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The economy of Wyoming is dependent on resource extraction that often leads to drastically altered ecosystems. A complete understanding of changes in soil properties after such activities is warranted prior to rehabilitating these ecosystems. Reclamation of land disturbed for energy development in Wyoming is often limited by the harsh climate, nutrient-poor soils further degraded by disturbance, invasive species, and herbivory. We assessed entire soil profiles on reclaimed and undisturbed soils of six well-pad locations in two natural gas fields in southwest Wyoming for differences in morphological, chemical, physical and SOM properties. Reclaimed soils were found to have thinner and finer-textured A horizons than undisturbed soils, and reclaimed subsoils tended to be more alkaline than undisturbed subsoils. Deep subsoil horizons of reclaimed soils had less calcite ($CaCO_3$) than undisturbed soils. We also evaluated the effects of a controlled livestock treatment on soil and vegetation community characteristics on 10 reclaimed well pads in three natural gas fields. A stocking rate of 240 cattle ha^{-1} d^{-1} was applied to reclaimed well pads in the fall of 2009. Immediately after the treatment was applied, marked increases in labile organic C were observed. This effect diminished by the following spring and levels were comparable to those of the reclaimed reference sites. Newly-seeded vegetation responded to the controlled livestock treatment with higher desired species richness and density than that of the reclaimed reference plots ($P<0.1$).

PROPERTIES OF RECLAIMED SOILS AND THEIR RESPONSE TO A CONTROLLED LIVESTOCK TREATMENT

By

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE: INTRODUCTION

Wyoming has been the second largest producer of onshore natural gas in the United States since 2005 (EIA, 2011). Natural gas production requires extraction from boreholes on well pads connected by a network of linear disturbances including pipelines and roads to access and transport products. Well pads require an average disturbance of 1.2-2.0 ha (3-5 ac) to house all equipment required for drilling. Multi-well pads are often larger and their size depends on the number of wells drilled. The nature of this type of land disturbance can result in habitat loss or fragmentation (Walston et al., 2009), wildlife avoidance (Lyon and Anderson, 2003; Sawyer et al., 2009), changes in plant communities (Bergquist et al., 2007), and other indirect consequences.

From 1985 to 2006, sagebrush habitat declined by an estimated 2.7% from direct impacts and up to 58.5% by indirect impacts of natural gas development on the Pinedale Anticline Project Area (Walston et al., 2009). In response, regulatory agencies have established criteria for reclaiming land disturbed by natural gas extraction. In 2009, the Wyoming BLM issued the Wyoming Reclamation Policy outlining reclamation goals and requirements for all surface-disturbing activities in the state (BLM, 2009). Local BLM offices often had their own reclamation criteria, and adapted requirements in accordance with the statewide policy. The Pinedale and Rawlins field offices of the Bureau of Land Management (BLM) house three of the largest deep-well natural gas fields in Wyoming (Figure 1.1) and developed reclamation requirements specific to natural gas extraction activities. The Pinedale Field Office regulates reclamation on BLM land in the Jonah and Pinedale Anticline natural gas fields and the Rawlins Field Office regulates the Wamsutter natural gas field. The

Pinedale Field Office regulates natural gas production activities with several other federal agencies through two interagency teams: the Jonah Interagency Office (JIO) and the Pinedale Anticline Project Office (PAPO).

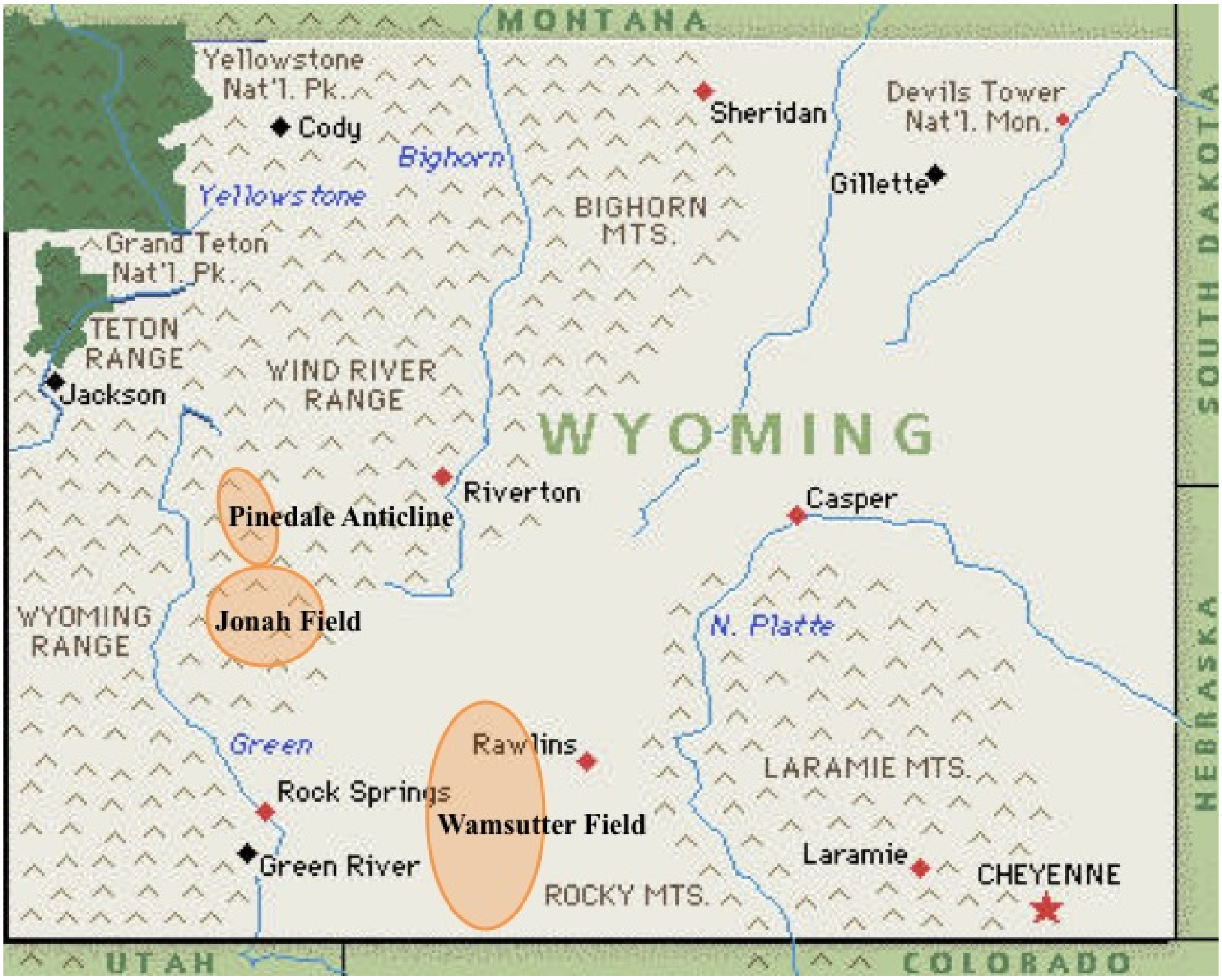

Figure 1.1. Approximate locations of the Pinedale Anticline, Jonah, and Wamsutter natural gas fields in southwest Wyoming, USA.

The BLM field offices define reclamation criteria for interim (or roll over) reclamation and final reclamation. Interim reclamation describes locations still producing gas, but with areas no longer necessary to maintain production (BLM, 2011). This area is then graded to approximate the surrounding landscape and prepared for reclamation activities. When the well no longer produces gas, all production equipment is removed from the location, and the well is plugged for permanent abandonment; the location is prepared for final reclamation (BLM, 2011). Reclamation criteria are often based on evaluation of the plant community in reference to adjacent native plant communities; assuming the native community reflects ecosystem stability and function. The reclamation goals set by the BLM include stabilizing the location and providing conditions to facilitate the establishment of a self-sustaining plant community (PAPO, 2010; JIO, 2008; BLM 2009).

Restoring plant communities disturbed by natural gas activities to the standards outlined by regulatory agencies is often difficult due to the harsh Wyoming climate, adverse soil conditions, and pressure from invasive plant species. The Wyoming Reclamation Policy requires operators to follow a general reclamation protocol to achieve reclamation objectives despite reclamation challenges. These requirements are as follows (BLM, 2009):

- Manage all waste materials
- Ensure subsurface integrity, and eliminate sources of ground and surface water contamination
- Re-establish slope stability, surface stability, and desired topographic diversity
- Reconstruct and stabilize water courses and drainage features
- Maintain the biological, chemical, and physical integrity of the topsoil and subsoil
- Prepare site for revegetation
- Establish a desired self-perpetuating native plant community
- Re-establish complementary visual composition
- Manage invasive plants
- Develop and implement a reclamation monitoring and reporting strategy

Natural gas well pad reclamation procedures vary in Wyoming based on the energy development company, local regulations, and site-specific conditions. Preparing for successful reclamation begins prior to well pad construction with an inventory of soil resources as mandated by the Wyoming Reclamation Policy (BLM, 2009). Ideally, only suitable topsoil material will be salvaged and stockpiled for use during reclamation. However, soil salvage is not always accurate and topsoil may be mixed or diluted with less suitable subsoil material (Visser et al., 1984; Mummey et al., 2002; Mozharova & Vladychenskii, 2003). Subsoils accumulate salts and clays in the arid climate of Wyoming, which may decrease the suitability of the salvaged material as a growth medium. In sagebrush-steppe plant communities, microbial populations are spatially dynamic and concentrated in the upper 5 cm of soil (Bolton et al., 1993). Thus, mixing and dilution can also impact soil nutrient cycling by displacing microbial communities and diluting soil organic matter (SOM). The disturbance from stripping and stockpiling native soil destroys soil structure and aerates the soil; leading to increases in SOM mineralization (Six et al., 2000).

After drilling activities are completed and prior to respreading topsoil, well pads are re-graded to approximate the pre-disturbance topography and ripped for compaction relief (BLM, 2009). While these efforts are anticipated to improve conditions for plant establishment, they require additional disturbance to subsoil material. Stockpiled topsoil is then applied, typically to a uniform depth, across the graded well pad. Native soils in the sagebrush steppe seldom have uniform topsoil depths across the landscape and instead host deeper, richer soil around the base of individual plants often referred to as “islands of fertility” (Schlesinger et al., 1996). The re-spread topsoil is then cultivated using seedbed preparation methods such as imprinting or disking to maximize conditions for seed germination. Well pads are seeded to stabilize soils and stimulate native plant establishment. Seeding methods vary across Wyoming gas fields based on the type of seed, topography, and available equipment. Regardless of seedbed preparation and seeding methods, cultivation practices further disturb soil structure (Six et al., 2000).

The altered soil morphology and physical, chemical, and biological properties found on reclaimed well pads impacts the ability of the soil to function as a plant growth medium. Plant establishment in the cold, dry climate of southwest Wyoming is dependent on water and nutrient availability. Soil organic matter is a major driver in improving plant and water availability in soils and is intrinsically linked to soil physical, chemical, and biological properties (Schnitzer, 1991). In result, the changes in soil properties from drilling and reclamation activities potentially reduce SOM. The role of SOM in plant establishment as well as its rapid response to soil disturbance renders SOM an ideal parameter for understanding disturbance impacts and evaluating potential recovery of disturbed soils.

As defined by Schnitzer et al. (1991) "SOM consists of a mixture of plant and animal residues in various stages of decomposition, of substances synthesized microbiologically and/or chemically from the breakdown of products, and the bodies of live and dead microorganisms and small animals and their remains." Soil organic matter is often divided into various pools based on decomposition rates. Parton et al. (1987) define three pools of SOM in the Century Model: the active, slow, and passive pools (Figure 1.2).

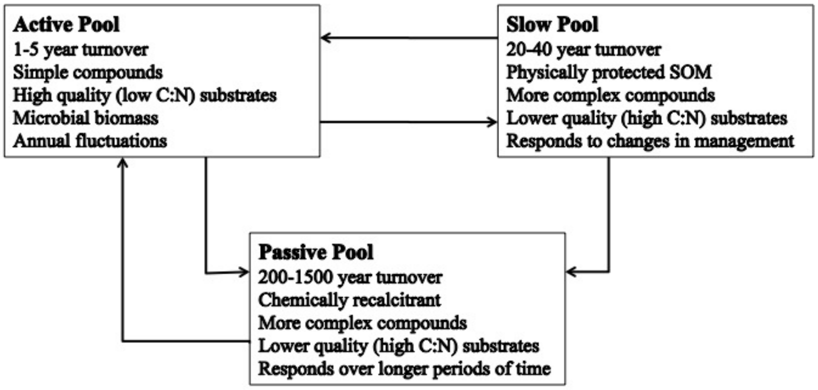

Figure 1.2. Major soil organic matter (SOM) pools, their estimated turnover rates, and basic characteristics. Adapted from Parton et al., 1987.

The active pool is comprised of SOM materials with short turnover (1-5 years) including microbial bodies and simple chemical compounds (Parton et al., 1987). The slow pool contains more complex chemical compounds as well as simple compounds physically protected from decomposition in soil aggregates. This pool has an intermediate turnover time of 20-40 years (Parton et al., 1987). The passive pool resides the longest in the soil (200-1500 years) and is made of chemically recalcitrant materials that may or may not be physically protected (Parton et al., 1987). Of these pools, the active pool is the most dynamic with annual fluctuations derived by biological activity, litter quality, temperature, and moisture (Parton et al., 1987). The slow pool is often used to observe changes in management practices as disturbance breaks physical protection (aggregates and soil structure) making some material more available for decomposition (Sohi et al., 2010). Disturbance diminishes the slow pool while increasing the active pool, thus both warrant attention when investigating SOM fluctuations in response to disturbance. These pools are commonly referred to as light fraction SOM. Presumably, the passive pool remains recalcitrant with disturbance as physical disturbance is not expected to alter the availability of mineral-associated SOM or the structure of complex chemical compounds (Sohi et al., 2010). The studies reported here focus on soil carbon (C) and nitrogen (N) components of the labile soil SOM pool as they relate to development and reclamation activities and to more recalcitrant total and mineral-associated soil C and N.

Soil organic matter properties impact various aspects of soil morphological, chemical, physical, and biological properties. Soil organic matter augments ecosystem function by adsorbing heat, retaining moisture, promoting structure, improving gas and liquid movement, enhancing micronutrient availability, supplying nutrients, buffering pH, and increasing cation exchange capacity (CEC) (Stevenson, 1994). All of these functions of SOM could stimulate recovery of drastically disturbed soils and facilitate plant establishment.

This study explores two aspects of reclamation and SOM. The first describes morphological, chemical, physical, and biological traits of undisturbed and reclaimed soil profiles. The second evaluates the short-term impacts of an unconventional reclamation method on SOM quantity and composition as well as establishment of vegetation on reclaimed natural gas well pads.

CHAPTER TWO: CHARACTERISTICS OF RECLAIMED AND UNDISTURBED SOIL PROFILES IN SOUTHWEST WYOMING

Abstract

Wyoming is one of the largest producers of on-shore natural gas in the United States. Natural gas development in southwest Wyoming requires a level platform for drilling (well pad) and a network of roads and pipelines to service and transport products. Well pad construction requires deep soil excavation to create a level platform. Soil morphological, chemical, physical, and biological properties were examined on six reclaimed well pad locations and adjacent undisturbed areas in two natural gas fields in southwestern Wyoming. Soil pits were excavated to 150 cm or until a restrictive layer was reached. Observations of soil morphology were made in the field and samples from each field-designated horizon were collected and brought to a laboratory for analysis. Undisturbed soils were typically Aridisols with argillic or calcic diagnostic subsurface horizons, whereas soils on reclaimed well pads were Entisols without signs of active elluviation or illuviation. Surface horizons of undisturbed soils were thicker and coarser-textured than those on the reclaimed well pads ($P<0.10$). Electrical conductivity (EC) was higher in the surface and shallow subsurface horizons of reclaimed soils than undisturbed soils ($P<0.10$). Higher EC in the rooting zone may reduce the suitability of the topsoil material on reclaimed well pads as a plant growth medium. Presence of calcium-rich salts and finer soil particles in surface soils could also stimulate aggregation of soil particles and promote soil structure development in otherwise structureless soil. Higher occluded-fraction organic carbon (C) and nitrogen (N) in the surface soils were attributed to this theory as well as the local geology.

Introduction

Reclamation of drastically disturbed soils in arid environments is limited by many factors, including the gap in knowledge of how reclaimed soils function compared to undisturbed soils. Morphology, as well as physical, chemical, and biological characteristics of soils provide insight to how soil functions in an ecosystem. The methods employed by reclamationists to reconstruct soil profiles involve understanding the overall functionality of the soil (Fulton and Wells, 2005). Reclaimed soils often differ in morphological, physical, chemical, biological, and SOM characteristics from undisturbed soils (Ganjegunte et al., 2009; Mozharova & Vladychenskii, 2003; Shrestha and Lal, 2011; Sukla and Lal, 2005). Suitable soil is often scarce on reclamation projects, which may lead to focusing reclamation efforts to the uppermost part of the rooting depth. Evaluation of subsoil SOM properties has grown in importance as larger scale questions are addressed such as the role of C stocks in subsoils in C sequestration and climate change. Further discussions examine the potential of reclaimed mine soils as C sinks (Shrestha et al., 2009; Ussiri and Lal, 2005). This idea initiates from research that established reclaimed soils contain less organic C than their undisturbed counterparts. Ussiri and Lal (2005) found reclaimed mine soils, particularly those amended with fertilizers and other soil amendments, sequestered more C than undisturbed soils for up to 30 years after initial reclamation. Understanding organic C pools in reclaimed soils is essential to achieve reclamation of disturbed ecosystems and utilize potential C sinks.

Soil organic matter is tightly linked to other soil properties and evaluation of additional soil properties may provide further insight into SOM dynamics in reclaimed soils. Soil morphology is drastically altered from drilling and reclamation activities through mixing and creation of artificial soil horizons. Despite this direct impact to soil morphology, soil development on mine tailings in France showed signs of accelerated soil horizonation when compared to soils developing on native geologic material (Neel et al., 2003). This accelerated horizonation was attributed to physical and chemical properties of the waste material and rapid establishment of plants (Neel et al., 2003). Drilling and reclamation activities will also accelerate the breakdown of geologic material through mechanical means. Furthermore, cultivating and seeding accelerate the establishment of plant species leading to more SOM and eventually, translocation of that material leading to horizon formation.

In addition to morphological changes, soil physical properties are also modified by drilling and reclamation activities. Investigation of soil physical properties on a coal mine in Wyoming found higher amounts of silt and clay particles in reclaimed soils than similar native soils (Toy and Shay, 1987). Mixing coarser textured horizons with finer textured horizons and breakdown of particles by mechanical means likely resulted in finer textured reclaimed soils. Although severe compaction from heavy equipment operation is thought to occur on disturbed and reclaimed soils, bulk density was comparable on reclaimed and native soils on a coal mine in Wyoming (Toy and Shay, 1987). Bulk density is intrinsically linked to particle size and parent material, which may have played a greater role in determining bulk density than compaction. Reclaimed soils are often finer-textured than native soils, which is typically explained by soil mixing (Toy and Shay, 1987; Mummey et al., 2002). Soil structure is greatly altered by drilling and reclamation activities. McSweeney and Jansen (1984) introduced the term “fritted structure” to describe the artificial soil structure created by mining and reclamation equipment. They found this artificial structure created by mining wheels enabled better plant establishment than the massive structure left by scrapers (McSweeney and Jansen, 1984). Despite this fact, scrapers are the most common method for excavating well pads, and reclaimed well pad soil profiles are expected to have poorly developed, massive soil structure. On a smaller scale, newly reclaimed soils had less macroaggregates than older reclaimed soils on coal mines in Wyoming (Wick et al., 2009); suggesting an initial lack of soil structure that recovers over time.

Soil chemical properties are often altered during drilling and reclamation activities through mixing of horizons and incorporation of residual drilling materials and overburden (Mozharova and Vladychenskii, 2003). Accumulated salts in subsoils are incorporated into upper soil horizons during topsoil salvage and reclamation activities. Furthermore, overburden material often influences the chemistry of the overlying topsoil. Reclaimed soils on a Wyoming coal mine had lower pH than undisturbed soils due to the acidic nature of the overburden material (Toy and Shay, 1987).

The lack of input of litter from primary producers, displaced microbial populations, and changes in other soil properties experienced by reclaimed soils lead to major changes in soil biological properties. Even 20 years after reclamation, microbial community abundance and structure on reclaimed coal mine soils in Wyoming were inferior to those of adjacent undisturbed soils (Mummey et al., 2002). Plant communities on reclaimed soils in Wyoming tend to include more invasive species (Bergquist et al., 2007) and less shrub species (Booth et al., 1999) than undisturbed soils.

The primary objective of this study was to quantify differences in soil morphology as well as soil chemical, physical, biological, and SOM properties of reclaimed and undisturbed soil profiles. Understanding changes in soil properties throughout the soil profile as a result of drilling and reclamation activities will help to identify methods to improve reclamation success. Interpreting these changes in terms of how they impact SOM could improve our ability to use reclaimed soils as C sinks and effective growth mediums.

Materials and Methods

Site Description

Soil profiles were examined on, and adjacent to, six recently reclaimed (< 1 year since reclamation) natural gas well pads. Three of the well pads were located on the Jonah natural gas field (42° 27’ N and 109° 44’ W) in Sublette County, Wyoming and three were located in the Wamsutter natural gas field (41° 40’ N and 107° 51’ W) in Sweetwater County, Wyoming. Both areas have frigid, arid climates with most of the precipitation occurring as snow (Table 2.1).

Table 2.1. Climate data for the Jonah and Wamsutter study areas in southwest Wyoming. Data obtained from Western Regional Climate Center from the Boulder and Wamsutter weather stations (WRCC, 2011). Values based on averages from 1989 to 2010.

	Elevation	**Max temp**	**Min temp**	**Precip**	**Frost Free**
	——m (ft)——	*—°C (°F)—*	*—°C (°F)—*	*—mm (in)—*	*—days—*
Jonah	2167 (7110)	12.7 (54.8)	-6.50 (20.3)	187 (7.38)	<91
Wamsutter	2081 (6827)	13.2 (55.8)	-2.61 (27.3)	180 (7.07)	91-120

Soils in both areas are derived from Tertiary valley fills consisting of sandstones and shales (Acosta-Martinez et al., 2004). Both study areas contain gentle slopes (0-10%) of varying aspects. Sagebrush steppe plant communities occur in the native rangeland adjacent to the well pads. Big sagebrush *(Artemisia tridentata)* is the most common plant in both areas, but some Gardner saltbush (*Atriplex gardnerii*) and rhizomatous wheat grass dominated communities are also present. Well pads were scraped of vegetation during construction activities. The upper 15-20 cm (6-8 in) of soil was salvaged in stockpiles and reapplied to the sites in the fall of 2009. The sites were seeded in the fall of 2009, but were void of vegetation during soil sampling.

Study Design

Reclaimed and undisturbed soil profiles were paired for each well pad. Well pads reclaimed in the fall of 2009 with safe working conditions were chosen as study locations. Pit locations were selected with consistent slopes and aspects for each pair. Soil pits were excavated to 150 cm (60 in) or to bedrock. Profiles were described in the field and classified to family (Soil Survey Division Staff, 2006). Horizons were determined by changes in color, texture, structure, calcium carbonate ($CaCO_3$) content, and other properties. At least 100-g samples were collected from each designated horizon or every 20 cm (8 in) when horizons could not be differentiated. Samples were stored in plastic bags at approximately room temperature (25°C) until arriving at the laboratory.

Laboratory Analyses

Upon returning to the laboratory, soil samples were air-dried at room temperature for 48 hrs and separated into two subsamples. One was sieved to 2 mm (0.08 in) in order to remove coarse fragments and the other was sieved to 6.35 mm (0.25 in) and reserved for density SOM fractionation (Sohi et al., 2001). For the latter procedure, approximately 10 g of each sample was placed in a 35-mL centrifuge tubes with 1.8 g cm^{-3} NaI. The free portion of the light SOM fraction was aspirated from the surface of the NaI solution after gently shaking and centrifuging the sample at 2000 rpm for 15 minutes. The occluded light fraction was collected in a similar fashion after vigorous shaking, 110 s of sonication to break down aggregates, and centrifuging at 2000 rpm for 20 minutes. Light fraction samples were collected on 20-µm nylon filters and rinsed with deionized water. The remaining soil sample was rinsed thoroughly and dried for determining mineral-associated C and N. All fractions were dried for 24 hr in a 60°C (140°F) oven and weighed. Dried SOM fractions were then ground and weighed to 5 mg (light fractions) or 20 mg (mineral-associated fraction). Subsamples were run on an elemental combustion analyzer to determine C and and N content (Carlo Erba Instruments, Milan, Italy). For the mineral-associated fraction, inorganic C was subtracted to account for calcite ($CaCO_3$)-C and yield organic C content. Inorganic C was measured using the pressure-calcimeter method (Sherrod et al., 2002).

The 2-mm (0.08-in) subsamples were analyzed for general soil properties and total organic C and N. Soil texture was determined by the hydrometer method (Gavlak et al., 2005). Electrical conductivity (EC) and pH were determined by submerging EC and pH electrodes into a 2:1 soil:water solution. Total C and N content of the soil was determined by combustion using a Carlo Erba NC-2100 elemental analyzer (Carlo Erba Instruments, Milan, Italy). Like the mineral-associated fraction, inorganic C was subtracted from total C to calculate total organic C. Bulk density was collected for the upper 30 cm of soil using the NRCS bulk density core method (NRCS, 2010c). The remaining depths were assigned values based on the soil survey bulk density data of similar soil series in the area (NRCS, 2011).

Data Analysis

A paired t-test was used to test for differences in morphological, chemical, physical, and SOM characteristics of reclaimed and undisturbed soil profiles. The whole solum (total organic C only), A horizons, subsurface horizons to a depth of 30 cm, and remaining subsurface horizons below 30 cm were analyzed separately since samples were taken by horizon and not normalized depth increments. An alpha of 0.10 was used to determine statistical difference.

Results

Undisturbed locations on both the Jonah and Wamsutter study areas were classified as Aridisols with calcic or argillic diagnostic subsurface horizons. Reclaimed soil profiles in both fields are Entisols that have remnants of diagnostic subsurface horizons without evidence of illuviation or eluviation. Soil chemistry, texture, and SOM characteristics differ by depth in each set of paired sites. Soil properties differed in the A horizon, the subsurface horizons to a depth of 30 cm, and the subsurface horizons from 30 cm to the maximum depth between disturbed and undisturbed soils.

Soil Morphology

Reclaimed soil profiles retained some properties of the adjacent undisturbed soils. However, structure and horizonation were vastly different between undisturbed and reclaimed profiles (Appendices 2.1 and 2.2). Reclaimed soils were structureless with either single grain or massive characteristics, while undisturbed profiles had well-developed platy, granular, prismatic, or blocky structure in the A and B horizons. The uppermost horizons in reclaimed soils consist of the material reserved for reclamation during construction activities, or topsoil. Fill material used to rebuild the topography typically occurs between topsoil material and the underlying native soils. The man-made boundaries of the reclaimed soils were usually abrupt. Physical and morphological characteristics of reclaimed and undisturbed soil profiles are found in Appendix 2.1. Chemical and SOM characteristics at each sampled depth are found in

Appendix 2.2. Figures 2.1 and 2.2 illustrate differences in selected soil properties of reclaimed and undisturbed soil by depth.

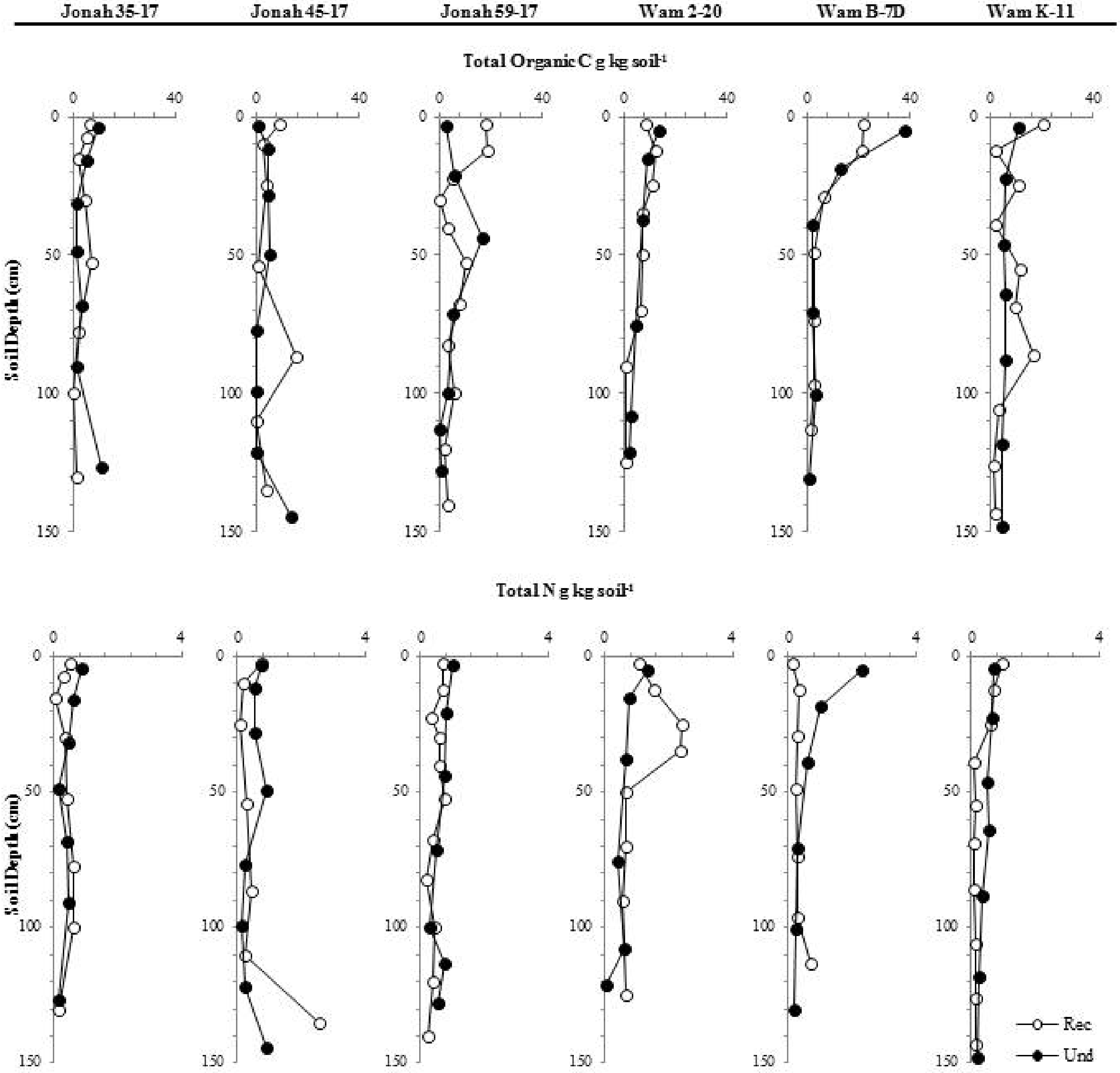

Figure 2.1. Total organic C (top) and total N (bottom) concentrations for reclaimed (Rec) and undisturbed (Und) soil profiles at three Jonah well pad locations (left) and three Wamsutter well pad locations (right) in southwest Wyoming.

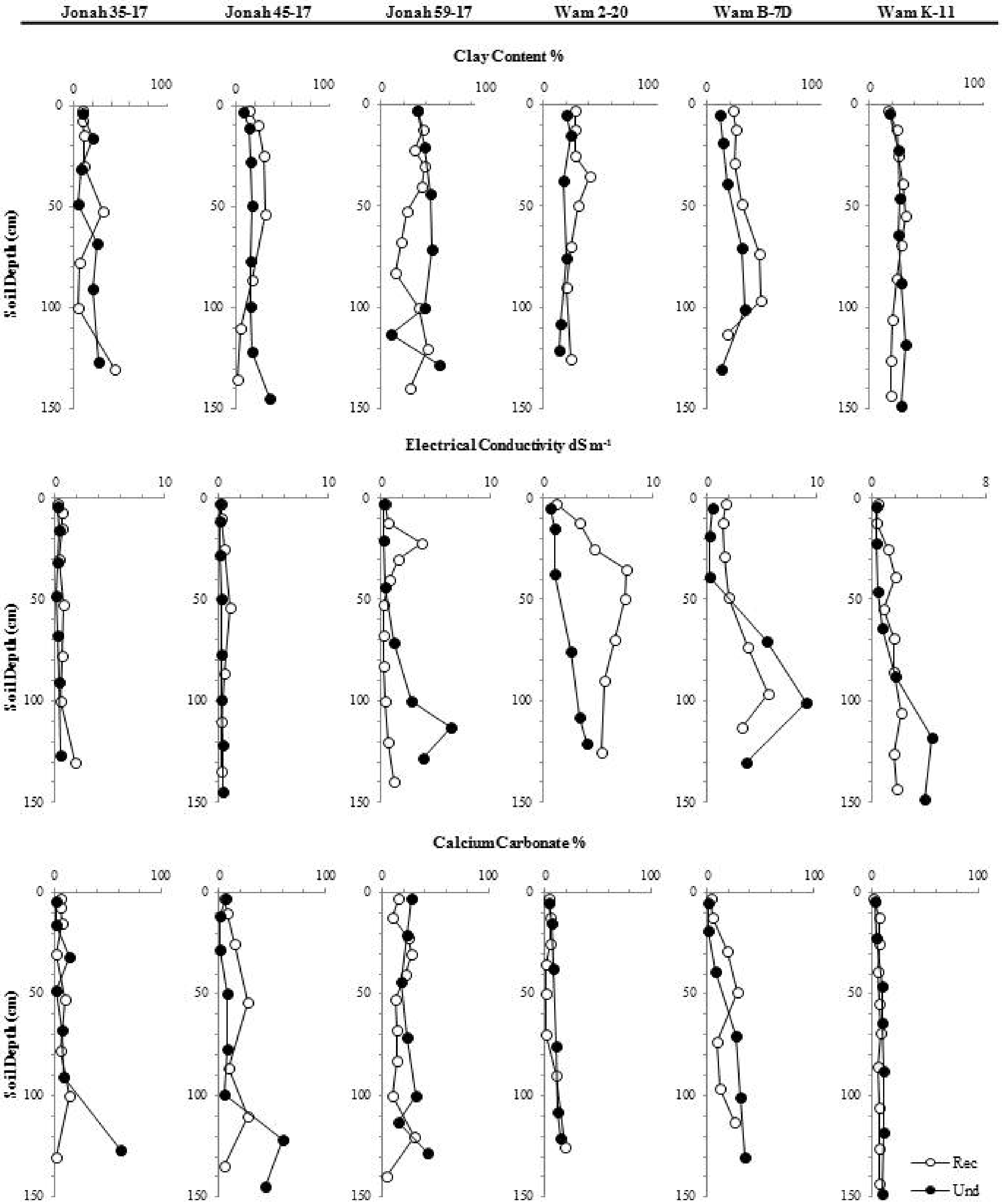

Figure 2.2. Clay content (top), electrical conductivity (middle), and calcium carbonate content (bottom) for reclaimed (Rec) and undisturbed (Und) soil profiles at three Jonah well pad locations (left) and three Wamsutter well pad locations (right) in southwest Wyoming.

The reclaimed soil at the Jonah 35-17 location consists of sandy, mixed, frigid Haplic Torriarents (Appendix 2.1). The soils are sandy loam in texture to a depth of 40 cm where, they transition to sandy clay loam. Soils are loamy sands below 65 cm until reaching the shale bedrock material at 110 cm. Topsoil material (uppermost horizons) tended to be looser, darker, and finer textured than the green sand backfill material. The adjacent undisturbed soils are coarse-loamy, mixed, frigid Ustic Calciargids. While the texture changes more frequently with depth than the reclaimed soil profile, the soft, decomposed shale bedrock material occurs near the same depth at 103 cm in undisturbed soils.

The reclaimed soils at the Jonah 45-17 location are fine-loamy, mixed, frigid Haplic Torriarents whereas the undisturbed soils are sandy, mixed, frigid Ustic Calciargids. The reclaimed soils at the Jonah 45-17 location had finer-textured backfill material than those at the Jonah 35-17 site. However, the soil in the adjacent undisturbed area had a sandy loam texture to a depth of 104 cm, where it transitioned to dense clay and shale material. The shale and sandy material seen in the undisturbed profiles comprised the backfill material in the reclaimed profile. The abrupt, angled boundary between 55 and 90 cm in the reclaimed profile is remnant of re-contouring the site to its pre-disturbance topography with backfill material.

The third Jonah site, Jonah 59-17, is in a low-lying area and has more clay than the other two sites. The undisturbed site hosts a plant community of rhizomatous wheatgrasses instead of the Wyoming big sagebrush communities seen at the other two Jonah locations. Reclaimed soils are clayey, mixed, frigid Haplic Torriarents; while the adjacent undisturbed area contains clayey, mixed, frigid Ustic Calciargids. In the field, reclaimed soils had strong reactions with HCl throughout the profile, including the surface, while reaction with HCl was not recordable in the undisturbed profile above 24 cm. However, both soils had measurable quantities of $CaCO_3$ throughout the profile (Appendix 2.2, Figure 2.2).

The Wamsutter 2-20 location sits downslope from an outcrop of shale and sandstone. The reclaimed soils at the Wamsutter 2-20 site are fine-loamy, mixed, frigid Haplic Torriarents. The reclaimed soil had a distinctive layer of black, thin plate-like flakes of shale at approximately 30 to 40 cm below the surface (identified as the 3C horizon; Appendix 2.1 and 2.2). A similar layer was observed in the nearby rocky outcrop, but not within the undisturbed soil profile. Remnant particles of this horizon were observed throughout the reclaimed profile in this location. This pedon had high amounts of high C-content light fraction SOM as well as the lowest pH of all 12 soil profiles (Apendix 2.2). The undisturbed soils at this location did not have a well-developed argillic horizon as seen in the other undisturbed profiles resulting in fine-loamy, mixed, frigid Ustic Haplocalcids.

The reclaimed soils at the Wamsutter B-7D location are fine-loamy, mixed, frigid Haplic Torriarents, whereas the undisturbed soils are coarse-loamy, mixed, frigid Ustic Calciargids. Reclaimed soil profiles at this location had lower surface soil C and N content (Appendix 2.2) and finer texture (Appendix 2.1) than the undisturbed soils. The reclaimed portion of the reclaimed profile ends near 38 cm; where the profile transitions to layers of weathered mudstone and sandstone. The undisturbed soils are much deeper, and transition to weathered sandstone material at 111 cm.

The final location in the Wamsutter field, Wamsutter K-11, hosts fine-loamy, mixed, frigid Haplic Torriarents in the reclaimed area and fine-loamy, mixed, frigid Ustic Calciargids in the adjacent rangeland. The reclaimed profile effervesces with HCl throughout and has few distinguishable horizons. Topsoil and backfill material were nearly indistinguishable and reached a depth of 62 cm. The underlying sandy clay loam and sandy loam material is very similar to the parent material observed in the undisturbed profile.

Paired Difference Comparisons

We observed significant differences ($P<0.1$) in pH, EC, sand content, occluded-fraction C and N, and mineral-associated fraction N between reclaimed and undisturbed soil (Tables 2.2-2.4). Properties varied in surface, upper subsoil (subsurface 1), and lower subsoil (subsurface 2) horizons. There was no difference in solum total organic C between reclaimed and undisturbed soils ($P>0.1$, Table 2.5).

Table 2.2. Average values for soil physical properties of reclaimed (Rec.) and undisturbed (Und.) soil profiles in the Jonah and Wamsutter natural gas fields of southwest Wyoming. A horizons consist of the uppermost horizon; the first subsurface horizon is the remaining soil in the top 30 cm; and the second subsurface horizon is the remainder of the soil profile. Percent difference is based on undisturbed values. Standard errors are in parentheses. Asterisks denote significance at the $P<0.1$ level (n=12).

	Thickness			**Sand**			**Clay**		
	Und.	**Rec.**	**Diff.**	**Und.**	**Rec.**	**Diff.**	**Und.**	**Rec.**	**Diff.**
	cm		*%*	*%*		*%*	*%*		*%*
A Horizon	8.0(0.730)	5.0(0.00)	-37.5*	51(6.26)	39(7.58)	-23.5*	16(3.51)	20(3.55)	25.5
Subsurface 1	31(3.66)	30(1.67)	-3.78	50(6.41)	39(7.10)	-22.1*	21(3.84)	25(3.20)	17.0
Subsurface 2	107(8.68)	110(5.87)	3.12	40(3.51)	41(9.00)	4.10	24(3.04)	25(2.95)	3.38

A horizons of undisturbed soils are thicker ($P=0.01$) and contain more sand ($P=0.05$) than the A horizons of reclaimed soils (Table 2.2). In addition, undisturbed soils also have higher sand content in the upper subsurface horizons ($P=0.0370$) than those of the reclaimed soils. Upper subsurface horizons in the reclaimed soils have higher pH ($P=0.07$) and EC ($P>0.05$) than undisturbed upper subsurface horizons (Table 2.3). Conversely, undisturbed lower subsurface horizons have greater $CaCO_3$ content ($P=0.03$) than lower subsurface horizons of reclaimed soils.

Table 2.3. Average values for soil chemical properties of reclaimed (Rec.) and undisturbed (Und.) soil profiles in the Jonah and Wamsutter natural gas fields of southwest Wyoming. A horizons consist of the uppermost horizon; the first subsurface horizon is the remaining soil in the top 30 cm; and the second subsurface horizon is the remainder of the soil profile. Percent difference is based on undisturbed values. Standard errors are in parentheses. Asterisks denote significance at the P<0.1 level (n=12).

	pH			**EC**			**CaCO3**		
	Und.	**Rec.**	**Diff.**	**Und.**	**Rec.**	**Diff.**	**Und.**	**Rec.**	**Diff.**
			%	*dS m*$^{-1}$		*%*	*%*		*%*
A Horizon	7.3(0.073)	7.5(0.084)	2.05	0.30(0.0777)	0.66(0.248)	120	6.8(4.21)	5.6(1.99)	-16.7
Subsurface 1	7.3(0.12)	7.7(0.074)	4.77*	0.35(0.137)	1.5(0.550)	329*	7.0(3.32)	9.8(2.49)	41.0
Subsurface 2	7.6(0.081)	7.6(0.16)	-1.09	2.2(0.697)	2.2(0.972)	0.506	19(2.93)	12(2.36)	-40.0*

A horizons of reclaimed soils had higher occluded-fraction organic C (P=0.06) and N (P=0.02) than A horizons of undisturbed soils (Table 2.4). Mineral-associated N was higher in the A horizons (P=0.01) and upper subsurface horizons (P=0.04) of undisturbed soils than reclaimed soils.

Table 2.4. Average values for SOM of reclaimed (Rec.) and undisturbed (Und.) soil profiles in the Jonah and Wamsutter natural gas fields of southwest Wyoming. A horizons consist of the uppermost horizon; the first subsurface horizon is the remaining soil in the top 30 cm; and the second subsurface horizon is the remainder of the soil profile. Percent difference is based on undisturbed values. Standard errors are in parentheses. Asterisks denote significance at the P<0.1 level (n=12).

	Total Organic C			**Total N**		
	Und.	**Rec.**	**Diff.**	**Und.**	**Rec.**	**Diff.**
	g C kg soil^{-1}		*%*	*g N kg soil*$^{-1}$		*%*
A Horizon	13(5.54)	14(12.7)	20.2	1.2(0.248)	0.70(0.138)	-39.8
Subsurface 1	7.0(1.36)	7.4(7.01)	116	0.71(0.0771)	0.65(0.277)	-8.55
Subsurface 2	4.0(0.485)	4.3(4.01)	74.2	0.40(0.0473)	0.53(0.133)	34.4
	Free Light Fraction C			**Free Light Fraction N**		
A Horizon	2.9(1.39)	4.3(2.88)	46.3	0.056(0.0266)	0.20(0.146)	249
Subsurface 1	0.94(0.409)	8.4(7.36)	791	0.022(0.0096)	0.28(0.244)	1177
Subsurface 2	0.83(0.366)	2.7(2.16)	223	0.026(0.0140)	0.095(0.0733)	265
	Occluded Light Fraction C			**Occluded Light Fraction N**		
A Horizon	0.65(0.301)	1.3(0.553)	102*	0.039(0.0207)	0.070(0.0265)	80.1*
Subsurface 1	0.58(0.287)	1.4(0.645)	136	0.028(0.0153)	0.075(0.0359)	165
Subsurface 2	0.63(0.296)	0.63(0.219)	-0.0140	0.022(0.0102)	0.026(0.0089)	21.5
	Mineral-Associated Fraction C			**Mineral-Associated Fraction N**		
A Horizon	9.1(4.38)	9.7(3.04)	5.91	1.1(0.223)	0.43(0.139)	-60.0*
Subsurface 1	5.5(1.17)	5.3(0.823)	-2.98	0.66(0.0758)	0.29(0.0933)	-55.9*
Subsurface 2	2.6(0.859)	3.7(0.811)	43.9	0.35(0.0575)	0.41(0.110)	18.0

Solum total organic C was statistically the same between reclaimed and undisturbed soil profiles in both study areas (P=0.42, Table 2.5). However, these are estimates of solum total organic C derived from approximate bulk densities from soil surveys (NRCS, 2011).

Table 2.5. Total organic C content for undisturbed and reclaimed sola from the Jonah and Wamsutter natural gas fields of southwest Wyoming. Total solum organic C was based on bulk density values estimated from soil surveys (NRCS, 2011). Percent difference is based on undisturbed values. Asterisks denote significance at the P<0.1 level.

Location	Undisturbed	Reclaimed	Difference
	——*Mg C ha $^{-1}$ soil*——	——*Mg C ha $^{-1}$ soil*——	———*%*———
Jonah 35-17	120	70.4	-41.2
Jonah 45-17	64.4	108	67.3
Jonah 59-17	85.1	130	53.3
Wamsutter 2-20	97.7	105	7.36
Wamsutter B-7D	110	111	1.41
Wamsutter K-11	115	143	24.7

Discussion

While reclaimed soils have similar traits to their undisturbed counterparts, vast differences in soil properties and horizonation exist between them. A horizons of undisturbed soils were thicker and comprised of coarser material than reclaimed soils. One study on cheatgrass invasion of a sagebrush-steppe plant community also found disturbed (cheatgrass-infested) soils to have thinner A horizons than adjacent undisturbed communities (Norton et al., 2004). However, these differences were attributed to differences in nutrient cycling dynamics between the two communities. Instead, difference in thickness of the A horizon in our study is attributed to mechanical manipulation. Construction of well pads requires stripping topsoil to a depth of 15 to 20 cm, and storing until needed for reclamation. However, the average thickness of the undisturbed soil’s A horizons were 8 cm, which means that the material salvaged for reclamation contains subsurface horizon material. Once reclaimed, it is expected that components of A horizons have been diluted with those of subsurface horizons.

The dilution of organic materials with clay particles and other illuvial materials of subsurface horizons are likely the cause of thinner and finer textured A horizons on reclaimed soils.

The upper subsurface horizons of reclaimed profiles demonstrate elevated pH and EC in comparison to those of undisturbed soils. During well pad construction, the upper 15 to 20 cm of soil is not all that is disturbed. Material is excavated until a level pad is created, and additional material is excavated for reserve pits. Deep soils are further disrupted prior to reclamation for compaction relief and recontouring. Salts from deep in soil profiles may mix with shallower horizons during these activities to elevate pH and EC in reclaimed soils, particularly those of the upper subsurface horizons (Visser et al., 1984; Mummey et al., 2002; Mozharova & Vladychenskii, 2003). This point is further supported by higher $CaCO_3$ content in lower subsurface horizons in undisturbed soils than those of reclaimed soils. Lime ($CaCO_3$) is often used to increase pH in acidic soils, and an increase in Ca, a major base cation, results in higher EC.

While the chemical and physical characteristics of soils responded as expected to destruction and reconstruction processes, SOM properties did not. No differences were observed in total organic C, total N, free fraction organic C, or free fraction N at any depth. SOM parameters were highly variable on reclaimed profiles and remained so at all investigated depths. A study on reclaimed soils in Ohio found total organic C to be variable across all soils, including undisturbed soils whereas total N variability was highest in undisturbed soils (Nyamadzawo et al., 2008). Furthermore, entire solum organic C was statistically the same between reclaimed and undisturbed soils. Total solum organic C was estimated, however, and actual measurements of bulk density in deep soil may have yielded different results.

Occluded SOM fractions had the opposite response to construction and reclamation activities than expected. Both occluded-fraction C and N in the A horizons of reclaimed profiles was higher than those of undisturbed soils. One potential explanation for this is the presence of an oily material in the reclaimed soil at the Wamsutter 2-20 location. Reclaimed soils from this site had higher C-content organic materials and more SOM than the adjacent undisturbed soil. However, undisturbed A horizons at this location also had higher occluded-fraction C and N content than seen in other undisturbed soils in this study. This suggests that this material is derived from local geology. According to the United States Geological Survey (USGS), this location is a part of the Luman Tongue of the Green River Formation, which contains oil shale, carbonaceous shale, and sandstone (Love and Christiansen, 1985). The high occluded SOM content of the reclaimed soils may be attributed to the presence of hydrocarbons in the parent material; however, this trend was not exclusively observed at this location (Appendix 2.2).

Another plausible explanation is that the A horizon of the reclaimed soil had more material that promotes flocculation. Clay particles and Ca ions encourage aggregation of soil particles, which, in turn, leads to physical protection of SOM. The finer texture and elevated EC of reclaimed soils further supports this hypothesis. Differences were not expected to occur within the mineral-associated pool of SOM; however, mineral-associated N was higher in both the A and upper subsurface horizons of undisturbed soils. This pool is often referred to as the recalcitrant pool of SOM because it rarely reflects changes in soil management in the short term (Sohi et al., 2010). One possible explanation for this result is that the processes of construction and reclamation damaged soil particles and freed SOM once associated to the soil minerals. In addition to water limitation, arid and semi-arid ecosystems are often N-limited (Hooper and Johnson, 1999). Thus, the liberated N may have been rapidly immobilized leading to lower mineral-associated N in reclaimed soils.

Conclusion

Overall, soil morphological, physical, chemical, and biological properties were drastically altered by well pad construction and reclamation activities. Of greater interest, perhaps, is that the impacts of this disturbance varied with depth and were not confined to the upper 15 cm of soil. Although lower levels of occluded SOM were not detected in reclaimed soils, this does not discredit the use of reclaimed soils as a C sink. As levels of total organic C were variable and inconclusive, more occluded C does not necessarily imply higher organic C on reclaimed sites, but may be the result of more compounds and particles that promote soil aggregation. The redistribution of materials that promote soil aggregation, such as $CaCO_3$ and clay, may stimulate reconstruction of soil structure and facilitate ecosystem recovery.

Although evidence of soil formation exists, the current climate of Wyoming is cooler and drier than the climate that helped to form undisturbed soils. Thus, the level of soil development witnessed in undisturbed soils may not be achieved in reclaimed soils. Implementation of reclamation methods, such as supplemental irrigation or organic amendments, may accelerate soil formation and ecosystem recovery. Future research should investigate impacts of reclamation techniques on rates of soil formation as well as the impacts of soil development rates on plant establishment on reclaimed landscapes.

Reclamationists in southwest Wyoming should consider the impacts of well pad construction and reclamation when planning soil salvage and seedbed preparation methods. Soil quality of subsoil horizons should be of particular concern, as subsoils will likely mix with the surface horizon. Changes in soil properties were not exclusively observed in the surface soil. Evaluation of soil beyond the surface horizons may need to be considered to establish deep-rooting plant species.

Monitoring these soils in the future will provide insight to development of reclaimed soils in arid environments. Assessment of C content in SOM and carbonates will provide a better estimate of C storage in reclaimed soils. C sequestration rates on arid reclaimed soils could also be gleaned from continued observation of these study sites.

Appendices

Appendix 2.1. Soil profile descriptions for reclaimed and undisturbed locations in the Jonah and Wamsutter natural gas fields of southwest Wyoming. Abbreviations are described in Appendix 2.3.

Horizon	Depth	Text.	Sand	Silt	Clay	Structure			Boundary	BD
—	*—cm—*	*class*	*————%————*			*grade*	*size*	*type*	——	*-g cm^{-3}-*
Jonah 35-17; reclaimed; sandy, mixed, frigid Haplic Torriarents										
A	0-5	SL	62	28	10	0	—	Sg	CS	1.52
1C	5-10/20	SL	65	25	10	0	—	M	AS	1.41
2C	10-20	SL	74	15	12	0	—	Sg	AS	1.59
3C	20-40	SL	73	17	10	0	—	M	GW	1.42
	40-65	SCL	45	23	31	0	—	M	GW	1.45
4C	65-90	LS	87	5	8	0	—	Sg	CS	1.45
CR	90-110	LS	84	11	5	0	—	Sg	CS	1.45
R	110-150	C	23	34	43	—	—	—	—	—
Jonah 35-17; undisturbed; coarse-loamy, mixed, frigid Ustic Calciargids										
A	0-8	SL	69	21	10	1	M	Sbk	CS	1.33
Bt1	8-24	SCL	58	21	21	3	Co	Sbk	CS	1.50
Bk	24-39	LS	82	9	9	1	M	Sbk	CW	1.36
	39-58	LS	88	7	5	1	M	Sbk	CW	1.42
Ck	58-78	L	28	47	25	1	M	Sbk	GW	1.45
CR1	78-103	L	31	48	21	0	—	M	GW	1.45
CR2	103-150	CL	26	47	27	0	—	M	—	1.45
Jonah 45-17; reclaimed; fine-loamy, mixed, frigid Haplic Torriarents										
A	0-5	SL	60	27	14	0	—	Sg	CS	1.16
1C	5-15	L	48	28	24	0	—	M	GW	1.45
2C	15-35	CL	42	29	29	0	—	Sg	CS	1.62
	35-55/90	CL	36	33	31	0	—	Sg	AI	1.43
CR	55/90-100	SL	60	23	17	0	—	Sg	AS	1.45
2CR	100-120	LS	83	12	5	0	—	Sg	GS	1.45
	120-150	S	91	8	1	0	—	Sg	—	1.45
Jonah 45-17; undisturbed; sandy, mixed, frigid Ustic Calciargids										
A	0-6	SL	72	20	8	1	M	Pl	CS	1.34
Bt	6-17	SL	74	12	14	2	M	Sbk	GS	1.62
Bt2	17-39	SL	68	16	16	3	M	Sbk	CS	1.45
Bk1	39-60	SL	66	17	17	2	M	Sbk	CW	1.43
Bk2	60-94	SL	65	20	15	1	F	Sbk	AW	1.45
1C	94-104	SL	54	30	16	—	—	—	AW	1.45
2C1	104-139	SiL	31	52	17	—	—	—	AB	1.45
2C2	139-150	CL	27	37	36	—	—	—	—	1.45

Appendix 2.1. (*continued)*

Horizon	Depth	Text.	Sand	Silt	Clay	Structure			Boundary	BD
—	*—cm—*	*class*	*————%*	*————*		*grade*	*size*	*type*	*——*	*-g cm^{-3}-*
Jonah 59-17; reclaimed; clayey, mixed, frigid Haplic Torriarents										
A	0-5	CL	28	40	32	0	—	Sg	CS	1.04
1C1	5-20	CL	28	35	37	0	—	M	AS	1.17
1C2	20-25	CL	33	37	30	0	—	M	AW	1.10
1C3	25-35	CL	28	34	38	0	—	M	AS	1.40
1C2'	35-45	CL	30	34	36	0	—	M	AS	1.45
1C3'	45-60	L	46	32	22	0	—	M	AS	1.45
2C	60-75	SL	61	22	17	0	—	Sg	CW	1.45
	75-90	SL	68	20	12.	0	—	Sg	CW	1.45
R	90-110	CL	33	35	32	—	—	—	AS	1.45
	110-130	C	28	30	42	—	—	—	DS	1.45
	130-150	L	28	47	25	—	—	—	—	1.45
Jonah 59-17; undisturbed; clayey, mixed, frigid Ustic Calciargids										
A	0-6	CL	43	25	32	1	M	Pl	CS	0.80
Bt1	6-36	CL	40	22	38	2	M	Pr	CW	0.97
Bt2	36-52	C	31	25	44	3	M	Abk	GS	0.89
Bt3	52-90	C	28	27	45	1	M	Abk	GS	1.45
Bk	90-110	CL	40	21	39	2	M	Abk	AS	1.45
CR	110-116	SL	57	34	9	3	F	Abk	AS	1.45
CR2	116-140	C	25	24	51	—	—	—	AS	1.45
2R	140-150	—	—	—	—	—	—	—	AS	1.45
Wamsutter 2-20; reclaimed; fine-loamy, mixed, frigid Haplic Torriarents										
A	0-5	CL	27	45	28	0	—	M	AS	1.41
1C	5-20	CL	25	47	28	0	—	M	AW	1.42
2C	20-30	CL	24	48	28	0	—	M	AW	1.32
3C	30-40	SiC	10	49	41	0	—	Pl	DS	1.31
4C1	40-60	CL	1	69	30	0	—	Sg	DS	1.38
4C2	60-80	SiL	12	63	25	0	—	Sg	DS	1.45
	80-100	SiL	12	67	21	—	—	—	DS	1.45
	100-150	SiL	11	65	24	—	—	—	—	1.45
Wamsutter 2-20; undisturbed; fine-loamy, mixed, frigid Ustic Haplocalcids										
A	0-10	L	34	46	20	1	M	Pl	CS	1.07
Bw	10-20	L	35	41	24	1	F	Sbk	GS	1.35
Bk	20-55	L	42	41	17	2	Co	Sbk	GS	1.39
BCk	55-96	L	34	45	21	1	M	Sbk	GS	1.38
CR	96-120	SiL	22	63	15	0	—	M	AS	1.45
R	120-122	SiL	20	66	14	—	—	—	—	1.45

Appendix 2.1. (*continued)*

Horizon	Depth	Text.	Sand	Silt	Clay	Structure			Boundary	BD
—	*—cm—*	*class*		*—%—*		*grade*	*size*	*type*	—	*-g cm^{-3}-*
Wamsutter B-7D; reclaimed; fine-loamy, mixed, frigid Haplic Torriarents										
A	0-5	SiL	17	61	22	0	—	M	GS	1.50
C	5-20	SiL	24	50	26	0	—	M	AS	1.50
Ck	20-38	L	26	50	24.	0	—	M	AW	1.53
1CR	38-60	SiCL	19	50	31	0	—	M	AS	1.31
	60-87	SiC	8	45	47	—	—	—	—	1.40
	87-106	C	17	36	47	—	—	—	—	1.40
2CR	106-120	L	45	38	17	0	—	Sg	—	1.40
Wamsutter B-7D; undisturbed; coarse-loamy, mixed, frigid Ustic Calciargids										
A	0-10	L	49	41	10	1	M	Gr	CS	1.41
Bt1	10-27	L	40	46	14	2	M	Sbk	GS	1.04
Bt2	27-51	L	40	43	17	2	M	Sbk	GS	1.18
Btk	51-90	CL	28	42	30	2	F	Sbk	GS	1.40
BCk	90-111	CL	23	44	33	1	M	Sbk	AS	1.40
CR	111-150	SL	53	35	12	0	—	M	—	1.40
Wamsutter K-11; reclaimed; fine-loamy, mixed, frigid Haplic Torriarents										
A	0-5	L	42	42	16	0	—	M	GS	1.33
1C	5-20	L	40	36	24	0	—	M	GS	1.42
	20-30	L	39	35	26	0	—	M	GS	1.15
	30-48	CL	36	35	29	0	—	M	CS	1.35
2C	48-62	CL	36	32	32	0	—	M	AS	1.40
3C1	62-76	CL	38	35	27	0	—	M	DS	1.40
3C2	76-96	L	41	35	24	0	—	M	DS	1.40
	96-116	SCL	58	21	21	0	—	M	DS	1.40
	116-136	SL	55	26	19	0	—	M	DS	1.40
	136-150	SL	55	26	19	—	—	Sg	—	1.40
Wamsutter K-11; undisturbed; fine-loamy, mixed, frigid Ustic Calciargids										
A	0-8	L	41	41	18	2	F	Pl	CS	1.41
Bt	8-37	L	42	32	25	1	Co	Pr	GW	1.24
Btk	37-55	L	41	32	27	2	F	Sbk	CS	1.31
Bk	55-73	L	41	33	26	2	F	Sbk	AS	1.40
BC	73-103	SCL	47	26	27	2	M	Sbk	CS	1.40
C1	103-133	SCL	48	20	32	0	—	Sg	CS	1.40
C2	133-150	SCL	57	15	28	0	—	Sg	—	1.40

Appendix 2.2. Soil profile chemical and soil organic matter properties for reclaimed and undisturbed locations in the Jonah and Wamsutter natural gas fields of southwest Wyoming.

Horizon	Depth	pH	EC	$CaCO_3$	C	N	Free C	Free N	Occ. C	Occ. N
—	*—cm—*	—	*—dS m^{-1}—*	*—%—*	*———g kg^{-1} soil———*					
Jonah 35-17; reclaimed; sandy, mixed, frigid Haplic Torriarents										
A	0-5	7.7	0.24	5.18	6.32	0.50	0.52	0.01	0.66	0.04
1C	5-10	7.2	0.63	4.82	5.03	0.30	0.23	0.01	0.55	0.04
2C	10-20	7.8	0.63	6.32	2.34	0.00	0.03	0.00	0.09	0.00
3C	20-40	7.6	0.35	1.33	4.47	0.36	0.05	0.00	0.26	0.01
	40-65	7.6	0.71	8.37	7.43	0.37	0.05	0.00	0.20	0.01
4C	65-90	7.6	0.65	4.33	2.25	0.60	0.06	0.00	0.03	--
CR	90-110	8.2	0.43	13.8	0.18	0.60	0.06	0.00	0.12	--
R	110-150	7.9	1.8	1.27	1.73	0.11	0.06	0.00	0.14	0.00
Jonah 35-17; undisturbed; coarse-loamy, mixed, frigid Ustic Calciargids										
A	0-8	7.2	0.15	0.0802	9.68	0.85	0.25	0.00	--	--
Bt1	8-24	7	0.35	0.139	5.61	0.58	0.03	0.00	0.35	0.02
Bk	24-39	7.3	0.16	13.6	1.73	0.43	0.18	0.00	0.15	0.01
	39-58	7.3	0.1	0.244	1.35	0.13	0.02	--	0.03	--
Ck	58-78	8.1	0.24	6.15	3.37	0.42	0.03	0.00	0.21	0.01
CR1	78-103	8	0.37	7.34	1.44	0.44	0.02	0.00	0.09	0.00
CR2	103-150	7.9	0.5	62.1	10.80	0.11	0.05	0.00	0.11	--
Jonah 45-17; reclaimed; fine-loamy, mixed, frigid Haplic Torriarents										
A	0-5	7.6	0.2	4.87	9.06	0.78	0.42	0.01	0.45	0.03
1C	5-15	7.8	0.24	8.11	2.84	0.19	0.11	0.00	0.17	--
2C	15-35	8	0.41	15.2	3.98	0.10	0.13	0.00	0.18	0.00
	35-55/90	7.6	1	26.8	0.98	0.30	0.43	0.01	0.55	0.04
CR	55/90-100	7.7	0.49	9.48	15.70	0.45	0.07	0.00	0.13	0.00
2CR	100-120	7.8	0.19	27.6	0.20	0.22	0.09	0.00	0.11	0.01
	120-150	7.7	0.24	4.86	4.17	2.56	0.07	0.00	0.04	0.00
Jonah 45-17; undisturbed; sandy, mixed, frigid Ustic Calciargids										
A	0-6	7.1	0.1	6.41	0.63	0.73	0.21	0.01	0.30	0.02
Bt	6-17	6.9	0.1	0.151	4.93	0.54	--	0.00	0.22	0.01
Bt2	17-39	7	0.09	0.246	4.56	0.57	0.01	--	0.21	0.01
Bk1	39-60	7.7	0.18	7.98	5.58	0.90	0.04	0.00	0.08	0.00
Bk2	60-94	8	0.19	7.13	0.17	0.22	0.03	0.00	0.05	--
1C	94-104	8.1	0.27	4.94	0.08	0.13	0.02	0.00	0.07	--
2C1	104-139	8	0.3	60.6	0.13	0.23	0.03	0.00	0.09	0.00
2C2	139-150	7.6	0.39	43.5	13.90	0.92	0.04	0.00	0.07	--

Appendix 2.2. (*continued*)

Horizon	Depth	pH	EC	$CaCO_3$	C	N	Free C	Free N	Occ. C	Occ. N
—	—*cm*—	—	—*dS m^{-1}*—	—*%*—	——————*g kg^{-1} soil*——————					
Jonah 59-17; reclaimed; clayey, mixed, frigid Haplic Torriarents										
A	0-5	7.1	0.4	15.1	17.90	0.71	0.05	0.00	0.61	0.04
1C1	5-20	7.4	0.55	9.5	19.10	0.72	0.08	0.00	0.53	0.04
1C2	20-25	7.5	3.7	24.8	5.55	0.35	0.08	0.00	0.22	0.01
1C3	25-35	7.7	1.6	26.8	0.46	0.62	0.15	0.00	0.31	0.03
1C2'	35-45	7.8	0.74	21.2	3.29	0.60	0.16	0.00	0.36	0.02
1C3'	45-60	7.6	0.24	11.1	10.30	0.74	0.06	0.00	0.24	0.01
2C	60-75	7.7	0.19	13.8	7.89	0.38	0.06	0.00	0.16	0.00
	75-90	7.7	0.16	12.9	3.35	0.20	0.04	0.00	0.12	0.00
R	90-110	8.1	0.28	8.43	6.01	0.42	0.10	0.00	0.16	0.01
	110-130	8	0.63	29.7	1.86	0.39	0.05	0.00	0.26	0.01
	130-150	8	1.1	3.69	3.34	0.22	0.03	0.00	0.14	0.00
Jonah 59-17; undisturbed; clayey, mixed, frigid Ustic Calciargids										
A	0-6	7.4	0.27	27.4	2.55	1.00	0.31	0.01	0.36	0.03
Bt1	6-36	7.7	0.23	22.5	6.18	0.79	0.16	0.00	0.60	0.05
Bt2	36-52	7.7	0.39	17.6	16.90	0.77	0.05	0.00	0.47	0.03
Bt3	52-90	7.9	1.2	22.8	5.40	0.51	0.12	0.00	0.25	0.01
Bk	90-110	7.7	2.8	31.2	3.36	0.31	0.06	0.00	0.14	0.00
CR	110-116	7.4	6.3	15.2	0.46	0.77	0.02	0.00	0.07	--
CR2	116-140	7.5	3.8	42.1	0.58	0.56	0.02	0.00	0.55	0.04
2R	140-150	—	—	—	—	—	—	—	—	—
Wamsutter 2-20; reclaimed; fine-loamy, mixed, frigid Haplic Torriarents										
A	0-5	7.6	1.1	4.13	8.28	1.07	5.72	0.18	4.02	0.20
1C	5-20	7.8	3.3	4.48	12.30	1.53	20.40	0.80	3.12	0.20
2C	20-30	8	4.6	4.81	11.40	1.45	69.80	2.19	4.86	0.20
3C	30-40	5.2	7.5	1.42	7.36	0.29	64.20	2.16	3.36	0.16
4C1	40-60	5.7	7.5	0.475	7.29	0.66	2.26	0.09	0.89	0.04
4C2	60-80	7.9	6.5	1.29	6.38	0.63	0.44	0.02	0.63	0.03
	80-100	7.5	5.6	11	1.03	0.53	0.19	0.01	0.84	0.02
	100+	7.5	5.4	19.1	0.93	0.65	0.16	0.01	0.77	0.04
Wamsutter 2-20; undisturbed; fine-loamy, mixed, frigid Ustic Haplocalcids										
A	0-10	7.6	0.62	3.65	13.90	1.31	6.38	0.08	2.09	0.14
Bw	10-20	7.5	0.97	6.84	9.13	0.75	2.69	0.06	1.91	0.12
Bk	20-55	7.4	1.1	7.47	7.27	0.65	2.10	0.05	2.06	0.08
BCk	55-96	7.4	2.5	10.5	4.37	0.39	2.30	0.04	1.34	0.04
CR	96-120	7.3	3.3	11.7	2.82	0.60	1.67	0.05	1.15	0.04
R	120-122	7.4	4	15.1	2.26	0.05	0.43	0.00	1.83	0.05

Appendix 2.2. (*continued)*

Horizon	Depth	pH	EC	CaCO$_3$	C	N	Free C	Free N	Occ. C	Occ. N
—	*—cm—*	—	*—dS m^{-1}—*	*—%—*	*—g kg^{-1} soil—*					
Wamsutter B-7D; reclaimed; fine-loamy, mixed, frigid Haplic Torriarents										
A	0-5	7.4	1.7	3.72	22.00	0.13	0.95	0.06	0.89	0.07
C	5-20	7.5	1.5	4.32	21.10	0.16	3.47	0.18	2.44	0.16
Ck	20-38	7.5	1.5	18.9	6.75	0.21	3.89	0.12	2.86	0.19
1CR	38-60	7.8	1.9	28.7	2.72	0.23	1.76	0.09	0.96	0.04
	60-87	7.7	3.7	8.55	2.70	0.30	1.16	0.04	1.54	0.05
	87-106	7.4	5.6	12	3.00	0.31	1.37	0.06	1.63	0.06
2CR	106-120	7.6	3.1	25.4	1.33	0.69	0.51	0.04	0.82	0.03
Wamsutter B-7D; undisturbed; coarse-loamy, mixed, frigid Ustic Calciargids										
A	0-10	7.2	0.42	1.15	38.30	2.30	7.88	0.17	0.66	0.02
Bt1	10-27	7.1	0.21	1.32	13.00	1.03	1.72	0.04	0.18	0.00
Bt2	27-51	7.4	0.27	8.29	2.38	0.61	2.09	0.04	0.29	0.01
Btk	51-90	7.3	5.4	26.5	2.26	0.28	2.05	0.07	0.21	--
BCk	90-111	7.4	9	30.6	3.63	0.18	3.52	0.22	0.12	0.00
CR	111-150	7.6	3.6	35.6	0.57	0.17	0.45	0.02	0.12	0.01
Wamsutter K-11; reclaimed; fine-loamy, mixed, frigid Haplic Torriarents										
A	0-5	7.5	0.32	0.847	20.40	0.00	18.00	0.91	1.29	0.04
1C	5-20	7.7	0.3	6.73	2.33	0.72	1.39	0.06	0.94	0.03
	20-30	7.6	1.1	6.53	11.20	0.60	1.25	0.03	0.64	0.03
	30-48	7.5	1.6	4.87	1.80	0.03	1.06	0.03	0.74	0.04
2C	48-62	7.7	0.75	6.38	12.00	0.04	1.52	0.09	0.88	0.04
3C1	62-76	7.6	1.5	8.22	9.84	0.11	1.87	0.06	0.51	0.03
3C2	76-96	7.4	1.5	5.06	16.80	0.11	0.66	0.02	0.36	0.01
	96-116	7.5	2	5.81	3.29	0.13	0.96	0.04	0.88	0.03
	116-136	7.6	1.5	5.72	1.64	0.14	0.73	0.03	0.90	0.03
	136-150	7.5	1.8	5.89	2.05	0.13	1.32	0.05	0.73	0.04
Wamsutter K-11; undisturbed; fine-loamy, mixed, frigid Ustic Calciargids										
A	0-8	7.5	0.26	1.99	11.10	0.69	2.54	0.07	0.51	0.02
Bt	8-37	7.6	0.26	3.81	6.22	0.67	1.28	0.04	0.27	--
Btk	37-55	7.8	0.32	8.43	5.16	0.50	1.15	0.05	0.33	0.03
Bk	55-73	7.5	0.66	8.42	6.04	0.55	1.81	0.05	0.83	0.06
BC	73-103	7.8	1.7	10.9	5.72	0.36	1.62	0.04	1.98	0.05
C1	103-133	7.6	4.2	9.14	4.41	0.23	1.06	0.03	2.20	0.07
C2	133-150	7.7	3.7	8.94	4.35	0.18	1.24	0.02	3.03	0.10

Appendix 2.3. Abbreviations for soil profile characteristics.

Parameter		Abbrev.	Definition
Texture		C	Clay
		CL	Clay loam
		L	Loam
		LS	Loamy sand
		S	Sand
		SCL	Sandy clay loam
		SL	Sandy loam
		SiC	Silty clay
		SiCL	Silty clay loam
		SiL	Silty loam
Structure	Grade	0	Structureless
		1	Weak
		2	Moderate
		3	Strong
	Size	Co	Coarse
		F	Fine
		M	Medium
	Type	Abk	Angular blocky
		Gr	Granular
		M	Massive
		Pl	Platy
		Pr	Prismatic
		Sbk	Subangular blocky
		Sg	Single grain
Boundary	Distinctness	A	Abrupt (0.5-2 cm)
		C	Clear (2-5 cm)
		D	Diffuse (>15 cm)
		G	Gradual (5-15 cm)
	Topography	B	Broken
		I	Irregular
		S	Smooth
		W	Wavy

CHAPTER THREE: VEGETATION AND SOIL ORGANIC MATTER RESPONSES TO A CONTROLLED LIVESTOCK TREATMENT ON RECLAIMED NATURAL GAS PADS OF SOUTHWEST WYOMING

Abstract

Achieving reclamation goals set by regulatory agencies in natural gas extraction project areas has proven difficult in Wyoming. The cool, dry climate and thin, nutrient poor soils degraded by drilling and reclamation activities challenge reclamationists in Wyoming. Methods to accelerate the establishment of a self-perpetuating native plant community are in high demand. This study examines the efficacy of one such method: controlled livestock treatment. On 10 reclaimed and seeded well pads in three natural gas fields, 25 head of cattle were fed certified weed-free hay and kept on 0.10-ha plots for 24 hrs. Each well pad also had a 0.10-ha reclaimed reference plot that did not receive the treatment. Soil samples were taken to a 5-cm depth across each plot prior to and immediately after the treatment in fall of 2009 as well as in the spring, summer, and fall of 2010. Soils were analyzed for chemical and physical properties in addition to soil organic matter (SOM) characteristics. Vegetation community characteristics were also examined during the summer 2010 sampling event. The controlled livestock treatment had an immediate impact on the labile SOM pool with effects returning to reference values by the spring 2010 sampling event. Potentially mineralizable carbon, microbial biomass carbon, and dissolved organic carbon showed immediate increases after the treatment. Longer lasting impacts of the treatment were evident in the vegetation data, where denser, more species-rich native plant communities established on cattle treatment plots.

Introduction

Reclamationists from various energy production and mining backgrounds have explored many ways to improve reestablishment of sustainable plant communities on reclaimed sites. Some methods aim to reduce overall impacts to soil, including direct hauling of topsoil instead of stockpiling (Anderson et al., 2008) and drilling on oak mat platforms instead of constructed well pads (McWilliams, 2008). However, these methods have limited potential for use on natural gas fields in southwestern Wyoming. Direct haul requires one location in the construction phase and a second ready for reclamation. In addition, well pads can be miles apart and host different pre-disturbance soils and plant communities. Terrain is often too steep (greater than 3% slopes) in southwest Wyoming to safely drill on oak mat platforms (McWilliams, 2008).

Other methods of reclamation utilize fertilizers or organic amendments to improve the nutrient status and stability of reclaimed soils as well as reap the benefits of increased SOM. These methods include mulching with woodchips or straw, seeding a cover crop, or incorporating organic wastes such as manures or biosolids into the reclaimed soil. On a uranium mine in Wyoming, a cover crop mulch was superior to crimped straw mulch in establishing a desirable plant community and improving infiltration on reclaimed soils when at least 40 cm of topsoil was applied over the mine spoil (Pinchak et al., 1985; Schuman et al., 1985). Organic amendments such as biosolids, municipal waste and garden compost have also been used to neutralize pH and decrease the effective bioavailability of heavy metals in acidic mine spoils (Alvarenga et al., 2009). A long-term study on biosolid additions oil shale reclamation sites in northwestern Colorado revealed biosolids improved plant establishment through lowering pH and increasing SOM and bioavailable nutrients 24 years after initial reclamation (Paschke et al., 2005). Shrestha et al. (2009) found soil organic carbon (SOC) sequestration to be higher on reclaimed mine soils amended with manure than traditional reclamation practices.

Transportation of organic amendments can be expensive and the remote natural gas fields of southwest Wyoming are sometimes hundreds of miles from municipalities with biosolid waste to spare. Methods that use local sources of organic amendments are more desirable to keep costs low. One such method uses livestock to both supply and apply organic amendments to soils on reclaimed natural gas well pads.

While the use of livestock in reclamation has gained popularity with land managers in recent years, livestock are often associated with excessive herbivory, soil compaction (Abdelmagid et al., 1987; Daniel et al., 2002), and other ecological damage (Fernandez et al., 2008; Ponzetti and McCune, 2001). However, livestock can be used as a reclamation tool to manipulate vegetation and improve soil conditions for plant establishment. Evidence in support of livestock as ecosystem engineers often involves consumption of standing forage to manipulate plant communities (Lecain et al., 2000; Manley et al., 1995; Popay and Field, 1996).

The controlled livestock treatment explored in this study is different from a grazing regime, as it is a treatment applied to an area with little to no standing forage. Grazing or browsing animals are confined at high density on an area void of vegetation and are fed and allowed to bed down on the site. The idea behind this is that the combination of hoof action and addition of organic materials will improve soil conditions for plant establishment. Some research has established the benefit of using livestock excrement as a fertilizer or growth medium on degraded rangeland soils, enhancing seed germination and/or plant growth

(Auman et al., 1998; Gokbulak, 2008; Gokbulak and Call, 2004). Little replicated research has assessed ecosystem recovery of a controlled livestock treatment on reclaimed soil, though much testimonial evidence exists. The need for affordable and effective reclamation practices, scientific reasoning, and testimonial evidence warrant further investigation into the ecological implications of controlled livestock treatments.

The aim of this study was to investigate the effects of a controlled livestock treatment on labile SOM characteristics and recovery of plant communities on reclaimed natural gas pads. This study quantified impacts of a controlled livestock treatment on reclaimed natural gas well pads over the first year following initial reclamation. Short-term soil impacts were expected to be most prominent in the surface and in labile SOM. We predicted higher carbon (C) and nitrogen (N) in potentially mineralizable, dissolved organic, microbial biomass, light fraction, and total soil organic matter (SOM) pools of livestock treated plots when compared to traditionally reclaimed plots. Furthermore, we expected positive responses in vegetation on livestock treatment plots including increased species richness, plant and total surface cover, plant density, and plant biomass. Both desirable and undesirable (weedy) species cover, density, and biomass were also expected to increase.

Materials and Methods

Site Description

Natural gas production company reclamationists selected well pads slated for reclamation in 2009 with safe working conditions and similar landscape settings in each of three active natural gas fields in Wyoming; the Pinedale Anticline (Anticline) (42.73° N; 109.83° W), Jonah (42.45° N; 109.73° W), and Wamsutter (41.67° N; 107.85° W) fields.

Three well pads were chosen in the Anticline and Wamsutter fields and four well pads were selected from the Jonah field. All study areas experience cool, dry climates with the majority of precipitation falling as snow. Precipitation and air temperature data from the study period is shown in Figure 3.1.

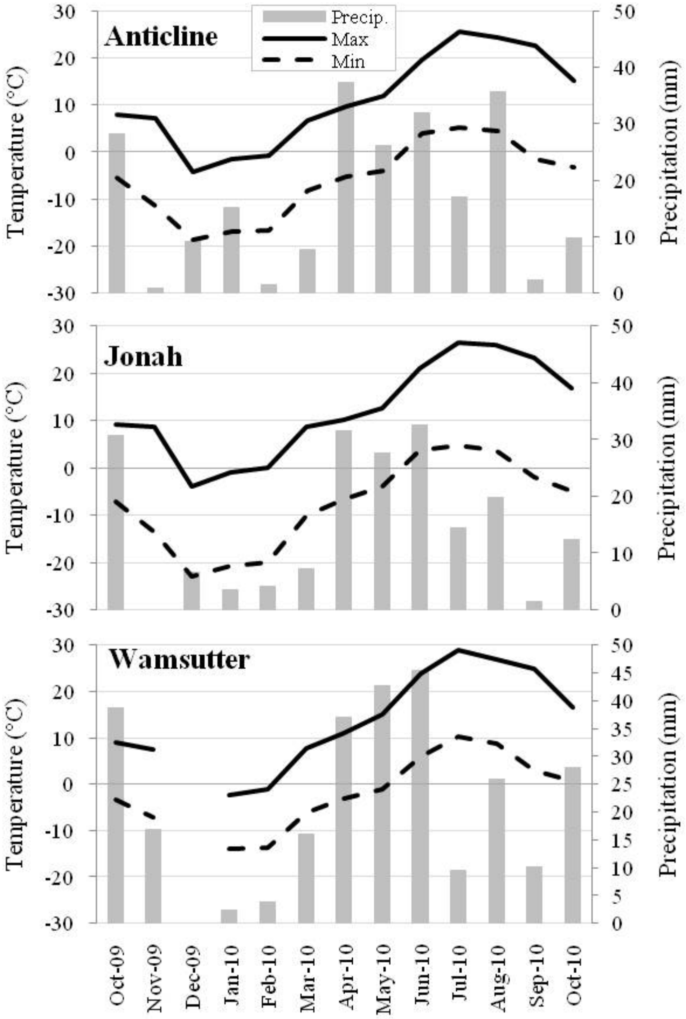

Figure 3.1. Climate data from the Pinedale (Anticline), Boulder (Jonah), and Wamsutter weather stations in southwest Wyoming during the study period (fall 2009 to fall 2010). Data obtained from the Western Regional Climate Center (WRCC, 2011). No data was available in December 2009 for the Wamsutter data logger.

Soils of the Anticline include Alfisols and Aridisols and at our study sites consist of gravelly silt loams formed in alluvial deposits. Soils in the Anticline study sites are mapped as part of the Jemdilon gravelly loam soil map unit (NRCS, 2011). Sandy clay loams of the Jonah formed in residuum of Tertiary valley fill deposits (Love and Christiansen, 1985) and are mapped as part of the Jonah-Burmaloaf complex (NRCS, 2011). Soils of the Wamsutter sites are Entisols and Aridisols and consist of loamy material that also formed in residuum of Tertiary valley fills (Love and Christiansen, 1985), but have not been mapped (NRCS, 2011).

Basic soil properties of undisturbed surface soils adjacent to the study sites are listed in Table 3.1. Surface soils on all three fields have slightly alkaline pH and low electrical conductivity (EC). Soil pH increases slightly with depth on undisturbed soils in all three fields, but EC remains low.

Table 3.1. Properties of undisturbed surface soil (0-5 cm depth) on the Anticline (Ant; n=3), Jonah (Jon; n=3), and Wamsutter (Wam; n=3) natural gas fields of southwest Wyoming. Parameters include total organic C (TOC), total N (TN), pH, electrical conductivity (EC), and bulk density (BD). Standard errors are in parentheses.

	TOC	TN	pH	EC	BD
	g kg^{-1} soil			*dS m^{-1}*	*g cm^{-1}*
Ant	17.6(2.31)	2.23(0.665)	7.7(0.018)	0.33(0.019)	1.30(0.0527)
Jon	9.98(1.99)	0.685(0.190)	7.8(0.031)	0.30(0.015)	1.30(0.0645)
Wam	18.8(2.14)	1.68(0.440)	7.7(0.015)	0.26(0.010)	1.33(0.0652)

Soil texture and ecological site descriptions that correspond to the undisturbed areas adjacent to the study sites are found in Table 3.2. Sagebrush-steppe plant communities with slightly different composition of species dominate undisturbed areas on all three natural gas fields.

Table 3.2. Soil particle- size distribution, texture (Text.) class, and ecological site description (ESD) of undisturbed surface soils (0-5 cm depth) and plant communities on the Anticline (Ant; n=3), Jonah (Jon; n=3), and Wamsutter (Wam; n=3) natural gas fields of southwest Wyoming. ESDs determined from the most recent approved ESD reports (NRCS, 2010a). Standard errors are in parentheses.

	Sand	**Clay**	**Silt**	**Text.**	**ESD**
		%		*class*	
Ant	28.8 (0.590)	13.1 (0.565)	58.1 (1.15)	SiL	Loamy (Ly) 10-14” Foothils and Basins West
Jon	56.7 (6.44)	21.0 (3.47)	22.3 (3.13)	SCL	Loamy (Ly) 7-9” Green River and Great Divide Basins
Wam	30.3 (2.56)	20.3 (2.00)	49 .4 (0.567)	L	Loamy (Ly) 7-9” Green River and Great Divide Basins

Study Design

All well pads were reclaimed using standard seed mixes and seedbed preparation methods for each field. Soils were stripped to a depth of 15-20 cm (6-8 in), stockpiled for a period of time, respread to a uniform depth, and seeded. Exact methods varied by local regulations and company policies. The soils on the Anticline were stripped, stockpiled, and spread more than once and were crimped with straw mulch. Residence times of stockpiles on the Anticline were variable and undocumented. Jonah and Wamsutter soils were not amended with straw mulch and stockpiles were not moved until they were respread. Soils on the Jonah were stripped, stockpiled, and respread within a 10-month time period. Wamsutter stockpiles had a maximum lifetime of 2 years. The controlled livestock treatment was superimposed on these reclaimed soils within one week of seeding according to the following procedure.

Two, 0.10-ha (0.25-ac) plots were constructed on each well pad and randomly selected to receive the controlled livestock treatment or were assigned the reclaimed reference plot (Figure 3.2). We installed three permanent 34-m (112-ft) transects and located three sampling points along each transect. Soil samples were then collected at sample points from three depths: 0-5, 5-20, and 20-30 cm (0-2, 2-8, and 8-12 in). Soils were bulked by depth and transect.

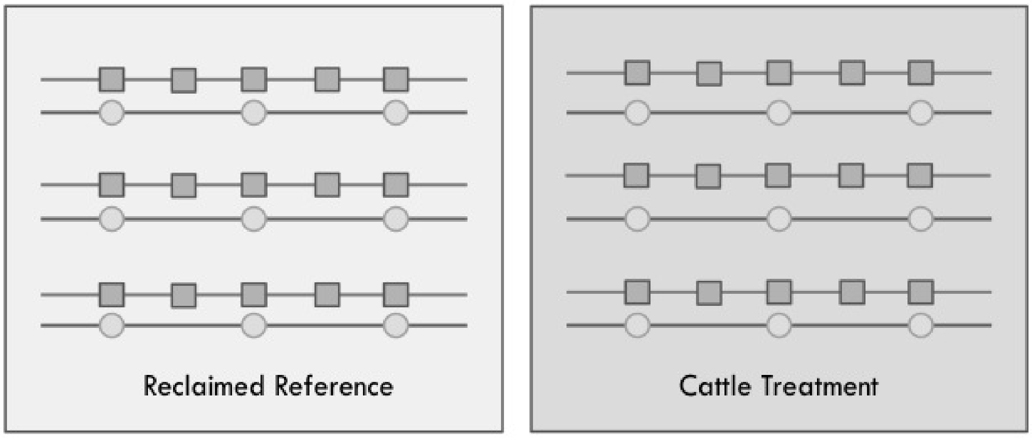

Figure 3.2. Sampling design for the controlled livestock (cattle treatment) plots and reclaimed reference plots on the Anticline, Jonah, and Wamsutter natural gas fields. Soil was sampled from three points along three transects (—○—) and vegetation parameters were analyzed in five Daubenmire frames along three transects (—□—).

Controlled livestock plots were sampled before and after the livestock treatment was applied in fall of 2009. Soil was also sampled in spring, summer, and fall of 2010. In addition to sampling soil in the summer of 2010, we also sampled vegetation. A schematic of seasons and parameters sampled are found in Table 3.3. Vegetation attributes were sampled in 20 by 50-cm (8 by 20-in) frames along each transect. At five locations along each transect, vegetation cover was ocularly categorized into one of six cover classes (0-5%, 5-25%, 25-50%, 50-75%, 75-95%, and 95-100%) by plant species (Daubenmire, 1968). In three quadrats along each transect, stem density was recorded and aboveground plant biomass was clipped to a height of 0.5 cm above the soil surface. Plant biomass was separated by species, dried for 48 hours at 60ºC, and weighed.

Table 3.3. Timeline for evaluating soil and vegetation parameters on reclaimed well pads in southwest Wyoming after a controlled livestock treatment.

	Sampling Event				
Parameter	**Pre Treatment Fall 2009**	**Post Treatment Fall 2009**	**Spring 2010**	**Summer 2010**	**Fall 2010**
Total OC & N	X	X			X
Active-pool OC & N†	X	X	X	X	X
SOM fractions	X	X			X
EC and pH	X	X			X
Bulk Density	X	X	X		
Texture			X		
Vegetation				X	

† Potentially mineralizable C and N, dissolved organic C and N, and microbial biomass C and N.

Controlled Livestock Treatment

All of our study areas either currently or historically hosted cattle as primary grazers. Local cattle producers were willing to cooperate with the project, thus determining cattle as the species of livestock used in our study. Controlled livestock plots were temporarily fenced and certified weed-free grass hay was scattered throughout the fenced area. The wet meadow species in the hay are not adapted to the dry conditions of the study sites, so hay was not considered an additional seed source. On the Jonah and Anticline production areas, 25 cows occupied the 0.10-ha (0.25-ac) plots for 24 hours; while 12 bulls occupied the Wamsutter area plots for 48 hrs. This stocking rate was determined by estimating the amount of SOM lost through construction and reclamation activities and then calculating how much organic material, in the form of feces, urine, and excess feed, a single cow contributes in a day. According to the Natural Resources Conservation Service (NRCS, 2010b), a typical 454 kg (1000 lb) beef cow produces 4.85 kg (10.7 lb) of manure per day, which yields 1.13 kg (2.5 lbs) of dry organic material per 454 kg animal per day (van Vliet et al., 2007). Also, cattle typically waste about 30 percent of total hay fed on the ground, or as much as 8.16 kg (18 lbs) per animal per day for low-quality forage. Data from reclaimed coal mines suggest that 35 to 69 percent of SOM is lost by the time the soil is reclaimed (Anderson et al., 2008; Ingram et al., 2005; Mummey and Stahl, 2004; Wick et al., 2009a,b). Assuming a bulk density of 1.3 g cm^{-1} and an initial SOM content of 1.5 percent, 183 to 362 cattle ha^{-1} d^{-1} (74 to 147 cattle ac^{-1} d^{-1}) would be required to replenish the estimated lost SOM. We adjusted our final stocking rate of 240 cattle ha^{-1} d^{-1} (100 cattle ac^{-1} d^{-1}) after discussing feasible rates with the cattle producers who cooperated with this project.

Laboratory Methods

Bulked soil samples were divided into two subsamples in the field: one was immediately chilled to 4.0°C (39°F) while the other was air dried upon returning to the laboratory. Chilled samples were used to analyze the dynamic SOM pools while dried samples were used for general soil properties and physical SOM fractions. Dry samples were assessed in fall seasons only, while dynamic pools were analyzed after each sampling event (Table 3.3).

Approximately 10 g of moist soil was used to determine gravimetric moisture content (Gardner, 1986). An additional 10 g of field moist soil was immediately extracted with 50 mL of 0.5 *M* K_2SO_4 using Q5 filters, upon returning to the laboratory. Extracts were frozen for storage and then run on a microplate spectrophotometer (Powerwave HT, BioTek Instruments, Vinooski, VT) for NH_4-N and NO_3-N. For NH_4-N, 40 μL of sample was mixed with 80 μL of sodium salicylate ($NaC_7H_6O_3$) solution and 80 μL of bleach-sodium hydroxide (NaOH) solution and allowed to develop color for 1 hr before reading on the spectrophotometer (Weatherburn, 1967). For NO_3-N analysis, we used 10 μL of sample to

190 µL of vanadium chloride (VCl_3)-hydrocholric acid (HCl) solution (Doane and Horwath, 2003) and allowed color to develop for 18 hr before reading.

A 22-g sample of each field moist soil was brought to approximately 23% moisture content to determine mineralizable C and N. The moist soil then underwent a 14-d aerobic incubation at room temperature as described in Zibilske (1994) for C and Hart et al. (1994) for N. Potentially mineralizable C was measured by drawing CO_2 from the incubation jars using 30-mL syringes on the first, fourth, seventh, and fourteenth days of the incubation period. These samples were then analyzed on an infrared gas CO_2 analyzer (LI-820, LI-COR Inc, Lincoln, NE) on the days they were drawn. The cumulative C released over the 14-d incubation period is the potentially mineralizable C content of the soil. A 10-g sub-sample of the 22-g soil sample was then analyzed for gravimetric moisture to correct for actual moisture content. After the 14-d incubation period, the remaining soil was extracted with 50 mL of 0.5 *M* K_2SO_4 and analyzed for NH_4-N and NO_3-N as described for mineral N above. This represents the amount of organic N mineralized under optimal temperature and moisture after a 14-d incubation period, or potentially mineralizable N.

Microbial biomass was determined using the chloroform fumigation extraction method as described by Horwath and Paul (1994). For this procedure, we fumigated 10-g soil samples for 48 hr prior to extracting them with 50 mL of 0.5 M K_2SO_4. Extracted samples from both fumigated and non-fumigated samples were then run on a total organic C and total N analyzer (TOC-VCSH with TN Unit, Shimadzu Scientific Instruments, Inc., Columbia, MD). Non-fumigated samples provide the values for dissolved organic C and dissolved organic N and are subtracted from fumigated values to produce microbial biomass C and microbial biomass N.

Microbial biomass C and N were calculated using Equations 3.1 and 3.2, respectively. In the equations, F represents the flush of C or N released after fumigation and C_F/N_F describes the C to N ratio of fumigated samples. A K_C of 0.35 was used as a conversion factor for calculating microbial biomass C and a K_N calculated from the fumigated C:N ratio was used to adjust microbial biomass N based on substrate quality as suggested by Horwath and Paul (1994; Equation 3.3).

$$Microbial\,Biomass\,C = \frac{F_C}{K_C}$$ **Equation 3.1**

$$Microbial\,Biomass\,N = \frac{F_N}{K_N}$$ **Equation 3.2**

$$K_N = {}^{-}0.014 \times \left(\frac{C_F}{N_F}\right) + 0.39$$ **Equation 3.3**

Soil that was not chilled in the field was air dried for 48 hr and 2-mm (0.08-in) sieved upon returning to the laboratory. Soil texture was determined by particle size distribution using the hydrometer method (Gavlak et al., 2005). Electrical conductivity (EC) and pH were determined in 2:1 soil:water solution using EC and pH electrodes, respectively. Bulk density samples were collected separately in the field using the NRCS bulk density core method on the Jonah and Wamsutter sites and the NRCS bulk density test for gravelly and rocky soils on the Anticline (NRCS, 2010c). Instead of microwaving samples to dry them as suggested in the NRCS methods, we dried the samples for 24 hr in a 105°C (221°F) oven.

Total C and N content of the soil was determined by combustion using a Carlo Erba NC-2100 elemental analyzer (Carlo Erba Instruments, Milan, Italy). Prior to combustion, dried samples were finely ground and approximately 20 mg were placed into titanium cups. Inorganic C content was estimated using the pressure calcimeter method described by Sherrod et al. (2002) and inorganic C content was subtracted from total C to calculate total organic C.

Physical SOM fractionation was used to quantify different organic C and N pools. Dried soil was sieved to 6.35 mm (0.250 in) and 10-g samples placed in 35-mL centrifuge tubes. The density fractionation method described by Sohi et al. (2001), using 1.80 g cm^{-1} NaI, was used to obtain light fraction and mineral-associated fraction organic C and N. The free portion of the light fraction SOM was collected off the surface of the NaI solution after gently shaking and centrifuging at 2000 rpm for 15 minutes. The occluded light fraction was collected in a similar fashion after vigorous shaking, 110 s of sonication, and centrifuging at 2000 rpm for 20 minutes. Light fraction samples were collected on 20-µm nylon filters and rinsed with deionized water. The remaining soil sample was rinsed thoroughly and used for determining heavy fraction or mineral-associated C and N. All fractions were dried for 24 hr in a 60°C (140°F) oven and weighed. Dried SOM fractions were then ground and weighed to 5 mg (light fractions) or 20 mg (mineral-associated fraction) and run on an elemental combustion analyzer (Carlo Erba Instruments, Milan, Italy). For the mineral-associated fraction, inorganic C was subtracted as described previously to account for $CaCO_3$-C and yield only organic C content. The C to N ratios of all SOM pools were used to determine SOM quality.

Data analysis

Differences between controlled livestock treatment plots and reclaimed plots were determined using analysis of variance (ANOVA). All comparisons were analyzed using the statistical program SAS 9.2 (2011). Transects were averaged to provide one value per plot and ANOVA was performed to determine differences between treatment means (Table 3.4).

Table 3.4. ANOVA table of P-values of labile organic matter properties of surface soils (0-5 cm) on study plots in southwest Wyoming by sampling date (TIME; fall 2009, spring 2010, summer 2010, or fall 2010), natural gas field (LOC; Anticline, Jonah, or Wamsutter), treatment (TRT; controlled livestock or reclaimed reference), and their interactions. Asterisks represent significance at the P < 0.1* level.

					Response					
	Mineral	**Potentially Mineralizable**			**Dissolved**			**Microbial Biomass**		
Factors	**N**	**C**	**N**	**C:N**	**Organic C**	**N**	**C:N**	**C**	**N**	**C:N**
TIME	0.261	0.658	0.701	0.203	0.124	0.318	0.950	0.988	0.317	0.693
LOC	0.132	0.303	0.329	0.581	0.241	0.514	0.247	0.472	0.511	0.251
TRT	0.224	0.191	0.735	**0.096***	**0.013***	**0.010***	0.539	0.496	0.382	0.443
LOC*TRT	0.701	0.163	0.568	0.524	0.921	0.962	0.687	0.808	0.407	0.454
TIME*LOC	0.509	**0.080***	0.249	0.270	0.494	0.375	0.534	0.599	0.308	0.572
TIME*TRT	0.846	**0.027***	0.409	0.111	0.240	0.508	0.618	0.319	0.337	0.350
TIME*LOC*TRT	0.263	0.491	0.315	0.585	0.581	0.369	0.169	0.195	0.153	0.385

Student's t-test was used to quantify differences between values in location-treatment and season-treatment combinations. An alpha of 0.1 was used to determine statistical significance. The most prominent results were observed in the surface soil (0-5 cm) and are presented herein.

Results

Cattle treatments implemented in the fall of 2009 caused immediate, marked increases in concentrations of most active SOM pool components, including labile organic C and quality (C:N), dissolved organic C, and microbial biomass C; but only in the 0-5 cm depth increment. These SOM effects diminished to near reference concentrations by the following spring, but the livestock had clearly impacted establishment of seeded vegetation across all three locations ($P = 0.005$), with over twice as many stems m^{-2} than the reference sites in the summer following seeding and livestock treatment. Vegetation parameters exhibited strong correlation with soil properties, particularly on livestock plots.

Soil Organic Matter

Impacts of the livestock treatment on SOM were detected immediately after treatment application and dissipated over the course of the study (Figure 3.3). Soil organic matter properties beneath the cattle treatment plots and reclaimed reference plots were indistinguishable prior to treatment application; SOM characteristics and general soil properties were not statistically different between the two treatments. Over the course of the first year, there were significant differences in the season by treatment interaction for potentially mineralizable C, potentially mineralizable SOM quality (C:N), and dissolved organic C in soils (Figure 3.3).

Immediately after treatment was applied (fall 2009), soils beneath controlled livestock plots contained the highest concentrations measured of potentially mineralizable C, potentially mineralizable SOM quality (C:N), dissolved organic C, dissolved organic N, microbial biomass C, and microbial biomass N. Potentially mineralizable C was higher under the controlled livestock treatment in fall of 2009 than under the reclaimed reference plots in fall 2009 ($P=0.002$).

The ratio of potentially mineralizable C:N followed a similar trend with the soils beneath the controlled livestock plots in fall 2009, which were higher than under the reclaimed reference plots in fall 2009 ($P<0.001$; Figure 3.3C). Potentially mineralizable C and potentially mineralizable SOM quality (C:N) were highest in the fall of 2009 and returned to reference levels by the spring sampling event and remained for the duration of the study. In addition to this relationship, reclaimed reference plots in both fall seasons had higher potentially mineralizable SOM quality (C:N) than reclaimed reference plots in the spring of 2010 ($P=0.088$) and summer 2010 ($P=0.068$). Dissolved organic C was higher after the controlled livestock treatment in fall of 2009 than the controlled livestock treatment in spring 2010 ($P<0.001$), summer 2010 ($P=0.001$), and fall 2010 ($P=0.002$; Figure 3.3D).

Differences in SOM determined by density fractionanation occurred only in the occluded light fraction, with values in soils beneath Wamsutter > Anticline > Jonah (Table 3.5). Wamsutter soils treated with livestock had significantly more occluded light fraction organic C than soils beneath the reclaimed reference plots.

Table 3.5. Soil organic matter properties (0-5 cm depth) of controlled livestock treatment (CLT) and reclaimed reference (No-CLT) plots on reclaimed well pads in southwest Wyoming. Significant differences between treatments and locations for a given variable are noted with different letters. Different letters indicate significant differences between among treatments and locations at $P < 0.10$.

		Light Fraction Organic Matter				**Mineral-associated Fraction**	
		Free Fraction		**Occluded Fraction**			
		OC	**N**	**OC**	**N**	**OC**	**N**
		g kg $^{-1}$ soil					
Anticline	**CLT**	3.15	0.149	**0.623C**	0.0486	12.0	0.768
	No-CLT	3.14	0.144	**0.703C**	0.0594	15.9	0.692
Jonah	**CLT**	1.82	0.087	**0.300D**	0.0234	4.45	0.643
	No-CLT	1.77	0.126	**0.198D**	0.0138	4.43	0.508
Wamsutter	**CLT**	4.74	0.251	**1.24A**	0.0833	7.76	0.483
	No-CLT	3.65	0.219	**0.904B**	0.0643	5.05	3.42

Table 3.6 General surface soil (0-5 cm depth) properties of controlled livestock treatment (CLT) and reclaimed reference (No-CLT) plots on the Anticline (Ant; n=3), Jonah (Jon; n=4), and Wamsutter (Wam; n=3) natural gas fields of southwest Wyoming. Parameters include total organic C (TOC), total N (TN), texture (Text.), pH, electrical conductivity (EC), and bulk density (BD). Standard errors are in parentheses.

		TOC	**TN**	**Text.**	**pH**	**EC**	**BD**
		g kg^{-1} soil		*class*		*dS m^{-1}*	*g cm^{-3}*
Ant	**CLT**	6.85(1.18)	2.05(0.380)	L	7.5(0.050)	1.2(0.51)	1.30(0.0913)
	No-CLT	8.49(1.76)	1.19(0.104)	L	7.6(0.056)	0.62(0.080)	1.23(0.0918)
Jon	**CLT**	9.07(3.14)	0.564(0.188)	SCL	7.8(0.065)	0.82(0.28)	1.30(0.0768)
	No-CLT	7.85(1.81)	0.596(0.161)	SCL	7.9(0.080)	0.75(0.26)	1.24(0.101)
Wam	**CLT**	22.5(3.69)	1.87(0.594)	L	7.3(0.12)	2.0(0.57)	1.33(0.0905)
	No-CLT	17.4(2.00)	1.54(0.435)	L	7.5(0.077)	0.98(0.35)	1.41(0.0511)

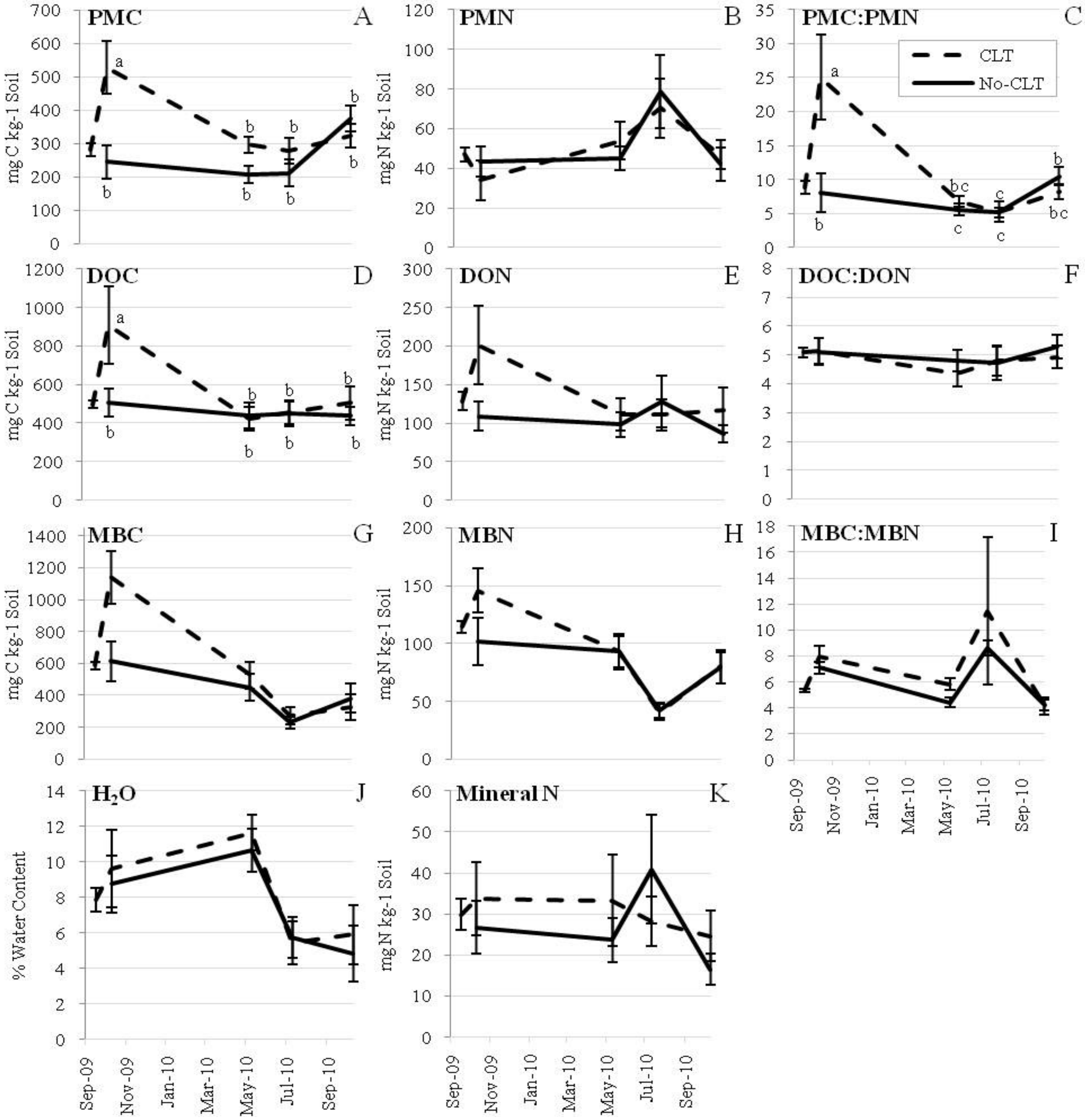

Figure 3.3. First year labile pool soil organic matter (SOM) dynamics in the 0-5 cm depth for the controlled livestock treatment (CLT) and the reclaimed reference (No-CLT) plots on reclaimed natural gas well pads in southwest Wyoming. The first data point on the CLT lines represents the conditions of CLT plots prior to treatment application. Significant differences between treatments and sampling events for a given variable are noted with different letters ($P<0.1$). Soil properties examined include potentially mineralizable carbon (A), potentially mineralizable nitrogen (B), potentially mineralizable SOM quality (C), dissolved organic carbon (D), dissolved organic nitrogen (E), dissolved SOM quality (F), microbial biomass carbon (G), microbial biomass nitrogen (H), microbial biomass SOM quality (I), water content (J), and mineral nitrogen (K).

No treatment effects were observed in general soil properties on any of the three study areas (Table 3.6). Total organic C, total N, pH, EC, and bulk density were statistically similar (P>0.1) between controlled livestock and reclaimed reference plots prior to treatment application and remained so after treatment application. Texture showed no difference between treatments.

Vegetation

In the first growing season after treatment, differences in surface cover, desired species richness, and desired species density were observed between treatments across all locations (Table 3.7). Although there was no difference measured in desired and undesired species cover between the controlled livestock and reclaimed reference plots, total surface cover was higher on the controlled livestock plots (P<0.001). Richness and density of desired plant species was also higher on controlled livestock plots than reclaimed reference plots (P=0.044 and P=0.005; respectively). Overall production was low on both controlled livestock treatment and reclaimed reference plots.

Table 3.7. Vegetation data collected in the first growing season after reclamation on controlled livestock treatment (CLT) and reclaimed reference (No CLT) plots on natural gas well pads in southwest Wyoming. Desired species include those that were seeded as well as native species recruited from the seed bank. Undesired species include weedy species. Asterisks represent significance at the p < 0.1* and p < 0.01** levels between treatments.

	Plant Cover		**Surface**	**Richness**	**Density**		**Biomass**	
	Desired	**Undesired**	**Cover**	**Desired**	**Desired**	**Undesired**	**Desired**	**Undesired**
	%			*No. of Species*	*stems m^{-2}*		*g m^{-2}*	
CLT	1.8	4.2	**36.0****	**2.0***	**84.9****	25.7	3.1	9.9
No-CLT	1.3	3.7	16.1	1.5	41.7	21.8	2.8	10.6

There were no differences between treatments by lifeform. Grasses were the dominant lifeform on both the controlled livestock and reclaimed reference plots, especially for desired species. Weedy forb species comprised the majority of undesired species on both plots;

however, *Bromus tectorum* (cheatgrass) was identified on Anticline controlled livestock plots. A complete list of species observed during plant community measurements in all study areas and treatment plots as well as the adjacent undisturbed area are found in Table 3.8.

Table 3.8. Plants identified along transects on controlled livestock treatment (CLT) plots, reclaimed reference (No-CLT) plots, and adjacent undisturbed reference (UND) plots during cover, richness, density, and biomass measurements on natural gas fields in southwest Wyoming. Species codes are listed in Appendix A.

Location	Treatment	Grasses	Forbs	Shrubs	Weeds
Anticline	**CLT**	ELEL, LECI, PASM	None	ARTRW, ATCA, KRLA	ALAL, BRTE, CHAL, MONU, POAV, SATR
	No-CLT	ELEL, LECI, PASM	SPCO	ATCA, KRLA	ALAL, CHAL, MONU, POAV, SATR
	UND	ACHY, CAFI, ELEL, PASM, POFE, POSE	ASPU, CRCE, PHHO, STAC, XYGL	ARTRW, CHVI	SATR
Jonah	**CLT**	ACHY, ELEL, LECI, PASM, POFE, POSE	EROV, OEPA, PEGL, VIAM	ATGA, KRLA	CHAL, DEPI, PHAD, SATR
	No-CLT	ELEL, HECO, PASM	LILE, OEPA, PEGL	ARTRW, ATGA, KRLA	BASC, DEPI, MONU, SATR
	UND	ACHY, CAFI, ELTR, PASM, POFE, POSE	EROV, LEPI, PHHO	ARTRW, ATGA, CHVI, KRLA	None
Wamsutter	**CLT**	ACHY, ELEL, PASM, POSE	None	None	DEPI, HAGL, MONU
	No-CLT	ACHY, ELEL, PASM, POFE	None	None	MONU
	UND	ACHY, ELEL, PASM, POFE, POSE	ERRE, PEGL, PHHO, XYGL	ARTRW, ATGA, KRLA, OPPO	None

Treatments also differed in relationships among vegetation characteristics and soil properties (Figure 3.4). Controlled livestock treatment plots tend to have stronger relationships between soil and vegetation parameters than control plots. Total ground cover was positively correlated with potentially mineralizable SOM quality (C:N) and negatively correlated with total SOM quality (C:N) for both treatments. Total ground cover was significantly correlated to potentially mineralizable SOM quality (C:N) in controlled livestock plots (P=0.007); but not for reclaimed reference plots (P=0.371; Figure 3.4A). On the other hand, total ground cover for both controlled livestock and reclaimed reference plots was highly negatively correlated to total organic C:N ratio (P=0.009 and P=0.006; respectively; Figure 3.4B).

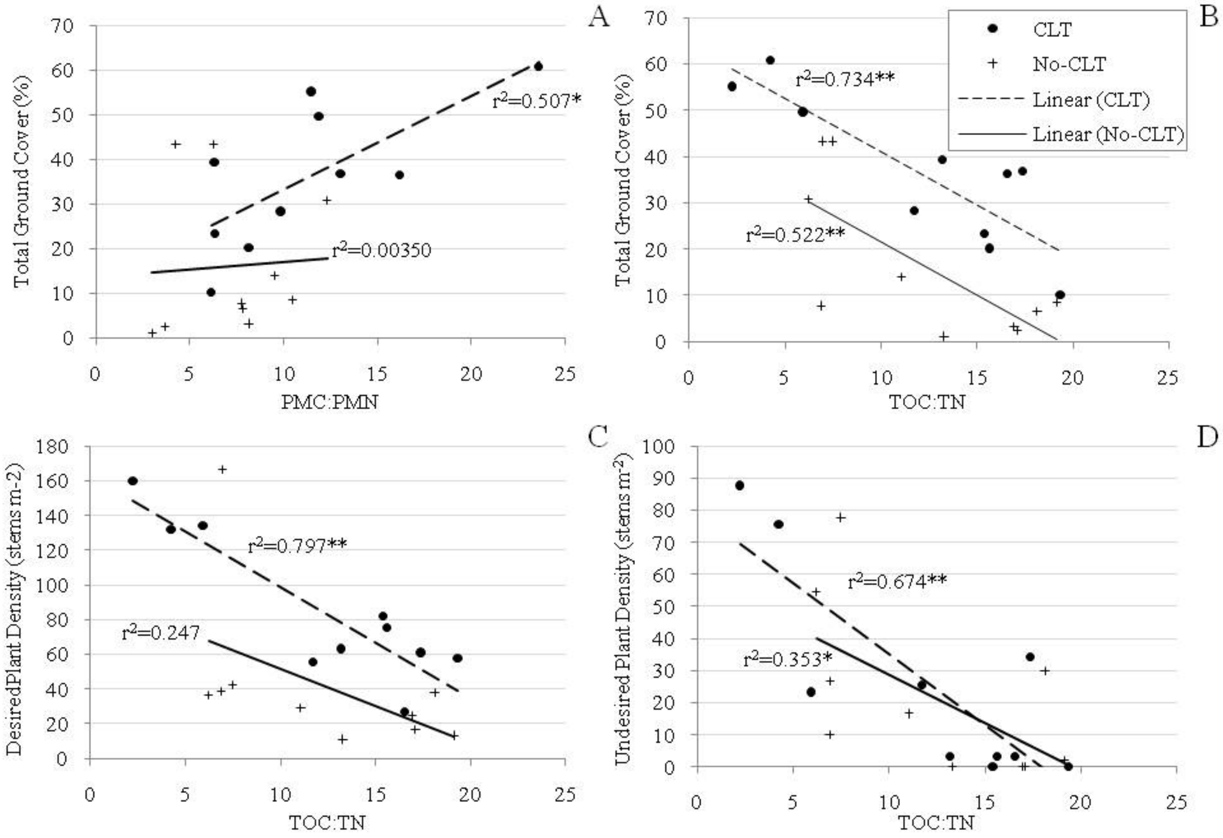

Figure 3.4. Relationships between soil potentially mineralizable C to potentially mineralizable N ratios (A) and total organic C to total N ratios (B-D) with total ground cover (A and B) and desirable (C) and undesirable (D) plant species stem densities for controlled livestock treatment (CLT) and reclaimed reference (No-CLT) plots on reclaimed natural gas well pads in southwest Wyoming. Asterisks note significant correlations at the $P < 0.05^*$ and $P<0.001^{**}$ levels.

Desirable and undesirable plant density typically displayed a negative relationship with total organic SOM quality (C:N). There was a significant correlation between desired plant density and total organic SOM quality (C:N) for the controlled livestock plots

(P=0.014), but not for the reclaimed reference plots (P=0.059; Figure 3.4C). Undesired plant density correlated to total SOM quality (C:N) for both the controlled livestock (P=0.006) and reclaimed reference plots (P=0.027; Figure 3.4D). Other SOM characteristics and general soil properties were not related to vegetation parameters.

Discussion

Overall, impacts of the controlled livestock treatment on SOM were observed immediately after treatment application and generated a positive response in the establishing plant community. The high C content of the amendment is likely responsible for the immediate differences observed between treatments. This labile SOM was probably mineralized in the early spring following our treatment and before our spring sampling event, resulting in SOM characteristics similar to those of the reclaimed reference soil. Furthermore, the available nutrients in conjunction with other positive effects of the treatment, improved conditions for germination such that desired species had higher density and richness than reclaimed reference plots.

Effects of the controlled livestock treatment on soil properties were most prominent immediately after the treatment was applied. While pre-controlled livestock treatment and reclaimed reference plots were indistinguishable, post-controlled livestock treatment plots had higher potentially mineralizable C, potentially mineralizable C:N ratio, dissolved organic C, and microbial biomass C than reclaimed reference plots in fall of 2009 (Figure 3.3). Controlled livestock plots held over twice as much potentially mineralizable C as reclaimed reference plots. This is attributed to the high C content of the hay and feces left after the treatment. These results are similar to those of agricultural plots in a shrub-steppe ecosystem treated with composted dairy waste. In the dairy waste study, a 175-d incubation period resulted in cultivated soils treated with dairy compost mineralizing more C than untreated plots with native vegetation (Cochran et al., 2007).

The increase in potentially mineralizable C:N ratio is attributed to the elevated mineralizable C in combination with no change in mineralizable N. A study in Spain analyzed the ability of organic amendments to improve degraded agricultural soils. Urban waste, composted urban waste, and urban waste mixed with straw were all found to increase microbial biomass C (Ros et al., 2003). Increases in microbial biomass C in the Ros et al. (2003) study dissipated nine months after the amendments were applied. This coincides with results from the controlled livestock treatment, and may be attributed to the consumption of the most readily bioavailable compounds shortly after organic amendment application.

Dissolved organic C levels in our study support this hypothesis. Immediately after the treatment was applied, soils beneath the treated plots had significantly higher dissolved organic C concentration than those beneath the reclaimed reference plots. By the spring, dissolved organic C concentration beneath the treated plots was indistinguishable from beneath the reclaimed reference plots. Bastida et al. (2008) also found both microbial biomass and water soluble C increased briefly after applications of biosolids and composted material to an arid Mediterranean soil, and then decreased to reference levels. However, both soil microbial biomass and dissolved organic C contents had rebounded to levels observed immediately after treatment application one year later because the increase in vegetation biomass led to another pulse of microbial activity (Bastida et al., 2008). This phenomenon has not occurred in our study and is likely due to the delayed recovery of the vegetation community under Wyoming's harsh climate.

Contrary to labile C, most soil labile N levels were variable and did not yield significant differences. Microbial biomass N was higher in the fall of 2009 than all other seasons, but no differences were observed between treatments. Mineral N and potentially mineralizable N were highly variable in our study. An agricultural study in Alberta analyzed soil N dynamics after annual cattle manure applications and found soil plant available N and mineralizable N did not respond to amendments in the first year (Miller et al., 2010). Instead, differences in plant available N and mineralizable N were observed after several years of organic amendment application. In our study, mineral N was likely immobilized due to the high C content in excess hay on the controlled livestock plots. Burgos et al. (2006) found this to be true in sandy soils for two organic amendments. They observed that municipal biosolids compost and agro-forest compost both initially immobilized N (Burgos et al., 2006). Nitrogen content is inherently variable in soils and the controlled livestock treatment may have increased this variability, leading to inconclusive results. One study found that sheep and cattle urine deposition changes the N content in soil and leads to spatially dynamic N content (Somda et al., 1997).

Density fractionation SOM varied by location, but demonstrated minimal response to the controlled livestock treatment. Intrinsic differences among study areas are due to variability in biologic production and turnover, parent material, climate, time, and topography. Higher concentration of occluded-fraction C in soil of our Wamsutter plots than in those of the two other study areas may be the result of soils developed in residuum and transported materials from Tertiary carboniferous rocks with isolated occurrences of oil shale. The presence of hydrocarbons in soil can obscure measurements of labile organic C (Rawlins et al., 2008). Higher precipitation and finer soil texture likely explain the higher occluded C content in soils in the Anticline plots compared to the Jonah plots. The mixing that occurs during reclamation often leads to higher clay and $CaCO_3$ content in surface soils than undisturbed soils, both of which promote soil aggregation. Wick et al. (2009a) found the highest amount of microaggregates, 53-250 μm (0.002-0.010 in), during the first year of reclamation. In spite of this fact, the first year after reclamation had the lowest amount of interaggregate light fraction C (Wick et al. 2009a).

Livestock increased the concentration of occluded-fraction C, but only in soils of the Wamsutter plots. Soil organic matter also encourages aggregation of soil particles, which may have led to higher protected organic C on controlled livestock plots. Differences between treatments in this pool only occurred in Wamsutter, a result that may have been due to more available C that was fixed into aggregates. Treatment effects and interactions did not occur in the mineral-associated SOM pool during this study. This recalcitrant pool typically does not react to short-term soil management changes (Sohi et al., 2010). This pool contributes the most total organic C and total N to soils and reflects the fact that there were no treatment effects to total organic C and total N.

One trend that remains constant throughout measured SOM pools is that the effects of the controlled livestock treatment tend to dissipate over the course of the first year. The drastic change observed between the fall 2009 and spring 2010 seasons suggests the active pool was mineralized between treatment application and the spring of 2010. Average monthly maximum temperatures were above freezing in November, March, and April; and all three study areas received early spring precipitation (Figure 3.1) This suggests conditions could have been adequate to enable biological decomposition of the organic amendments. Other organic amendment studies have encountered similar trends of initial spikes in labile pools followed by stabilization until the plant community recovers (Bastida et al., 2008; Burgos et al., 2006; Miller et al., 2010). The plant community was not expected to recover over one growing season in our study, which could explain why we did not see a lasting effect of the treatment. One extended study in Colorado suggests long-term impacts of organic amendments on reclaimed soils are plausible in sagebrush ecosystems. Paschke et al. (2005) observed reclaimed plots that received biosolid (56 Mg ha^{-1}) or biosolid-wood waste (134 Mg $ha^{-1}$and Mg ha^{-1}) organic amendments maintained higher vegetative cover and soil fertility than control plots 24 years after application. Higher stocking rates warrant investigation to achieve longer-term impacts on SOM components.

Regardless of lasting impacts of the controlled livestock treatment on soil properties, the treatment initiated establishment of a perennial plant community denser and richer in species than the reclaimed reference sites (Table 3.7). More plants to contribute litter to the soil may enhance SOM on the controlled livestock plots in the long-term. Surface cover in the first growing season was higher on controlled livestock plots than the reclaimed reference plots primarily due to increased litter from the excess feed. The residual hay acts as mulch and may have improved conditions for seedlings by stabilizing soil and providing physical protection. Furthermore, the higher water content of the soils under the livestock treatment suggests the additional litter helps to retain soil moisture (Figure 3.3). Production (biomass) was low on all plots during the first growing season. Future sampling may reveal more differences in plant community structure between treatments.

The controlled livestock treatment resulted in a patchy application of organic amendments due to the distribution by animals instead of machines. The heterogeneous nature of this type of treatment may be responsible for higher species richness on the controlled livestock plots. A range of conditions provides more microsites for a variety of species to establish. Furthermore, the patchy nature of the organic material on the controlled livestock plots may mimic the irregular pattern of soil fertility in Wyoming's shrublands. Emulating the islands of fertility of healthy shrubland plant communities is a goal of many restoration projects. These islands have been recreated using a variety of methods including nurse crops of native grasses (Maestre et al., 2001) and cattle dungpats (Gokbulak and Call, 2004). One study on cattle dungpats revealed that the seed position within or adjacent to a dungpat greatly influenced seedling emergence, and responses varied by species (Gokbulak, 2008). This suggests that by increasing the variety of soil conditions, one may provide a range of safe sites (Harper, 1977). Desired species density on controlled livestock plots was double that of reclaimed reference plots and visibly patchier.

Protection and nutrient availability among other factors provided by the controlled livestock treatment are likely responsible for enhanced germination. Because we did not measure hoof impacts separately from the addition of organic amendments, it is impossible to tell which factor of the controlled livestock treatment influenced plants the most, or if it was the combination that improved conditions for plants. Linear relationships were determined between soil characteristics and those of the plant community, which suggests the organic amendments did contribute to plant establishment (Figure 3.4). Plots that received the controlled livestock treatment tended to have higher correlation between plant community characteristics and soil parameters than those that did not receive the treatment. Whether or not the controlled livestock treatment will have a lasting impact on vegetation communities and soil properties remains to be seen.

Conclusion

In the short-term, the controlled livestock treatment influenced labile pools of SOM as well as plant communities in Wyoming natural gas well pad reclaimed sites. While impacts to the labile SOM pool typically diminished over the first growing season, an immediate positive response from the plant community suggests the controlled livestock treatment will have a lasting effect on the reclaimed well pad.

Future evaluation of these study sites will reveal if short-term effects result in long-term recovery of disturbed soils and plant communities. Manipulation of stocking rates and evaluating the economic feasibility of applying controlled livestock treatment on larger projects warrant further investigation. More research is needed to understand the spatial heterogeneity of this treatment in reference to the patchy nature of adjacent undisturbed ecosystems. This reclamation tool has the potential to reintroduce islands of fertility to soils that have been homogenized and distributed in uniform thicknesses. Until these aspects of the controlled livestock treatment are evaluated, this reclamation tool should be used with reservation.

Appendix

Appendix 3.1. Plant species by lifeform encountered on the study areas in southwest Wyoming.

Grasses		
Indian ricegrass	*Achnatherum hymenoides*	**ACHY**
Threadleaf sedge	*Carex filifolia*	**CAFI**
Bottlebrush squirreltail	*Elymus elymoides*	**ELEL**
Slender wheatgrass	*Elymus trachycalum*	**ELTR**
Needle and thread	*Hesperostipa comata*	**HECO**
Basin wildrye	*Leymus cinerus*	**LECI**
Western wheatgrass	*Pascopyron smithii*	**PASM**
Fendler bluegrass	*Poa fendleriana*	**POFE**
Sandberg bluegrass	*Poa secunda*	**POSE**
Bluebunch wheatgrass	*Pseudoroegneria spicata*	**PSSP**
Forbs		
Woolypod milkvetch	*Astragalus purshii*	**ASPU**
Northern miner's candle	*Cryptantha celosioides*	**CRCE**
Cushion (ovalleaf) buckwheat	*Eriogonum ovalifolium*	**EROV**
Spreading wallflower	*Erysimum repandum* L.	**ERRE**
Wild blue flax	*Linum lewisii*	**LILE**
Pale evening primrose	*Oenothera pallida*	**OEPA**
Sawsepal (smooth) penstemon	*Penstemon glaber*	**PEGL**
Spiny (Hood's) phlox	*Phlox hoodii*	**PHHO**
Scarlet globemallow	*Sphaeralcea coccinea*	**SPCO**
Stemless mock goldenweed	*Stenotus acaulis*	**STAC**
Wild vetch	*Vicia americana*	**VIAM**
Woody aster	*Xylorhiza glabriuscula*	**XYGL**
Shrubs		
Wyoming big sage	*Artemisia tridentata var. wyomingensis*	**ARTRW**
Four-wing saltbush	*Atriplex canescens*	**ATCA**
Gardner's saltbush	*Atriplex gardneri*	**ATGA**
Green rabbitbrush	*Chrysothamnus vicidiflorus*	**CHVI**
Winterfat	*Krascheninnikovia lanata*	**KRLA**
plains pricklypear	*Opuntia polyacantha* Haw.	**OPPO**
Weeds		
Alyssum (pepperweed)	*Alyssum alyssoides*	**ALAL**
Kochia / burningbush	*Bassia scoparia*	**BASC**
Cheatgrass	*Bromus tectorum*	**BRTE**
Lambsquarters/goosefoot	*Chenopodium album*	**CHAL**
Tansy mustard	*Descurainia pinnata*	**DEPI**
Halogeton	*Halogeton glomeratus*	**HAGL**
Povertyweed	*Monolepis nuttalliana*	**MONU**
Glandular yellow phacelia	*Phacelia adenophora*	**PHAD**
Knotweed	*Polygonum aviculare*	**POAV**
Russian thistle	*Salsola tragus*	**SATR**

CHAPTER FOUR: CONCLUSION

Investigation of reclaimed soil profiles revealed distinct differences and subtle similarities of undisturbed soils. Differences of soil morphological, chemical, physical, and biological properties within horizons occurred at all investigated depths. A horizons of undisturbed soils were thicker and coarser-textured with less occluded and more mineral-associated SOM fraction N than reclaimed soils. The upper subsurface horizons of reclaimed soils were finer-textured, more alkaline, and had less mineral-associated fraction N than undisturbed reference soils. The deepest group of horizons demonstrated higher calcite ($CaCO_3$) in undisturbed soils compared to the reclaimed profiles.

Further examination of the development of reclaimed soils over time will reveal temporary and lasting effects of drilling and reclamation activities on soil properties. Carbon sequestration rates and potential of reclaimed soils in southwest Wyoming could be discovered through further investigation. Soil formed in southwestern Wyoming under a more temperate climate than currently exists. The amount of soil development possible in a temperate climate may not be achieved under the current climatic conditions of southwestern Wyoming. Therefore, methods to accelerate soil formation could facilitate faster recovery of ecosystems and warrant additional research.

The controlled livestock treatment influenced soil and vegetation community properties of reclaimed well pads. Treatment effects were observed immediately in labile SOM pools, though they dissipated before the next sampling event. However short-lived these effects seem, the vegetation community positively responded to the treatment several months after treatment effects receded to reference levels. The plant communities of the cattle treatment plots were more diverse and dense in desirable plant species than the reclaimed reference plots. This suggests longer-term impacts of the cattle treatment are plausible.

Further research should investigate optimal stocking rates and the economic feasibility of using controlled livestock on larger scale reclamation projects. The patchy nature of the soil surface provided by the controlled livestock treatment should be examined more closely. The spatial distribution of amendments provided by livestock should be compared to mechanical means of organic amendment application as well as the islands of fertility observed in the undisturbed rangelands adjacent to natural gas development areas.

Overall, construction and reclamation of natural gas well pads influence soils to great depths. With many soil properties altered, tools to return reclaimed soils to their predisturbance state are highly desirable. Controlled livestock treatments, like the one used in this study, may accelerate that process by initiating the establishment of a more robust plant community on reclaimed soils.

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