, C.4.1.

C.4 Interim or Final Reclamation Criteria
Successful reclamation to facilitate restoration of habitat function will be measured in stages as follows: Within 1 year of initiation of interim or final reclamation sites will demonstrate the establishment of a viable desirable seedling density or frequency. Desirable seedling density or frequency, compared to reference site, shall consist of a vigorous, diverse, native (or otherwise approved) plant community or ecologically comparable species as approved by BLM Authorizing Officer (AO).

C.4.1 Vegetative Criteria for Interim Reclamation
1. Native Forbs: The average density or frequency of desirable forbs must be a minimum of 75% of the reference site within 5 years. Diversity of forbs on a reclaimed site must be equal to or greater than the reference site within 5 years.

2. Native Shrubs: The average density or frequency of the shrub component must be at least 50 % of the reference site within 5 years. This includes both shrubs and half shrubs (e.g. winterfat, fringed sage, etc.). At least 15% density or frequency of the shrub component must be by the dominant species from reference site. The diversity of shrubs must be equal to or greater than the reference site.

3. Native Grasses: Reclaimed sites must have a minimum of three native perennial grass species present, two of which must be bunch grass species. These are to be planted at rates appropriate to achieve abundance and diversity characteristics similar to those found on the reference site.

4. Non-Native Weeds: Sites must be free from all species listed on the Wyoming and federal noxious weed lists. All state and federal laws regarding noxious weeds must be followed. Other highly competitive invasive species such as cheatgrass and other weedy brome will be actively treated if found in the reclaimed areas.

C.4.2 Full Site Final Reclamation Criteria
1. Ground Cover & Ecological Function
To ensure soil stability and nutrient cycling, ground cover must be equal to or greater than the reference site and vegetative litter must be decomposing into the soil.

5.2. Annual nuisance weedy plants such as kochia, halogeton, lambsquarters, etc. will have an allowed threshold of 10% canopy cover on each pad as a whole and 4% canopy cover on each one mile of ROW at which time the Pads and ROW will be considered free of undesirable species. NOTE: At final reclamation for bond release the threshold will not exceed 1% canopy cover of annual weedy species for any location or ROW (BLM, 2008).

Upon successful reclamation, sites undergo bond release and oil and gas companies are given provisions to develop additional land. Review of these requirements shows that reclaimed natural gas well-pads are evaluated on not only the general population of native and non-native plant species present following reseeding, but also on specific percents of shrubs and grasses. It is therefore necessary for reclamationists to monitor and plant sites to support a minimal number of plants under varying life forms. Although minimal significant differences were found in the total seeded species treatment effects in our study, the further partitioning of seeded species into functional groups did yield additional significant differences. The Jonah Field averaged only 1.00 forb m^{-2} and 3.00 shrubs m^{-2} on its control plots. The low and medium straw treatments on the Jonah Field had significantly more forbs, however, and both sites had significantly higher shrubs, over twice as many, in the low straw treatments compared to the control. This could be of serious interest to reclamationists trying to meet the native shrub requirement outlined above which includes "half shrubs" interpreted to consist of some species we identified as forbs, such as winterfat.

Results from our vegetation results, also of interest to reclamationists required to adhere to monitoring requirements, were our treatment effects on ground cover. The extremely windy conditions throughout Wyoming can challenge placement of soil amendments, especially looser and lighter materials such as straw. This was a concern in utilizing straw for this study, but these treatments along with the WC maintained observable cover over the entire year, likely in part due to their incorporation by disking. Included in stipulations for final bond release are parameters outlining requirements for "Ground Cover and Ecological Function" listed above. Most of the C additions had significantly lower bare ground than the control, an important additional restorative benefit.

Treatment Costs

Successful use of these C additions can only be considered if they prove cost effective. A recent analysis, based on Wyoming data from 1997-2007, found the average cost of reclaiming a single well-pad to be $29,136 (Andersen and Coupal, 2009). This same report found 58% of the active wells examined, were under sagebrush steppe land cover classifications. These communities have proven difficult to reclaim, as vegetation is often at a climax stage, soils are often alkaline, and the climate is cold and dry. Measures that expedite and secure successful reclamation can prove more valuable than their immediate overhead expenditure. Costs for several Colorado well sites undergoing typical reclamation practices averaged from about $17-23,000 per well, with an estimated $20,000 in additional costs for sites where initial reclamation failed (Chenoweth et al., 2010). This makes estimated costs, even for the most expensive highly applied treatments, worth their initial investment should they prevent the need for additional site management.

CONCLUSION

When considering the variables significantly affected by the treatments compared to the control, we found the investigated soil conditions experienced more positive treatment effects than did the vegetative groups. This is likely due to the short duration of our study where the more sensitive soil properties revealed more significant results to initial changes compared to the more resilient vegetative communities at the reclamation sites. Our results also indicate that more heavily invaded sites such as the Jonah Field, which only had positive treatment effects compared to the control, will likely benefit more from C additions than less invaded sites, such as the Pinedale Anticline, which experienced some negative treatment effects compared to the control.

Every treatment utilized in this study significantly positively affected several soil properties compared to the control plots, with most of them significantly decreasing pH and bare ground at both sites, and $CaCO_3$ levels on the Pinedale Anticline. The high straw treatment was the only treatment with significantly higher soil moisture, but this treatment also suppressed grass and forb densities on the Pinedale Anticline. Treatments had generally positive significant effects on labile soil and physical OMC pools investigated. The high WC and straw applications generally showed a higher number of significant positive effects on soil conditions than the other treatments, but this was also true for negative effects on native seeded vegetation on the Pinedale Anticline.

The low straw treatment also presented as having several significant positive benefits to soil properties, and the most positive effects on native vegetation at both sites. The high WC+C treatment on the Jonah Field and the medium and high WC+C and low WC treatments on the Pinedale Anticline had significantly more total seeded species than several other treatments, but not the control, at each site. The high WC+C treatments on the Jonah Field were the only plots with more total seeded native species counted than non-seeded invasives. The low and medium straw treatments had significantly more forbs on the Jonah Field than the control plots. The low straw treatment also had significantly more shrubs than the control at both sites, with all shrubs counted being sagebrush, a challenging plant to establish at early seral stages.

Most of the treatments successfully reduced mineral N, but also levels of labile organic N. The decreases in N did not significantly decrease invasive plant densities compared to control plots, but same treatments with the lowest concentreations of total mineral N at fall sampling on the Pinedale Anticline's high straw and WC treated plots also had the lowest reported means of non-seeded invasive and native plants. Total mineral N was also lowest under these treatments on the Jonah Field.

Carbon additions showed potential to help meet requirements upheld for sites to be deemed successfully reclaimed, especially given criteria on the number of shrub, forbs, and ground cover required by final site reclamation evaluation. Sites like those found on the Pinedale Anticline, where native plant species dominate vegetation communities, may not be challenged to meet reclamation requirements and may be more likely to undergo negative treatment effects, compared to sites like the highly-invaded Jonah Field, which may be significantly benefitted from C additions. High pH soils and invasive plants are among the top challenges land managers face during reclamation. If alkaline soil conditions; prevalent invasive plant species; or a lack of native shrubs and forbs; prevent sites from being released from bonding, this can prevent additional production and development for companies facing roll-over limits, causing additional costs associated loss of production. The fact that the Jonah Field site had no variables which experienced a significant negative effect from a treatment throughout the study; had positive treatment effects to soil properties by all treatments; and only had positive treatment effects on native vegetative groups, which showed low numbers in control plots; further supports the idea that more highly invaded communities will benefit the most from C additions.

The WC treatment was the most expensive, followed by the WC+C, then straw. Their differences in price relative to total estimated reclamation costs were not excessive, however, especially if they prevent repeated management practices caused by failed reclamation. Our study was short in duration, yet we saw significant positive treatments effects to all of the soil properties investigated. Given these effects on soil properties, which are the growth medium, we expect eventual additional positive effects on native vegetation. Future assessment is needed to realize the sustained treatment effects and efficacy of C additions as a reclamation tool on southwest Wyoming's natural gas well pad sites.

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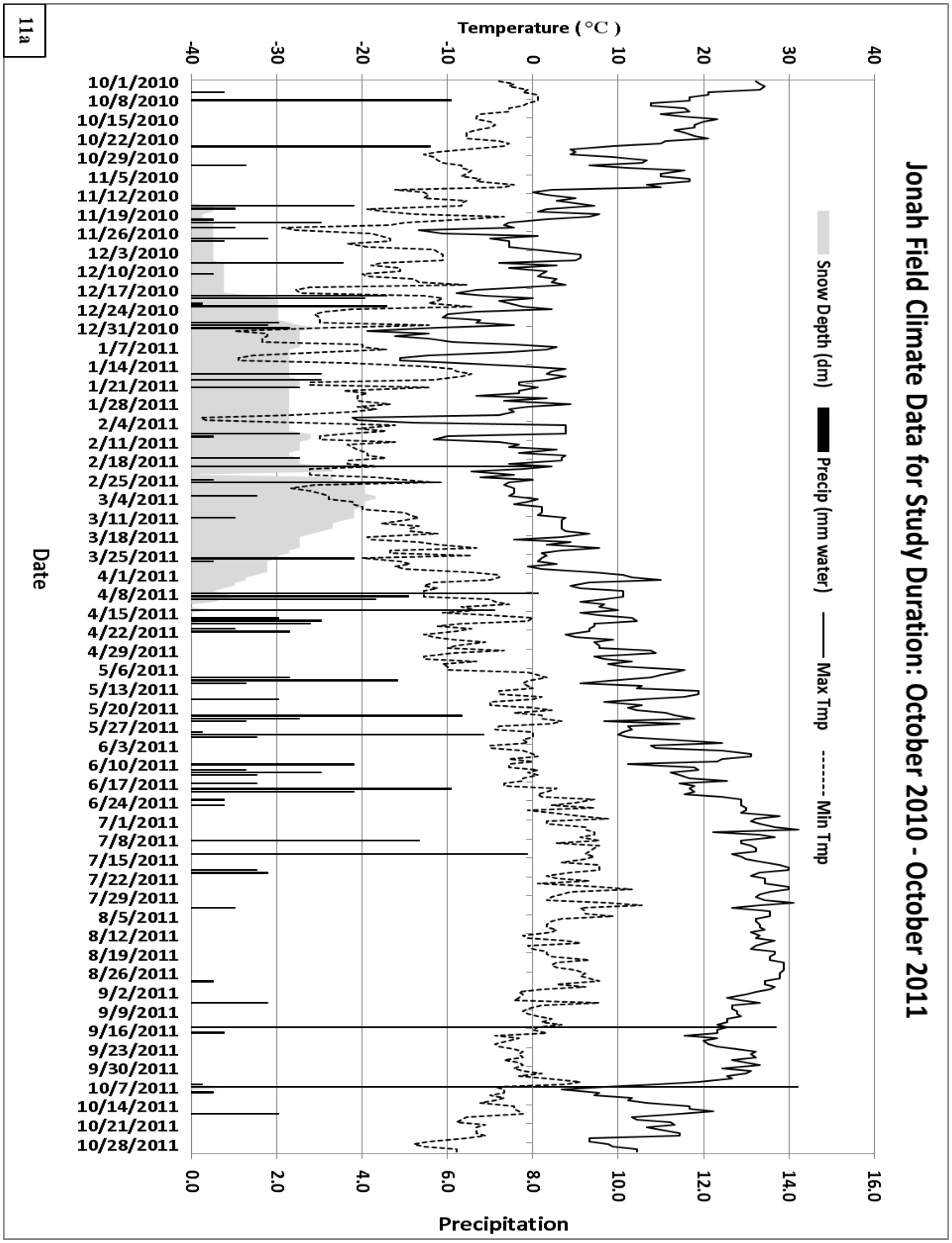
APPENDIX A: Daily Climate Data for Duration of Study



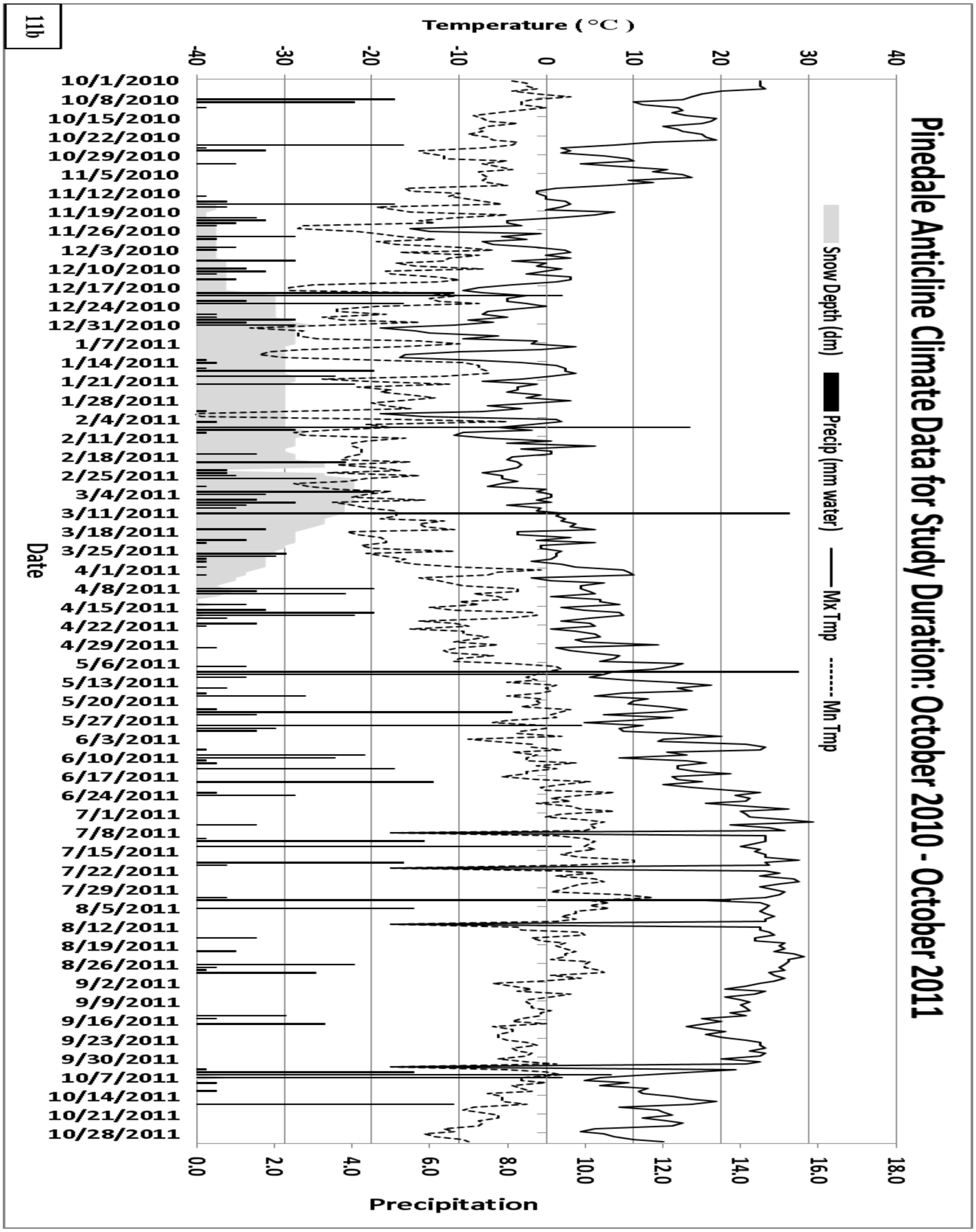


Figure 11a. Daily values for maximum and minimum temperature, precipitation, and snow depth from study duration for Jonah Field study site and **11b**. Pinedale Anticline study site

APPENDIX B: Detatailed Description of ESD Plant Species for the Study Sites

Table 34. Ecological Site Descriptions of Jonah Field (JF) and Pinedale Anticline (PA) sites (NRCS, 2010).

Site	Major Grasses	Other Grasses	Major Woody plants	Other Woody Plants
JF	*Pascopyrum smithii* (western wheatgrass), *Elymus elymoides* (bottlebrush squirreltail), *Achnatherum hymenoides* (Indian ricegrass)	*Koeleria macrantha* (prairie junegrass), *Calamagrostis montanensis* (plains reedgrass), *Carex duriuscula* (needleleaf sedge), *Poa secunda* (Sandberg bluegrass)	*Artemisia tridentata* spp. *wyomingensis* (Wyoming big sagebrush)	*Artemisia longiloba* (early sagebrush), *Artemisia arbuscula* (low sagebrush), *Picrothamnus desertorum* (bud sagebrush), *Ericameria teretifolia* (green rabbitbrush), *Atriplex gardneri* (Gardner's saltbush), *Atriplex confertifolia* (shadscale saltbush), *Krascheninnikovia lanata* (winterfat), *Tetradymia canescens* (spineless horsebrush)
Access entire Jonah Field site ESD (R034AY104WY) w/links toauthorities online at: http://esis.sc.egov.usda.gov/ESDReport/fsReport.aspx?id=R034AY222WY&rptLevel=communities&approved=yes				
PA	*Pascopyrum smithii* (western wheatgrass), *Pseudoroegneria spicata* (bluebunch wheatgrass), *Hesperostipa comata* (needle and thread) *Achnatherum lettermanii* (Latterman's needlegrass) *Poa secunda* (Canby bluegrass),	*Koeleria macrantha* (prairie junegrass), *Achnatherum hymenoides* (Indian ricegrass), *Elymus elymoides* (bottlebrush squirreltail) *Poa secunda* (Sandberg bluegrass), *Poa fendleriana* (mutton bluegrass), *Carex filifolia* (threadleaf sedge), *Carex duriuscula* (needleleaf sedge), *Calamagrostis montanensis* (plains reedgrass)	*Artemisia tridentata* spp. *wyomingensis* (Wyoming big sagebrush)	*Ericameria teretifolia* (green rabbitbrush), *Krascheninnikovia lanata* (winterfat)
Access entire Pinedale Anticine site ESD (R034AY222WY) w/links toauthorities online at: http://esis.sc.egov.usda.gov/ESDReport/fsReport.aspx?id=R034AY122WY&rptLevel=communities&approved=yes				

APPENDIX C: Compost Analysis Report

US COMPOSTING COUNCIL

Seal of Testing Assurance

Terra Firma Organics, Inc.

Shayne Hansen
PO Box 2713
Jackson, WY 83001
307-413-1828

Product Name: 87522
Sample Date: 5/26/10 3:00 PM
A & L Lab Number: 50586
A & L Report Number: F10147-6004

COMPOST TECHNICAL DATA SHEET

A & L Great Lakes Laboratories, Inc. 3505 Conestoga Drive Fort Wayne IN 46808

Compost Parameters	*Method*	*Reported as (units of measure)*	*Test Results*	*Test Results*
Plant Nutrients:		%, weight basis	%, wet weight basis	%, dry weight basis
Nitrogen	TMECC 04.02-D	Total N	0.54	0.78
Phosphorus	TMECC 04.03-A	P_2O_5	0.25	0.37
Potassium	TMECC 04.04-A	K_2O	0.70	1.02
Calcium	TMECC 04.05-CA	Ca	2.11	3.06
Magnesium	TMECC 04.05-MG	Mg	0.52	0.76
Moisture Content	TMECC 03.09-A	%, wet weight basis	30.93	
Organic Matter Content	TMECC 05.07-A	%, dry weight basis	27.73	
pH	TMECC 04.11-A	pH units	8.2	
Soluble Salts *(electrical conductivity EC_5)*	TMECC 04.10-A	dS/m (mmhos/cm)	1.66	
Particle Size	TMECC 02.02-B	% < 9.5 mm (3/8 in.), dw basis	99.52	
Stability Indicator *(respirometry)*				*Stability Rating:*
CO_2 Evolution		mg CO_2-C/g OM/day mg CO_2-C/g TS/day	1 1	Very Stable
Maturity Indicator (bioassay)				
Percent Emergence	TMECC 05.05-A	average % of control	100	
Relative Seedling Vigor	TMECC 05.05-A	average % of control	100	
Select Pathogens	TMECC 07.01-B	PASS/FAIL: per US EPA Class A standard, 40 CFR § 503.32(a)	PASS	*FecalColiform*
Trace Metals	TMECC 04.06	PASS/FAIL: per US EPA Class A standard, 40 CFR § 503.13, Tables 1 and 3	PASS	*As, Cd, Pb, Hg, Mo, Ni, Se, Zn*

Participants in the US Composting Council's Seal of Testing Assurance Program have shown the commitment to test their compos products on a prescribed basis and provide this data, along with compost end use instructions, as a means to better serve the needs o their compost customers.

REPORT NO.
10147-6004
ACCOUNT NUMBER
87522

A & L GREAT LAKES LABORATORIES, INC.

3505 Conestoga Dr. • Fort Wayne, IN • 46808 • 260-483-4759 • FAX 260-483-5274
www.algreatlakes.com • lab@algreatlakes.com

QUALITY ANALYSES FOR INFORMED DECISIONS

TO: TERRA FIRMA ORGANICS, INC
PO BOX 2713
JACKSON, WY 83001-2713

FOR: PILE 1 COMPOST

COPY: AL RATTIE

STA

ATTN: DANE BUK

COMPOST ANALYSIS REPORT

LAB NUMBER: 50586
SAMPLE ID: 87522

DATE SAMPLED: 05/26/2010
DATE RECEIVED: 05/27/2010
DATE REPORTED: 06/14/2010 PAGE: 1

PARAMETER	UNIT	ANALYSIS RESULT	DRY BASIS RESULT	ANALYSIS METHOD
Moisture @ 70 C	%	30.93		TMECC 03.09-A
Dry Matter	%	69.07		TMECC 03.09-A
Total Nitrogen (N)	%	0.54	0.78	TMECC 04.02-D
Phosphorus (P)	%	0.11	0.16	TMECC 04.03-A
Phosphate (P205)	%	0.25	0.37	TMECC 04.03-A
Potassium (K)	%	0.59	0.85	TMECC 04.04-A
Potash (K2O)	%	0.70	1.02	TMECC 04.04-A
Magnesium (Mg)	%	0.52	0.76	TMECC 04.05-MG
Calcium (Ca)	%	2.11	3.06	TMECC 04.05-CA
Arsenic	mg/kg	2.771	4.012	SW846-6020 04.06-As
Cadmium	mg/kg	0.433	0.627	SW846-6020 04.06-Cd
Chromium	mg/kg	7.349	10.640	SW846-6020 04.06-Cr
Copper	mg/kg	13.179	19.081	SW846-6020 04.06-Cu
Mercury	mg/kg		< 0.001	SW846-6020 04.06-Hg
Molybdenum	mg/kg	0.525	0.760	SW846-6020 04.06-Mo
Nickel	mg/kg	6.609	9.568	SW846-6020 04.06-Ni

TMECC - Test Methods for the Examination of Composting and Compost. The U.S. Composting Council.

US COMPOSTING COUNCIL

Seal of Testing Assurance

Terra Firma Organics, Inc.

Shayne Hansen
PO Box 2713
Jackson, WY 83001
704-588-9070

Product Name: 87522

Sample Date: 5/26/10 3:00 PM

A & L Lab Number: 50586

A & L Report Number: F10147-6004

COMPOST TECHNICAL DATA SHEET

A & L Great Lakes Laboratories, Inc. 3505 Conestoga Drive Fort Wayne IN 46808

Compost Parameters	*Method*	*Reported as (units of measure)*	*Test Results*	
Plant Nutrients:		%, weight basis	Not Reported	
Moisture Content	TMECC 03.09-A	%, wet weight basis	30.93	
Organic Matter Content	TMECC 05.07-A	%, dry weight basis	27.73	
pH	TMECC 04.11-A	pH units	8.2	
Soluble Salts *(electrical conductivity EC_5)*	TMECC 04.10-A	dS/m (mmhos/cm)	1.66	
Particle Size	TMECC 02.02-B	% < 9.5 mm (3/8 in.), dw basis	99.52	
Stability Indicator *(respirometry)*				*Stability Rating:*
CO_2 Evolution		mg CO_2-C/g OM/day	1	Very Stable
		mg CO_2-C/g TS/day	1	
Maturity Indicator (bioassay)				
Percent Emergence	TMECC 05.05-A	average % of control	100	
Relative Seedling Vigor	TMECC 05.05-A	average % of control	100	
Select Pathogens	TMECC 07.01-B	PASS/FAIL: per US EPA Class A standard, 40 CFR § 503.32(a)	PASS	*FecalColiform*
Trace Metals	TMECC 04.06	PASS/FAIL: per US EPA Class A standard, 40 CFR § 503.13.	PASS	*As, Cd, Pb, Hg, Mo, Ni, Se, Zn*

Participants in the US Composting Council's Seal of Testing Assurance Program have shown the commitment to test their compost products on a prescribed basis and provide this data, along with compost end use instructions, as a means to better serve the needs of

APPENDIX D: Seed Mixes for Jonah Field and Pinedale Anticline

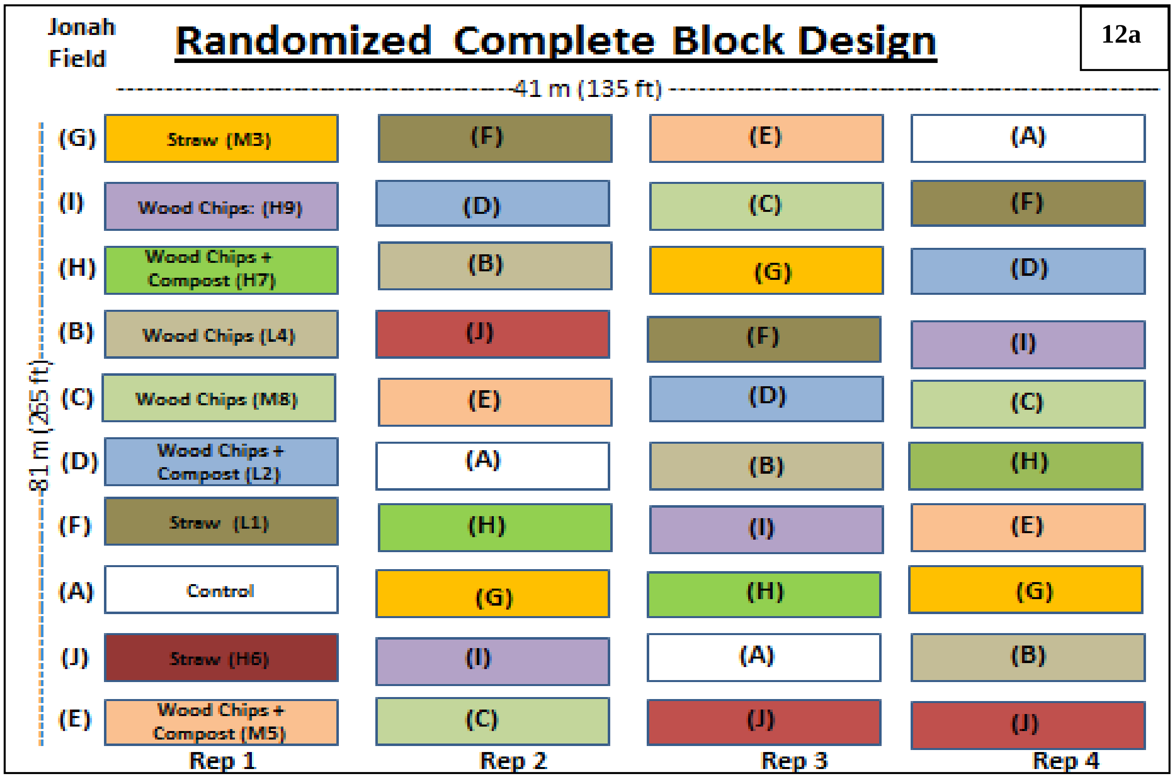
Table 35. Jonah Field seed mix provided by Encana Oil and Gas Corporation

Location:				**Grass Seed Mix "A" (Alkaline Moderalty Deep)**			
SEEDING OBJECTIVES:							
Utilized by Wildlife. Cattle Grazing in the Future							
SPECIES	**CULTIVAR ***	**% SEED MIX COMP.**	**LBS PLS FOR FULL SEEDING****	**SEEDS/LB PLS OF SEED**	**SEEDI NG RATE (SEEDS / SQFT)**	**PLS SEEDIN G RATE (LBS/AC)**	**TOTAL LBS PLS NEEDE D**
Slender wheatgrass (Rev)	pryor	25%	8	159,000	7.3	2.00	8.0
Sandberg bluegrass (VNS)	high plains	5%	1	925,000	1.1	0.05	0.2
Bottlebrush squirreltail (VNS)	sand hallow	5%	5	192,000	1.1	0.25	1.0
Blue Bunch Wheat Grass	goldar	15%	6	155.000	3.2	0.90	3.6
Basin Wildrye	trailhead	20%	5.6	122,000	3.1	1.12	4.5
Needle and Thread	common	15%	5	115,000	2.0	0.75	3.0
Streambank Wheatgrass	sodar	15%	6	152,000	3.1	0.90	3.6
							0.0
							0.0
							0.0
							0.0
							0.0
							0.0
TOTALS:		**100%**			**21**	**6.0**	**23.9**
SPECIES	**CULTIVAR ***	**% SEED MIX COMP.**	**LBS PLS FOR FULL SEEDING****	**SEEDS/LB PLS OF SEED**	**SEEDI NG RATE (SEEDS / SQFT)**	**PLS SEEDIN G RATE (LBS/AC)**	**TOTAL LBS PLS NEEDE D**
Shadscale		15%	8	64,900	1.8	1.20	4.8
Winterfat	open range	10%	1	160,000	0.4	0.10	0.4
Gardner's saltbush		20%	1	70,000	0.3	0.20	0.8
Trident saltbush		5%	5	65,000	0.4	0.25	1.0
Scarlet globemallow		5%	2	500,000	1.1	0.10	0.4
Matt saltbush		15%	1	100,900	0.3	0.15	0.6
Wyeth buckwheat		5%	4	135,700	0.6	0.20	0.8
WY Big sagebrush		25%	1	2,400,000	13.8	0.25	1.0
penstemon, palmer		5%	1.5	586,088	1.0	0.08	0.3
aster, blueleaf (gray)		5%	1	800,000	0.9	0.05	0.2
evening-primrose, pale (white)		5%	1.5	700,000	1.2	0.08	0.3
biscuitroot, Canby's		5%	8	100,000	0.9	0.40	1.6
TOTALS:		**120%**			**23**	**3.1**	**12.2**

Table 36. Pinedale Anticline seed mix provided by QEP Energy

Seed Mix 10 Scientific Name	**Common Name**	**Pure Live Seed (PLS)/Acre**	**Comments**
		11.20	**up to 20% more may be applied**
Pascopyron smithii	Western Wheatgrass (Rosana)	0.50	L
Elymus trachycaulus	Thickspike Wheatgrass (Critana)	0.50	L
Pseudoregnaria spicatum	Bluebunch Wheatgrass (Goldar)	2.50	L
Oryzopsis hymenoides	Indian Ricegrass	1.00	L
Sitanian hystrix	Bottlebrush Squirreltail	1.00	L
Stipa lettermanii	Letterman Needlegrass	0.50	L
Stipa comata	Needle-and-Thread	0.50	L
Poa secunda	Sandberg Bluegrass	0.25	S
Cleome serrulata	Rocky Mountain Beeplant	1.00	L
Penstemon cyananthus	Sky Blue Penstemon	0.05	S
Penstemon procurus	Small-flowered Penstemon	0.05	S
Penstemon strictus	Rocky Mountain Penstemon	0.25	S
Achillea millefolium	Western Yarrow	0.15	S
Castillija miniata	Scarlet Indian Paintbrush	0.05	S
Linum lewisii	Lewis Blue Flax (Maple Grove)	0.30	L
Kraschenninikovia lanata	Common Winterfat (WY coll)	1.00	F
Atriplex canescens	Four-wing Saltbush	1.00	L
Artemesia frigida	Fringe Sage	0.10	S
Artemisia tridentata wyomingensis	Wyoming Big Sagebrush	0.50	B (separate)

APPENDIX E: Field Plot Layout of Jonah Field and Pinedale Anticline Study Sites



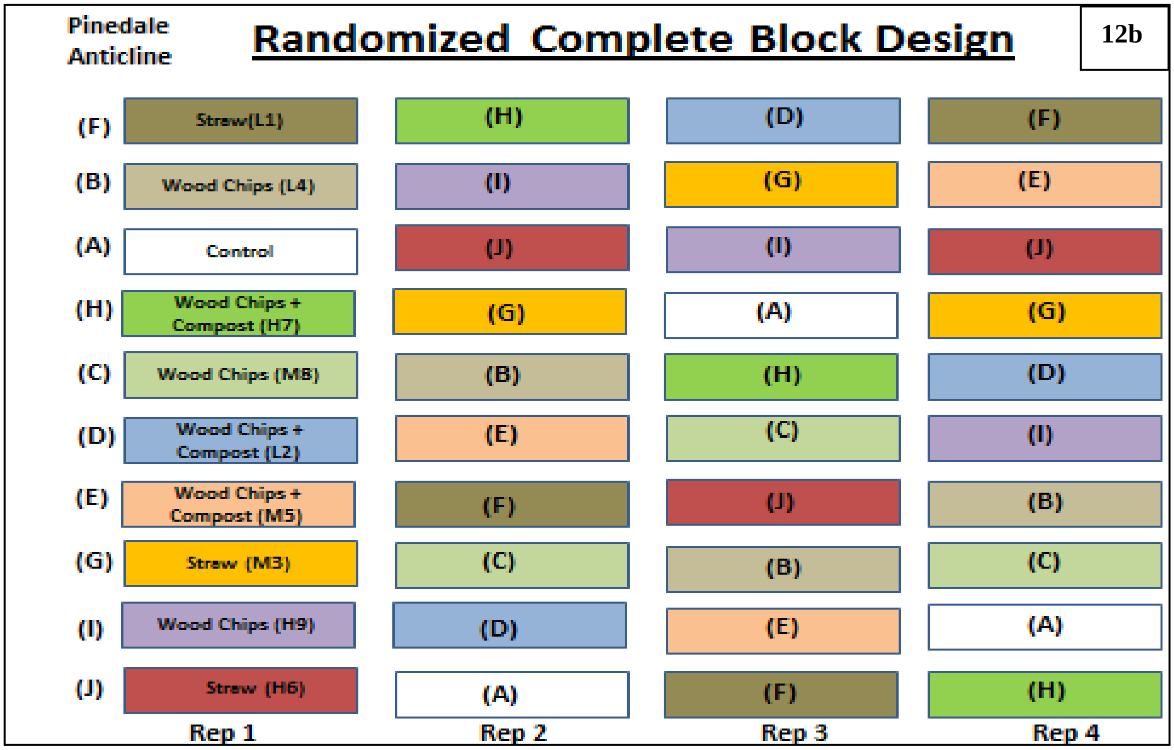


Figure 12a. Field plot layout on the Jonah Field and **12b**. the Pinedale Anticline

APPENDIX F: Details of Time Sensitive and Non-Time Sensitive Lab Analysis Details

Time Sensitive Analyses

Upon return to the lab from the field, BD samples were weighed for moist weight then set out to air-dry with dry samples. Analysis of time sensitive samples began immediately, and included extraction of time zero (To) samples with 50.0 ml of potassium sulfate (K2SO4); chloroform fumigation of microbial biomass (MB) samples; and incubation of PMC and PMN. Gravimetric moisture was also measured by oven drying on day one and day 14. PLFA samples were frozen until analyzed.

Table 37. Time sensitive lab analyses conducted on soil samples.

Analyses	**Gravimetric Moisture**	**MB, DOC, DON**	**PMC**	**PMN**	**PLFA**
Sample Analyzed	Time zero (To) Day 14 (Tf)	Non-fumigated (To) Fumigated (MB)	Day 1,4,7,14 CO_2 (PMC)	Time zero (To) Day 14 (PMN)	Immediately upon thawing
Sample Size	To- 10.0 g Tf- 10.0 g	To- 10.0 g MB- 10.0 g	5.00- 7.00 ml	To- 10.0 g PMN- 22.0 g	5.00 g
Nutrient/ Substrate Measured	moisture content	DOC, DON, MBN,MBC	PMC	initial & potential NO_3^-, NH_4^+	Total MB Bacteria: Total, Gram +, Gram – Fungi: Total, AM
Equipment/ Solution	oven	Shimadzu TOC-VCPH w/ TNM-1Analyzer	Licorr	Biotek 0.50 M K_2SO_4	Gas Chromatograph
Method	Gardner, 1986	Horwath and Paul, 1994	Zibilske, 1994	Doane and Horwath, 2003	Frostegard and Baath, 1991 Buyer et al., 2002

Table 38. Biomarkers used to measure phospholipid fatty acids.

Microbial Pool	**Gram +**	**Gram -**	**AM Fungi**	**Fungi**
Biomarkers	053: 14:0 ISO 077: 15:0 ISO 078: 15:0 ANTEISO 099: 16:0 ISO 122: 17:0 ISO 123: 17:0 ANTEISO	103: 16:1 w9c 129: 17:0 CYCLO 151: 18:1 w9c	107: 16:1 w5c	149: 18:2 w6c

Non-Time Sensitive Analyses

Non-time sensitive analyses included measuring: pH; EC (EC); particle size analysis (PSA); total C and N from each sample, as well as from a 5.0-7.0 mg subsample of the free (F) light fraction collected from organic matter fractionation; inorganic C (IC), and bulk density (BD).

Table 39. Non-time sensitive lab analyses conducted on soil samples.

Analysis	**pH**	**EC**	**PSA**	**Fractionation**	**Total C & N**	**IC**	**BD**
Sample Size	10.0 g	10.0 g	60.0 g	10.0 g	20.0-25.0 mg	10.0 g	2 clods
Pre-Treatment	2 mm sieve	2 mm sieve	2 mm sieve HMP rinse	6.35 mm sieve	2 mm sieve ground	2 mm sieve ground 6 *M* HCl	air dry
Equipment/ Solution	pH meter	EC probe	5.0 % HMP	1.8g/cm^3 NaI	Carlo Erba Elemental Analyzer	Pressure Calcimeter	Paraffin
Method	Thomas, 1996	Thomas, 1996	Gavlak et al., 2005	Sohi et al., 2001	Nelson & Sommers, 1982	Sherrod et al., 2002	Blake, 1986

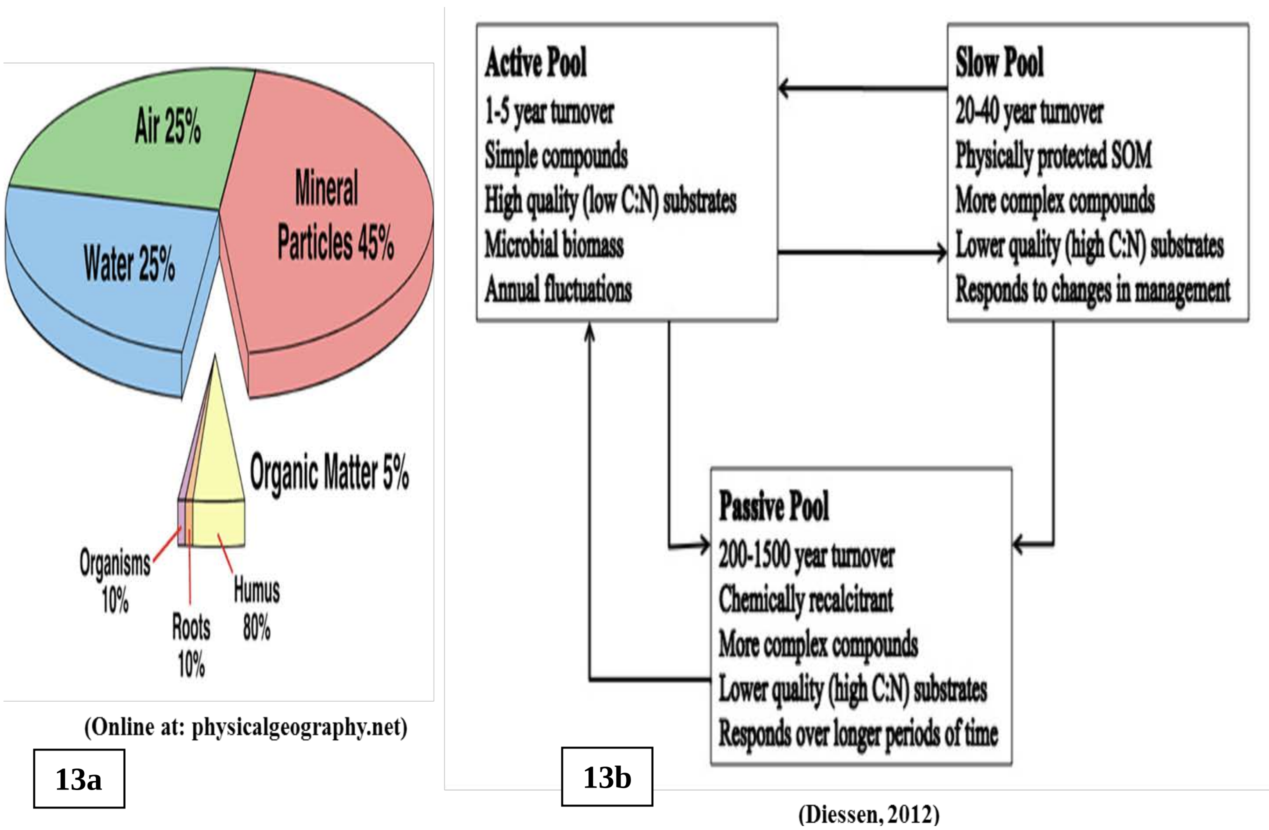
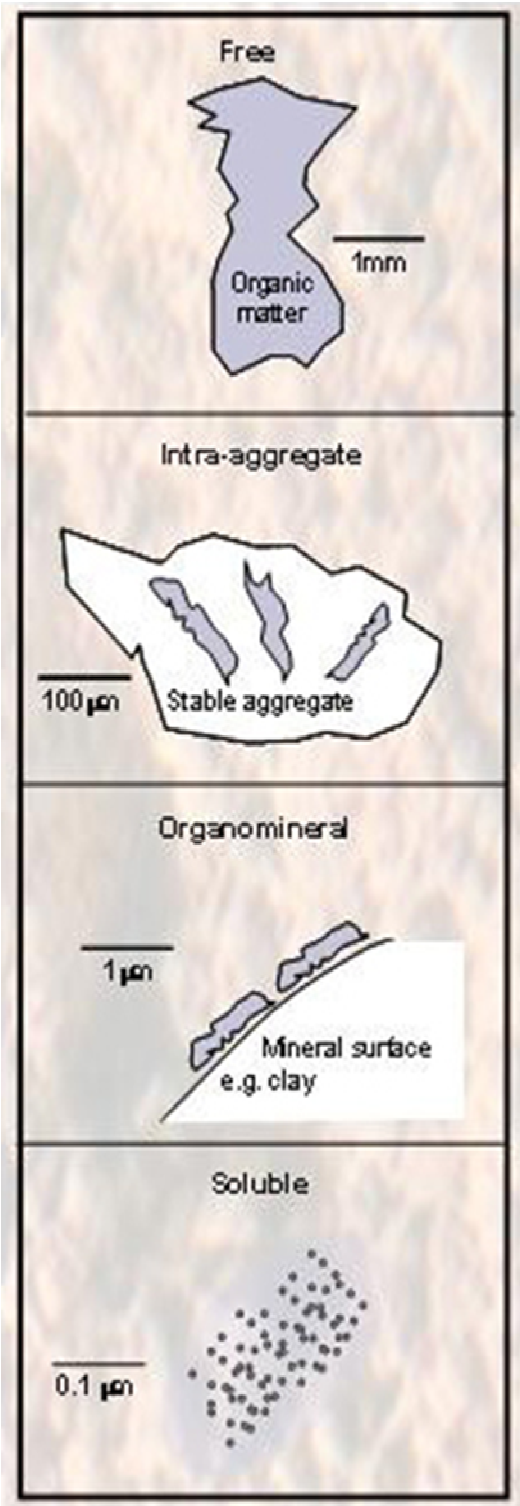


Figure 13a: Image of soil composition and **13b.** image of major SOM pools as described by Parton et al., (1987).



"In sequence the procedure isolates: organic (light fraction) particles material freely located between stable soil aggregates (free organic matter), fine organic particles (light fraction) protected within stable aggregates (intra-aggregate organic matter), and residual heavy (organomineral) material and, importantly, a soluble fraction remaining in the separation medium"

Figure 14:Schematic and description of OM physical fractions (Rothamsted Research Group, 2012).

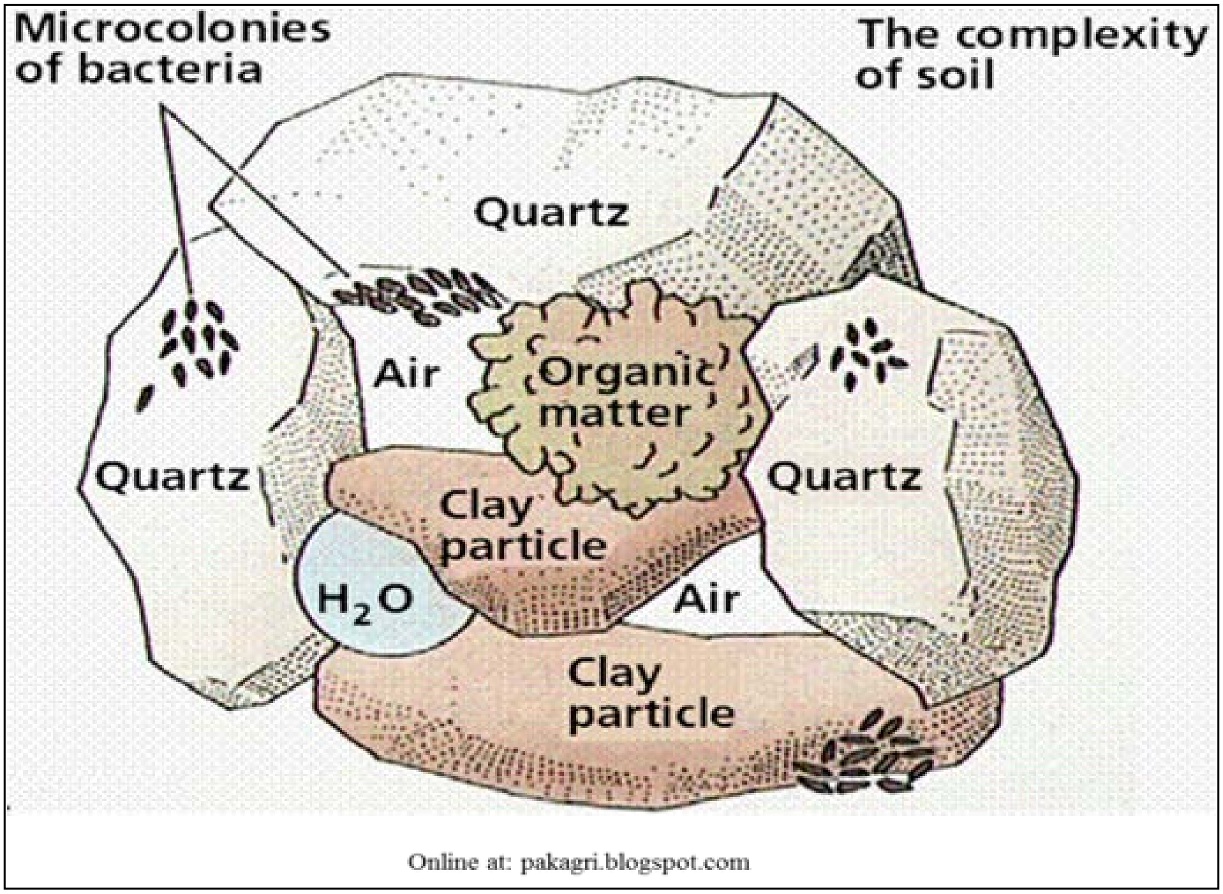


Figure15 : Image of soil aggregate which protects bound OM (a nutrient source), H_2O, and O_s from loss.

APPENDIX G: ANOVA Tables

Vegetative Measurements: Summer 2011

Table 40. ANOVA table for vegetation data collected during summer 2011.

Group	Treatment	Site by Treatment Interaction
	P-Value	
Shrubs	0.0264	0.1445
Forbs	0.0001	0.0001
Grass	0.0001	0.0001
Volunteer Barley	0.0001	0.0001
Non-Seeded Invasives	0.4235	0.0901
Total Seeded: Grasses, Forbs, Shrubs	0.0011	0.0134

Table 41. ANOVA table for cover data collected during summer 2011.

Class	Treatment	Site by Treatment Interaction
	P-Value	
Vegetation	0.0009	0.0060
Litter/Treatment	0.0001	0.1205
Rock	0.8288	0.8265
Cover	0.0003	0.4532

Soils: Spring 2011

Table 42. ANOVA table spring 2011 soils data.

Variable	Treatment	Site by Treatment Interaction	Covariate
	P-Value		
Gravimetric Moisture	0.0002	0.0246	0.3460
PMN Ammonium	0.0111	0.0004	0.7626
Ammonium	0.0053	0.0156	0.0101
PMN Nitrate	0.0001	0.4778	0.0077
Nitrate	0.0001	0.9927	0.0275
Potentially Mineralizable N	0.0001	0.5472	0.0061
Initial Mineral N	0.0001	0.9586	0.0020
Total N	0.0014	0.0001	0.4291
Microbial Biomass N	0.0001	0.0753	0.0614
Disolved Organic N	0.0002	0.7407	0.0027
Potentially Mineralizable C	0.0001	0.3593	0.0050
Total Organic C	0.8995	0.1897	0.6892
Dissolved Organic C	0.0010	0.0010	0.0607
Microbial Biomass C	0.6737	0.0829	0.0492
Bulk Density	0.1010	0.2541	NA
Total Fatty Acids	0.0243	0.1290	NA
Bacteria	0.0117	0.0788	NA
G-POS Bacteria	0.0019	0.0167	NA
G-NEG Bacteria	0.1457	0.3942	NA
Arbuscular Mychorrhizal Fungi	0.3022	0.2608	NA
Fungi	0.1201	0.5183	NA
Sand	0.9150	0.0113	NA
Clay	0.4504	0.0230	NA
Silt	0.9292	0.1444	NA

Soils: Fall 2011

Table 43. ANOVA table spring 2011 soils data.

Variable	Treatment	Site by Treatment Interaction	Covariate
	P-Value		
pH	0.0001	0.0724	0.0607
Electrical Conductivity	0.6131	0.4059	0.2212
Gravimetric Moisture	0.0373	0.2195	0.4526
Calcium Carbonate	0.0398	0.0439	0.0001
PMN Ammonium	0.2701	0.0410	0.9886
Ammonium	0.1727	0.0881	0.5278
PMN Nitrate	0.0001	0.0116	0.4200
Nitrate	0.0003	0.1408	0.8646
Potentially Mineralizable N	0.0001	0.0131	0.4183
Total Mineral N	0.0003	0.5001	0.6665
Total N	0.8648	0.8191	0.0055
Microbial Biomass N	0.0001	0.0001	0.0056
Dissolved Organic N	0.0046	0.0886	0.0303
Potentially Mineralizable C	0.0001	0.9744	0.0012
Total Organic C	0.3747	0.1476	0.0124
Dissolved Organic C	0.0001	0.0217	0.0014
Microbial Biomass C	0.0039	0.0703	0.0342
% Free Light Fraction	0.0912	0.2467	0.0004
Free Light Fraction N	0.0001	0.0649	0.5954
Free Light Fraction C	0.0119	0.3586	0.1224

APPENDIX H: Supplemental Soils Data from Spring and Fall 2011

Table 44. Nitrate and ammonium for the Jonah Field and Pinedale Anticline soils from spring 2011. Values are means; (standard error); different letters indicate significant differences at P≤ 0.10.

Nitrate		**Ammonium**		**Ammonium**	
***Treatment**	**Jonah Field & Pinedale Anticline**	**Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	mg kg $^{-1}$soil		*mg kg $^{-1}$soil*		*mg kg $^{-1}$soil*
Control	19.4 (2.03) A	WC+C (M5)	2.74 (0.0397) a	WC+C (L2)	3.59 (0.245) a
WC (L4)	12.4 (2.02) B	WC+C (L2)	2.32 (0.159) ab	Straw (H6)	3.38 (0.139) ab
WC+C (L2)	10.6 (2.02) BC	WC (M8)	2.25 (0.201) abc	WC+C (H7)	3.14 (0.098) abc
WC+C (M5)	6.36 (1.98) CD	Straw (H6)	2.08 (0.186) bc	Straw (M3)	3.10 (0.266) abc
WC+C (H7)	4.39 (1.99) D	Straw (M3)	1.99 (0.203) bc	WC (M8)	2.82 (0.214) bcd
WC (M8)	4.24 (1.99) D	WC (H9)	1.96 (0.131) bc	Straw (L1)	2.56 (0.161) cd
Straw (L1)	3.95 (1.99) D	Control	1.91 (0.153) bc	WC+C (M5)	2.34 (0.420) d
Straw (H6)	3.68 (2.01) D	WC (L4)	1.79 (0.108) bc	WC (H9)	2.33 (0.099) d
WC (H9)	2.41 (1.98) D	WC+C (H7)	1.76 (0.150) bc	WC (L4)	2.29 (0.427) d
Straw (M3)	0.990 (1.98) D	Straw (L1)	1.71 (0.138) c	Control	2.27 (0.140) d

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Table 45. Potential nitrate and potential ammonium for the Jonah Field and Pinedale Anticline soils from spring 2011. Values are means; (standard error); different letters indicate significant differences at P≤ 0.10.

Potential Nitrate		**Potential Ammonium**		**Potential Ammonium**	
Treatment	**Jonah Field & Pinedale Anticline**	**Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	mg kg $^{-1}$soil		*mg kg $^{-1}$soil*		*mg kg $^{-1}$soil*
Control	22.5 (2.25) A	WC (L4)	1.84 (0.397) a	WC+C (L2)	3.66 (0.245) a
WC+C (L2)	16.6 (2.13) B	WC (M8)	1.61 (0.159) ab	WC+C (H7)	2.58 (0.139) ab
WC (L4)	12.6 (2.15) BC	WC+C (H7)	1.53 (0.201) ab	Straw (M3)	2.57 (0.098) b
WC+C (M5)	8.59 (2.12) CD	Straw (M3)	1.41 (0.186) ab	Straw (L1)	2.55 (0.268) b
WC (M8)	8.44 (2.14) CD	WC+C (M5)	1.40 (0.203) ab	WC (M8)	2.51 (0.214) bc
WC+C (H7)	6.89 (2.11) DE	Straw (H6)	1.39 (0.131) ab	WC+C (M5)	2.21 (0.161) bcd
Straw (L1)	5.21 (2.12) DE	WC (H9)	1.28 (0.153) b	Straw (H6)	2.00 (0.420) cd
Straw (H6)	3.39 (2.14) E	Control	1.21 (0.108) b	WC (L4)	1.91 (0.099) d
WC (H9)	3.03 (2.23) E	WC+C (L2)	1.15 (0.150) b	WC (H9)	1.85 (0.427) d
Straw (M3)	1.69 (2.13) E	Straw (L1)	1.07 (0.138) b	Control	1.74 (0.140) d

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Table 46. Nitrate and ammonium for the Jonah Field and Pinedale Anticline soils from fall 2011. Values are means; (standard error); different letters indicate significant differences at P≤0.10.

Nitrate		Ammonium		Ammonium	
***Treatment**	**Jonah Field & Pinedale Anticline**	**Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	mg kg^{-1}soil		*mg kg^{-1}soil*		*mg kg^{-1}soil*
Control	9.01 (0.940) A	WC (M8)	2.26 (0.725)	WC+C (H7)	5.28 (0.706)
WC+C (H7)	5.54 (1.62) B	Straw (L1)	2.05 (0.343)	Straw (L1)	4.80 (0.479)
WC (L4)	5.41 (0.653) B	Straw (M3)	1.87 (0.077)	Straw (M3)	4.48 (0.508)
WC+C (M5)	5.20 (0.858) B	Control (0)	1.80 (0.609)	Control (0)	3.89 (0.210)
WC+C (L2)	5.08 (0.576) B	WC+C (M5)	1.69 (0.512)	WC+C (L2)	3.71 (0.231)
WC (M8)	4.74 (1.12) B	WC+C (L2)	1.67 (0.415)	WC+C (M5)	3.62 (1.11)
Straw (M3)	4.53 (0.993) BC	WC (L4)	1.52 (0.319)	WC (L4)	3.15 (0.885)
Straw (L1)	4.19 (0.490) BC	Straw (H6)	1.42 (0.207)	WC (H9)	2.97 (1.06)
Straw (H6)	2.63 (0.752) C	WC (H9)	1.40 (0.144)	WC (M8)	2.96 (0.392)
WC (H9)	2.52 (0.680) C	WC+C (H7)	1.04 (0.309)	Straw (H6)	2.85 (0.254)

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Table 47. Potential nitrate for the Jonah Field and Pinedale Anticline from fall 2011. Values are means ; (standard error); different letters indicate significant differences at P≤ 0.10.

Potential Nitrate		Potential Nitrate	
Treatment	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	mg kg^{-1}soil		mg *kg^{-1}soil*
WC (M8)	21.8 (1.35) a	WC+C (M5)	17.7 (2.76) a
Control	16.2 (3.67) ab	WC+C (L2)	17.7 (0.806) ab
WC (L4)	13.8 (3.24) b	Control	17.0 (1.18) ab
WC+C (M5)	13.6 (4.29) b	Straw (L1)	15.4 (1.00) bc
Straw (M3)	12.7 (5.18) b	WC (L4)	10.4 (1.15) cd
Straw (L1)	11.9 (3.12) b	Straw (M3)	10.3 (0.807) cd
WC+C (H7)	10.8 (3.97) b	WC+C (H7)	7.33 (2.40) d
WC+C (L2)	10.6 (1.2.96) b	WC (M8)	7.05 (1.47) de
Straw (H6)	2.33 (1.80) c	Straw (H6)	4.32 (2.72) de
WC (H9)	1.93 (0.707) c	WC (H9)	0.605 (0.323) e

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Table 48. Potential ammonium for the Jonah Field and Pinedale Anticline from fall 2011. Values are means ; (standard error); different letters indicate significant differences at $P \leq 0.10$.

Potential Ammonium		**Potential Ammonium**	
Treatment	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	mg kg⁻¹soil		*mg kg⁻¹soil*
Straw (L1)	2.16 (0.192)	WC+C (M5)	2.34 (0.039)
Control	1.89 (0.179)	Straw (H6)	1.84 (0.116)
Straw (H6)	1.89 (0.332)	Straw (L1)	1.73 (0.171)
WC (L4)	1.85 (0.277)	WC+C (H7)	1.68 (0.179)
WC (M8)	1.82 (0.322)	WC (H9)	1.67 (0.169)
Straw (M3)	1.77 (0.297)	WC (M8)	1.57 (0.061)
WC+C (M5)	1.62 (0.181)	WC (L4)	1.51 (0.290)
WC (H9)	1.53 (0.179)	Straw (M3)	1.48 (0.187)
WC+C (L2)	1.20 (0.325)	WC+C (L2)	1.37 (0.143)
WC+C (H7)	1.13 (0.199)	Control	1.28 (0.180)

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Table 49. Final electrical conductivity for the Jonah Field and Pinedale Anticline soils from fall 2011. Values are means; (standard error).

Electrical Conductivity		**Electrical Conductivity**	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	$dS\ m^{-1}$		*$dS\ m^{-1}$*
WC+C (L2)	0.237 (0.221)	WC+C (H7)	0.432 (0.164)
WC (L4)	0.234 (0.283)	Control	0.429 (0.310)
Straw (M3)	0.232 (0.221)	WC+C (M5)	0.425 (0.426)
Straw (H6)	0.223 (0.305)	Straw (L1)	0.412 (0.174)
WC (H9)	0.223 (0.136)	WC (H9)	0.383 (0.237)
WC+C (M5)	0.220 (0.228)	WC (L4)	0.371 (0.475)
Control	0.208 (0.135)	Straw (H6)	0.363 (0.122)
Straw (L1)	0.202 (0.308)	Straw (M3)	0.360 (0.372)
WC+C (H7)	0.195 (0.075)	WC (M8)	0.360 (0.374)
WC (M8)	0.184 (0.124)	WC+C (L2)	0.355 (0.328)

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Table 50: G-negative bacteria for the Jonah Field and Pinedale Anticline soils. Values are means; (standard error); different letters indicate significant differences at P≤ 0.10.

G-Negative Bacteria		**G-Negative Bacteria**	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	nmol FA g^{-1} soil		*nmol FA g^{-1} soil*
WC+C (L2)	0.351 (0.022)	WC+C (M5)	0.592 (0.042)
Straw (M3)	0.304 (0.028)	WC (L4)	0.540 (0.046)
WC+C (H7)	0.301 (0.041)	Control	0.536 (0.079)
Control	0.294 (0.041)	WC (H9)	0.534 (0.047)
WC (M8)	0.294 (0.063)	WC+C (L2)	0.520 (0.060)
WC (L4)	0.288 (0.066)	WC (M8)	0.464 (0.061)
WC (H9)	0.274 (0.035)	WC+C (H7)	0.424 (0.059)
WC+C (M5)	0.264 (0.033)	Straw (M3)	0.415 (0.068)
Straw (H6)	0.247 (0.031)	Straw (L1)	0.414 (0.055)
Straw (L1)	0.241 (0.066)	Straw (H6)	0.357 (0.056)

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Table 51: Total fungi for the Jonah Field and Pinedale Anticline soils. Values are means; (standard error); different letters indicate significant differences at P≤ 0.10.

Total Fungi		**Total Fungi**	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	nmol FA g^{-1} soil		*nmol FA g^{-1} soil*
WC+C (H7)	0.135 (0.019)	WC+C (M5)	0.231 (0.026)
WC+C (M5)	0.117 (0.019)	WC (H9)	0.230 (0.026)
WC (M8)	0.111 (0.032)	WC+C (L2)	0.202 (0.036)
WC+C (L2)	0.105 (0.008)	WC (L4)	0.190 (0.026)
Straw (M3)	0.101 (0.010)	Straw (M3)	0.170 (0.058)
WC (H9)	0.100 (0.015)	Control	0.160 (0.033)
WC (L4)	0.097 (0.028)	WC+C (H7)	0.156 (0.014)
Control	0.092 (0.021)	WC (M8)	0.156 (0.032)
Straw (H6)	0.083 (0.008)	Straw (H6)	0.127 (0.041)
Straw (L1)	0.078 (0.013)	Straw (L1)	0.124 (0.033)

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Table 52: Arbuscular mycorrhizal fungi for the Jonah Field and Pinedale Anticline soils. Values are means; (standard error); different letters indicate significant differences at P $\leq$ 0.10.

Arbuscular Mycorrhizal Fungi		**Arbuscular Mycorrhizal Fungi**	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	nmol FA g^{-1} soil		*nmol FA g^{-1} soil*
WC+C (L2)	0.049 (0.007)	WC+C (M5)	0.100 (0.010)
Straw (M3)	0.039 (0.007)	WC (H9)	0.097 (0.012)
Control	0.038 (0.006)	Control	0.097 (0.015)
WC+C (H7)	0.036 (0.007)	WC (L4)	0.092 (0.007)
Straw (H6)	0.035 (0.007)	WC (M8)	0.089 (0.013)
WC (L4)	0.034 (0.001)	WC+C (L2)	0.089 (0.004)
WC (M8)	0.032 (0.004)	WC+C (H7)	0.084 (0.015)
WC+C (M5)	0.030 (0.005)	Straw (H6)	0.066 (0.008)
WC (H9)	0.029 (0.004)	Straw (L1)	0.065 (0.010)
Straw (L1)	0.029 (0.016)	Straw (M3)	0.062 (0.013)

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Table 53. Microbial biomass C for the Jonah Field and Pinedale Anticline soils from spring 2011. Values are means; (standard error); different letters indicate significant differences at P$\leq$ 0.10.

Microbial Biomass C		**Microbial Biomass C**	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	mg MBC kg^{-1}soil		*mg MBC kg^{-1}soil*
WC (M8)	71.9 (8.91)	Straw (H6)	62.5 (9.35)
WC+C (M5)	71.4 (8.97)	Straw (M3)	56.2 (8.90)
WC+C (L2)	71.4 (8.94)	WC (H9)	48.1 (9.26)
WC (L4)	67.1 (8.96)	WC (L4)	46.8 (8.94)
Straw (L1)	66.6 (9.46)	Straw (L1)	38.7 (9.31)
Straw (M3)	62.5 (9.21)	Control	35.7 (8.91)
WC+C (H7)	57.7 (9.39)	WC (M8)	35.3 (9.41)
WC (H9)	57.7 (9.29)	WC+C (M5)	32.1 (9.42)
Control	54.7 (8.89)	WC+C (L2)	27.9 (9.02)
Straw (H6)	51.3 (9.33)	WC+C (H7)	25.7 (8.88)

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

Table 54. Total organic C on the Jonah Field and Pinedale Anticline soils from spring 2011. Values are means ; (standard error).

Total Organic C		**Total Organic C**	
***Treatment**	**Jonah Field**	**Treatment**	**Pinedale Anticline**
	g TOC kg $^{-1}$soil		*g TOC kg $^{-1}$soil*
Control	10.2 (1.02)	WC (H9)	19.9 (1.71)
WC+C (L2)	9.86 (0.896)	WC (L4)	19.6 (1.89)
WC (M8)	9.71 (1.54)	Straw (H6)	19.2 (0.862)
WC+C (M5)	9.57 (1.38)	WC+C (M5)	19.1 (1.33)
WC (H9)	9.30 (0.311)	WC (M8)	18.6 (1.43)
WC+C (H7)	9.26 (1.35)	Straw (L1)	18.2 (1.40)
Straw (M3)	9.08 (0.845)	Straw (M3)	17.8 (1.21)
Straw (L1)	8.49 (0.884)	WC+C (H7)	17.5 (1.05)
Straw (H6)	8.11 (1.10)	WC+C (L2)	15.9 (1.23)
WC (L4)	7.70 (1.22)	Control	15.5 (2.06)

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

APPENDIX I: Treatment Cost Data in English Units

Table 55 . Costs per acre of prior use of wood chips (WC) and straw on the Jonah Field and Pinedale Anticline

SITE & MATERIAL	Delivered Material	Application	Incorporation	Total Cost
	\$ ton $^{-1}$	*\$ acre $^{-1}$*		
Pinedale Anticline WC	150	200	25	375
Jonah Field WC	150	340	340	830
Pinedale Anticline Straw	195	25	25	400
Jonah Field Straw	125	200	200	525

Table 56. Costs of treatments used in this study with avaeraged application(App) and incorporation(Inc) costs estimated from historical costs for WC and straw on Jonah Field and Pinedale Anticline.

*Treatment	Application Rate	Delivered Material Cost	App/Inc Costs	Total Treatment Cost	Total Cost for Average Size Well-Pad (5.0 acre)
	ton acre $^{-1}$	*\$ ton $^{-1}$*	*\$*	*\$ acre $^{-1}$*	*\$*
Straw (L1)	1.00	150	277	427	2,135
WC+C (L2)	1.58	92	313	458	2,292
WC (L4)	2.86	75	313	528	2,638
Straw (M3)	3.00	150	277	727	3,635
WC+C (M5)	4.77	92	313	752	3,759
WC (M8)	8.56	75	313	955	4,775
Straw (H6)	5.00	150	277	1,027	5,135
WC+C (H7)	7.94	92	313	1,043	5,217
WC (H9)	14.2	75	313	1,378	6,890

***** Wood chips (WC); wood chips/compost (WC+C); and Straw followed in parentheses by application and N rate: low (L), medium (M) or high (H), and C addition ranking least to most C added: 1-9.

APPENDIX J: Full Site Final Reclamation Criteria

1. Ground Cover & Ecological Function
To ensure soil stability and nutrient cycling, ground cover must be equal to or greater than the reference site and vegetative litter must be decomposing into the soil.

2. Vegetative Criteria
a. Native Forbs: The average density or frequency and total diversity of forbs must be equal to or greater than the reference site within 8 years

b. Native Shrubs: The average density or frequency of the shrub component must be at least 80% of the reference site within 8 years. This includes both shrubs and half shrubs (e.g. winterfat, fringed sage, etc.). At least 25% density of frequency of the shrub component must be the dominant species from the reference site. The diversity of shrub must be equal to or greater than the reference site.

c. Native Grasses: Reclaimed sites must exhibit grass production equal to the reference site. A minimum of 3 native perennial species must be included with at least 2 bunch grass species.

d. Non-Native Weeds: Sites must be free from all species listed on the Wyoming and Federal noxious weed list. All state and federal laws regarding noxious weeds must be followed. Other highly competitive invasive species such as cheatgrass and other weedy brome grasses are also prohibited.

e. Plant Vigor: Plants must be resilient as evidenced by well-developed root systems and flowers. Shrubs will be well established and in a "young" age class at a minimum (e.g. not comprised of seedlings that may not survive until the following year (BLM, 2008).