AN EXAMINATION OF LAND PREPARATION METHODS TO ALLEVIATE COMMON ISSUES ASSOCIATED WITH PIPELINE RECLAMATION

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

Post-seeding land preparation methods can improve reclamation success; however, limited research is available for the Williston Basin. A field study evaluated four treatments: land imprinting, hydromulch, straw crimping, and the combination of hydromulch and land imprinting for their abilities to reduce simulated rainfall runoff and sediment losses and for their ability to promote plant growth. Straw crimping reduced total runoff and may likely be the best option for providing surface cover. However, vegetation establishment was found to be not significant among the treatments. Additionally, a laboratory study examined seven soils for their penetration resistances (PR) across variable water contents (Θg) and bulk densities (Bd). Overall, as Bd increased so did PR, with increases in Θg diminishing PR increases, yet still building strongly correlated relationships ($r^2 > 0.90$). These results will enable reclamation specialists to better define soil conditions and methods for improving soil water retention and overall soil function.

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DEDICATION

For my grandparents, Kermit and Marcy Hansen and Maurice and Sharon Lardy. For inspiring me to be a steward of the land.

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GENERAL INTRODUCTION

Demand for fossil fuels such as oil and natural gas has increased with growing human populations. Due to the introduction of new technologies for harvesting oil and natural gas in the Bakken and Three Forks formations of western North Dakota, production has surpassed transportation capabilities for natural gas, resulting in numerous pipeline projects across this region (US EIA, 2021). Natural gas is transported via pipelines and the installation of pipelines can result in negative environmental consequence. Pipeline right-of-ways (ROWs) often experience soil compaction, topsoil and subsoil mixing, a lack of vegetation establishment and/or increases in invasive species, and increased runoff (Johnston, 2015; Naeth et al., 1987; Naeth et al., 2020). In addition, destruction of soil structure during the construction process (Naeth et al., 1988) and lack of vegetation cover (Li & Pan, 2018) increase susceptibility to erosion. Oil and gas companies then are required to put more time and money into the reclamation process.

Pipeline installation and construction occurs as a means to transport a wide variety of commodities, including water, petroleum, and natural gas. This thesis focuses on oil and natural gas pipelines because they are the main mode of transportation for oil and natural gas in the western United States, including in North Dakota, which has nearly 48,000 km of pipelines for oil and natural gas (North Dakota Pipeline Authority, 2020). This document consists of three chapters where Chapters 2 and 3 are organized in manuscript format. Chapter 1 is a brief overview of pipeline installation, summarizing the problems associated with pipeline installation from soil, water, and plant perspectives. Chapter 1 also gives an overview of the literature known to be associated with the land preparation treatments of straw crimping, land imprinting, and hydromulching.

For many pipelines, increasing vegetation establishment would subsequently mitigate common issues associated with pipeline installation. However, North Dakota and the Williston Basin has experienced significant drought during the years 2020 and 2021. When vegetation establishment is unsuccessful, the ROW is left susceptible to increased soil runoff, erosion, and invasive species establishment. Therefore, a field study (Chapter 2) was conducted to examine the land preparation treatments of straw crimping, land imprinting, hydromulch, and the combination of land imprinting and hydromulch. The objectives were to determine how the land preparation methods influence the lag time between precipitation and initiation of runoff, total runoff as an equivalent depth, sediment load in the runoff, soil bulk density (Bd), and vegetation establishment under drought conditions. Additionally, a laboratory study (Chapter 3) was performed to describe and model penetration resistance (PR) for a variety of North Dakota soils as a function of soil metrics including Bd and gravimetric water content (Θg). The results of these studies provide land managers a better understanding of soil management practices and potential planting recommendations under specific environmental conditions.

CHAPTER 1: PIPELINE CONSTRUCTION AND THE EFFECTIVENESS OF VARIOUS LAND PREPARATION METHODS

Introduction

Oil and gas expansion is occurring at unprecedented levels in the western United States, specifically within the Williston Basin, which includes the Bakken and Three Forks formations in North Dakota (US EIA, 2021). As an example, oil production increased by over 13 times in North Dakota during the years 2006-2019 (North Dakota Department of Mineral Resources- Oil and Gas Division, 2021). Thus, infrastructure development, which is not just limited to pipeline installation and well pad construction, is necessary.

Pipeline Installation

The process of pipeline installation disturbs the soil to allow for a pipeline to safely reside beneath the soil surface. First, topsoil is stripped away from the right-of-way (ROW) and stockpiled for future reapplication (Fedkenheuer, 2000). Subsoil is then removed to the prescribed depth and stockpiled separately from the topsoil (Fedkenheuer, 2000). Once soil is removed, pipeline segments are connected and laid in the trench, which is typically at least one meter in depth (INGAA, 2022). Subsoil is then respread, followed by the topsoil. The ROW is then reseeded, typically with native vegetation in rangelands, landowner-specified perennials or crops in pasturelands and croplands, respectively. However, the soil disturbance may impact and diminish reclamation success.

Effects of Pipeline Installation

Soil Perspective

Pipelines are linear in nature, similar to roadways, with both having high edge-to-area ratios that results in habitat fragmentation, contributing to decreases in biodiversity, alterations in nutrient cycles, and limitations to key ecosystem functions (Haddad et al., 2015; Naeth et al., 2020). Issues include, but are not limited to, increased soil compaction due to heavy machinery, erosion, and mixing of topsoil and subsoil (J. Pennington, personal communication, ONEOK Inc., 2020; C. Martin, personal communication, Stealth Energy Group LLC., 2021; Naeth et al., 1987; Naeth et al., 1988; Naeth et al., 2020).

Compaction from heavy machinery is a contributing factor to the loss of soil biodiversity by reducing enzyme activity and microbial biomass, which are both important for healthy soils (Naeth et al., 1987; Nawaz et al., 2013; Stahl et al., 2002). Additional challenges often include decreases in soil organic matter due to stockpiling soil, decreases in plant available K, increases in plant available N and P and increases in soil pH and salinity due to mixing (Hammermeister et al., 2003; Anderson et al., 2008; Wick et al., 2009; Desserud & Naeth, 2013). Pipelines can also negatively impact other properties such as texture and soil temperature also due to mixing (Naeth et al., 2020).

Water Perspective

Compaction and mixing of topsoil and subsoil impact water on the landscape. This may include subsoil drainage and water holding capacity (Naeth et al., 1987). For example, soil organic matter contents are strongly associated with soil water holding capacity, macroporosity, and plant nutrient retention (Anderson et al., 2008; Bauer, 1974; Hudson, 1994). Additionally, the loss of macropores during pipeline installation likely reduces water infiltration soil water storage (Saffih-Hdadi et al., 2009; Soon et al., 2000). This results in increased runoff and susceptibility to erosion, particularly on bare soil and sloped surfaces (Batey, 2009).

Plant Perspective

Vegetative cover is key to reclamation success, as both above and belowground plant components reduce runoff and erosion (Li & Pan, 2018). Establishment of plants is necessary to help soil and organic matter stay in place, improving overall function due to said feedback loops between soil, water, and vegetation characteristics by building aggregates and improving water infiltration and holding capacities (Reynolds & Reddy, 2012; Wick et al. 2009). However, in compacted soils, root growth is limited as compaction increases (Bengough & Mullins, 1990). Shierlaw & Alston (1984) found that uptake of plant-available P, using the vanadomolybdate method, in ryegrass decreases in compacted soils as adsorption was diminished, yet the greatest impact was the reduction of root growth, with growth limited to the less compacted surface layer. Additionally, as soil dries, the soils' shear strength increases, limiting plant root elongation and the plants ability to access available water even if Bd does not change (Bengough et al., 2011; Rajaram & Erbach, 1999; Whitmore & Whalley, 2009). Some key soil issues have negative feedbacks, as low vegetation establishment decreases water infiltration and increases runoff (Reynolds & Reddy, 2012).

However, disturbed lands, such as pipelines, having high edge-to-area ratios are also susceptible to invasive species establishment such as *Bromus tectorum* L. (downy brome or cheatgrass), *Bromus inermis* L. (smooth brome), and *Poa pratensis* L. (Kentucky bluegrass) (Hansen & Clevenger, 2005; Johnston, 2015). *Poa pratensis* L. is particularly difficult to control on ROWs due to its ability to tolerate soils with high pH, which can occur when topsoil is mixed with lime-rich subsoil (Desserud & Naeth, 2013). Additionally, increases in soil N promote the establishment of invasive non-native plants and increases in weed production (Johnston, 2015; Mason et al., 2011).

Land Preparation Methods

Several land preparation methods are readily available with the goal of increasing vegetation establishment and water conservation. The methods discussed in this chapter are not exhaustive, but provide a wide sampling of various methods used in various climates across North America. The methods listed below were selected due to their use to restore large areas of rangeland.

Straw Crimping

Crimping or pinning of straw into the soil surface, whether from wheat (*Triticum aestivum*), oats (*Avena sativa*), or barley (*Hordeum vulgare*), aids to limit erosion (McLaughlin & Brown, 2006) and increase water infiltration (Jordán et al., 2010). The crimping, or pinning, of straw is done to produce a thick plant residue layer (Babcock & McLaughlin, 2019). The crimped straw slows the kinetic energy of water and thus better enables seed and sediment to remain in place better compared to non-crimped application (Jordán et al., 2010). Adams (1966) observed that a 5 cm thick application of straw without crimping reduced total runoff from 8.08 cm over a bare soil control to 0.05 cm over one year with 61.1 cm of rainfall in Texas. During that same period, soil erosion decreased from the control 4.7 Mg ha^{-1} to <0.2 Mg ha^{-1} in the straw (Adams, 1966).

Straw improves soil structure as organic matter accumulates, is a source of C for soil microbes, lowering soil N as N accumulates in microbes, reducing the likelihood of undesirable plants establishing within the ROW (Desserud & Naeth, 2013; Jordán et al., 2010; Morghan & Seastedt, 1999). During decomposition, straw may also release plant-available macronutrients such as N and K, which were reported by Christensen (1985) to be susceptible to leaching. Straw mulch is also an effective method to increase soil water content (Mollard et al., 2014; Mollard et al., 2016). For example, Mollard et al. (2014) found that both high (600 g m^{-2}) and low (300 g m^{-2}) rates for straw mulch and rangeland pasture hay, held in place using open mesh plastic wrap, had significantly higher volumetric soil water contents ($p \leq 0.05$) when compared to a bare soil control, where the high rate of straw mulch was the most effective at increasing volumetric water content. However, the low rates of straw mulch or rangeland hay (300 g m^{-2}) improved vegetation establishment in this semiarid setting when paired with broadcast seeding (Mollard et al., 2014).

Mollard et al. (2016) stated that in the northern mixed grass prairie of Canada, dry years often group together as drought, and high rates of straw mulch may help conserve water in the soil and improve plant success. As such, high rates (600 g m^{-2}) of straw mulch significantly increased volumetric water content when compared to the bare soil control for up to a year after application (Mollard et al., 2016). Thinner materials, having a smaller diameter than wheat straw (< 3 mm), such as hay at low rates will conserve less water, but may help recruit short-stature native grasses such as *Bouteloua gracilis* (Mollard et al., 2016).

Land Imprinting

Land imprinting creates many discreet V-shaped impressions into the soil surface to help retain seeds, water, soil, and plant residues, in the ROW (Dixon, 1995; Dixon & Carr, 1999). The imprinting design is to improve seed germination and plant establishment success by infiltrating and retaining more water near the seeds (Dixon & Carr, 1999; Oomes & Elberse, 1976). Similarly, microenvironments are well known to enhancing germination success (Naeth et al., 2018). Imprinting has been successful when restoring arid environments as these imprints counteract the effects of desertification (Dixon, 1990) by increasing infiltration and breaking crusted surfaces to allow for gas exchange (Dixon, 1995). However, there appears to be no published reports about land imprinting influence on the lag time for runoff to initiate, total runoff, and sediment loss.

Seeding can be completed simultaneously with the imprinting implement. Using a rangeland drill without imprinting in Arizona, Dixon & Carr (1999) observed one out of ten plantings to be successful. In contrast, seeding with imprints resulted in nine out of 10 planting to be successful. Montalvo et al. (2002) reported similar observations. Imprinting yielded higher plant densities and cover when compared to only drill seeding and hydroseeding in a study conducted near Hemet, CA.

Hydromulching

Hydromulch is a mixture of water, fiber mulch, and typically a tackifier and it is often applied using a pump and sprayer nozzle, typically at a rate between 2,250-3,350 kg ha^{-1} depending on the manufacturer and slope of treatment area (USDA-NRCS, 2012). The use of hydromulch with a tackifier to bind wood fibers together can stabilize disturbed soils, as well as reduce evaporation by reducing temperature fluctuations at the soil surface (ASWCC, 2009; O’Brien et al., 2018; Ricks et al., 2020). As a result of the binding properties of hydromulch, runoff may occur at a greater rate compared to spread straw. For example, Babcock & McLaughlin (2013) reported the time to initial runoff in plots receiving 1,970 kg ha^{-1} (low) and 2,960 kg ha^{-1} (high) of hydromulch were 17.5 and 13.8 min, respectively, whereas spread straw was 29.0 min. Additionally, the equivalent depth of runoff in the low, high, and straw plots were 23.0, 19.3, and 7.2 mm, respectively.

Reclamation specialists combine seed with the hydromulch, known as hydroseeding. Hydroseeding is an effective method that has been shown to increase vegetation establishment on sloped surfaces (Tamura et al., 2017). Tamura et al. (2017) noted the difficulty of revegetating sloped surfaces for specific plant communities, and the time required for establishment after seeding on slopes compared to more level surfaces was a factor to consider. They stated that various land preparation methods may perform better than others, which depended on the desired plant community. For example, hydroseeding was particularly successful for native plants, while imprints worked best in areas that experienced less wind erosion or with heavier seeds (Tamura et al., 2017).

Hydromulching is the costliest option as compared to straw crimping and land imprinting (Table 1). A large amount of water is required to apply hydromulch and certain ROWs may not allow access for the required equipment. This is a major limitation, as restoration often occurs on ROWs with moderate to steep slopes. Along with the high costs of applying hydromulch, there are other drawbacks too. For example, during high intensity rainfall events these mulches can fail (Benik et al., 2003) and depending on the type of hydromulch used and the rate of application they can degrade quickly (MacDonald & Robichaud, 2007).

Table 1. Costs of each method described in this chapter, provided by H2 Enterprises (Keenesburg, CO).

Cost	Straw Crimping	Land Imprinting	Hydromulch
Dollars (US) per hectare	550	445	2,600

Conclusion

Pipeline installation is occurring at unprecedented levels in the western United States. Upon completion of pipeline projects, ROWs may have issues related to compaction and erosion leading to unsuccessful vegetation establishment. Currently, a variety of land preparation methods are used with each method having varying degrees of success depending on landscape and environmental conditions. Overall, few reports are available in the scientific literature comparing the land preparation treatments of straw crimping, imprinting, and hydromulching.

Straw crimping is effective in many environments, reducing erosion and runoff. Land imprinting has seen success in arid climates and is capable of promoting vegetation establishment. Hydromulch has been shown to be one of the best erosion control tools, yet requires a large supply of water and specialized equipment. The selection of one of these methods, or alternative land preparation methods will depend on cost, soil conditions, availability of resources, and overall project goals.

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CHAPTER 2: EVALUATION OF LAND PREPARATION METHODS FOR PIPELINE RECLAMATION

Abstract

Pipeline right-of-ways (ROWs) with low revegetation success can be susceptible to increased runoff, water erosion, and invasive plant species. In the Williston Basin, land-preparation treatments have not been compared in side-by-side trials to evaluate performance for parameters such as runoff, erosion, and plant establishment. Four land-preparation treatments including wheat-straw crimping, land imprinting, wood-fiber hydromulch, and the combination of land imprinting and hydromulch were evaluated against a bare soil control in a replicated and randomized completed block field experiment near Williston, ND. Rainfall simulations were performed in September 2020 and June 2021 to examine the effectiveness of the treatments to reduce runoff and sediment losses. Vegetation establishment was also evaluated in August 2021. Wheat-straw reduced the equivalent depth of runoff by 60% as compared to the bare soil control in 2021. However, hydromulch with or without land imprinting significantly reduced sediment loads as compared to the bare soil control in both years. Vegetation establishment was not significantly different among treatments and the bare soil control using broadcast seeding, which may be due to drought conditions causing low establishment in all plots. Wheat-straw was the only treatment to significantly reduce runoff and numerically reduce sediment loads. However, all the land-preparation practices evaluated in this study may have limitations in assisting plant establishment during severe or persistent droughts.

Introduction

Due to the enhanced ability to recover oil from shale, oil production in the United States has reached record levels as recent as 2019 (US EIA, 2022b). North Dakota, as an example, between 2006-2019, had an oil production increase of 13-fold to over 524 million barrels of oil in 2019 (North Dakota Department of Mineral Resources- Oil and Gas Division, 2021), making North Dakota the second leading oil-producing state in the US since 2012 (US EIA, 2022a). The majority of this oil, natural gas, and extraction byproducts, such as produced waters, are transported via pipelines (US EIA, 2021).

In 2020, there were 48,000 km of natural gas pipelines in North Dakota (North Dakota Pipeline Authority, 2020) and is expected to increase as natural gas extraction exceeds existing pipeline capacity (US EIA, 2021). Installation of additional pipelines is also necessary for reducing natural gas losses from flaring (US EIA, 2021). Although necessary, installation of pipelines disturb large areas of land that subsequently need reclamation to return landscape functions. Typical pipelines are installed at least one meter deep, but have a ROW of 15-46 m wide (INGAA, 2022; S. Croat, Stealth Energy Group LLC., personal communication, 2022).

Post-installation, ROWs often have low vegetation establishment, are compacted, and vulnerable to erosion and invasive species encroachment (Desserud & Naeth, 2013; Naeth et al., 1987; Naeth et al., 2020). Reduced soil water content, infiltration, microbial activity, texture changes due to mixing, and greater variations in soil temperature are also related to pipeline construction or soil stockpiling (Gasch et al., 2016; Block et al., 2020; Naeth et al., 2020; Xiao et al., 2014). Loss of soil structure contributes to the susceptibility of wind and water erosion (Naeth et al., 1988) but increasing establishment of vegetation alleviates a number of these negative consequences as above and belowground biomass prevents major soil loss to erosion (Li & Pan, 2018). However, this is often challenging in arid and semi-arid environments due to spatial and temporal variability of precipitation, the occurrence of coarse-textured soils, and moderate to steep landscape slopes that are common in these regions (Bautista et al., 1996; Bochet et al., 2009; Lee et al., 2018; Ludwig et al., 2005).

Several land preparation methods have been implemented in different regions with varying success. Land imprinting, for example, has been used in arid environments (Dixon, 1990) but its use in semi-arid regions has not been documented. The use of water-applied hydromulch is effective at reducing erosion, but due to cost has limitations in many landscapes (Babcock & McLaughlin, 2013). Application of wheat (*Triticum aestivum*), oats (*Avena sativa*), or barley (*Hordeum vulgare*) straw is an option that when crimped into the soil surface can provide both a covering of soil from direct sunlight (Mollard et al., 2014; Mollard et al., 2016) and can reduce erosion (Jordán et al., 2010). The decomposition of straw also allows for the release of C, but may increase the C:N ratio in the soil that can limit plant-available N, which may be desirable to limit the establishment and growth of weed species (Desserud & Naeth, 2013; Morghan & Seastedt, 1999). However, there may be no advantage to utilizing hydromulch over straw for erosion control for increasing vegetation establishment (Lee et al., 2018).

Direct seeding into bare soil of a ROW is occasionally done, although hydromulch or straw (surface applied or crimped) is the standard practice in the Bakken and Three Forks region (S. Croat, Stealth Energy Group LLC., personal communication, 2022). However, there is a need to assess different soil preparation options post-pipeline installation to reduce runoff and erosion and enhance vegetation establishment. Therefore, the objectives of this field study were to: 1) use simulated rainfall to determine the effectiveness of straw crimping, land imprinting, hydromulching, and the combination of imprinting and hydromulch in reducing runoff and erosion, and 2) evaluate the ability of these land preparation methods to improve vegetation establishment. Results from this study will help guide reclamation specialists' best soil ROW management practices and also provide information for site preparation procedures that enhance vegetation establishment.

Materials and Methods

Site Description

This field study was conducted at the Williston Research Extension Center (WREC) near Williston, ND (48°07'18.0"N, 103°44'12.3"W), which is within the region of where oil and gas are extracted from the Bakken and Three Forks Formations. The study site is in a semi-arid region and has a 30-year average rainfall of 297 mm and an average annual temperature of 7 °C (NDAWN- Williston, 2022; NOAA U.S. Climate Normals, 2021; Peel et al., 2007). The field was comprised of a Williams- (Fine-loamy, mixed, superactive, frigid Typic Argiustolls) Bowbells (Fine-loamy, mixed, superactive, frigid Pachic Argiustolls) complex with 0-3% slope as well as a Vida- (Fine-loamy, mixed, superactive, frigid Typic Argiustolls) Zahill (Fine-loamy, mixed, superactive, frigid Typic Calciustepts) complex with 2-8% slopes (USDA-NRCS, 2019).

When treatments were established in the first week of September 2020, the area was in a D1(moderate drought) drought. Four weeks later, drought conditions worsened to a D2 (severe drought) status for 24 weeks followed by D3 (extreme drought) status for the remainder of the study period (March 16-August 10, 2021) (US Drought Monitor, 2022). The Williston, ND, North Dakota Agricultural Weather Network station, located near the study, reported 116 mm of growing-season rainfall in 2020 and 208.5 mm of growing-season rainfall in 2021. Both years were well below the 30-year average of 297 mm (Table 2) (NDAWN- Williston, 2022).

Table 2. Air temperature, rainfall, total potential evapotranspiration, and their departure from the 30-yr average for the growing season in 2020 and 2021.

		Year	
		2020	2021
Month	30-year average	Departure from 30-yr normal	
	Air temperature		
	°C		
Apr.	7	-3	-1
May	13	0	-2
June	18	1	3
July	22	0	3
Aug.	21	1	-1
Sept.	16	-1	2
	Rainfall		
	mm		
Apr.	27.7	-25.9	-20.3
May	54.4	-38.4	-18.0
June	71.9	-35.0	15.2
July	64.0	-16.5	-46.7
Aug.	44.2	-34.8	-9.9
Sept.	34.8	-33.3	-30.9
	Total Potential Evapotranspiration		
	mm		
Apr.	141.5	5.0	17.5
May	194.6	4.6	-4.0
June	200.0	22.3	59.3
July	228.5	0.3	18.1
Aug.	213.3	46.7	-15.4
Sept.	153.3	16.7	33.3

Study Design

A strip-plot design was used to randomize three blocks including treatments of a control using bare-tilled soil to resemble a ROW, wheat-straw crimping, land imprinting, wood-fiber hydromulch, and the combination of imprinting and hydromulch. However, plots receiving hydromulch within each block needed to be paired next to each other within each block due to the logistics of hydromulch application. Strip-plot design was necessary to arrange the treatments with 2% slopes across the north end of each block and 5% slopes across the south end of each block (Figure 1). Topographical maps and a construction level were used to identify 2% and 5% slopes. The strips containing each treatment were each 10 m wide, making each block 50 m wide and 115 m long. The area of the three blocks and border separations totaled approximately about 2 ha. There were 30 total plots between both slopes and among all treatments. Simulated rainfall was performed within subplots in September of 2020 and June of 2021 (Figure 1). The subplot locations used in 2020 were not reused in 2021. Vegetation establishment assessments were done in August 2021.

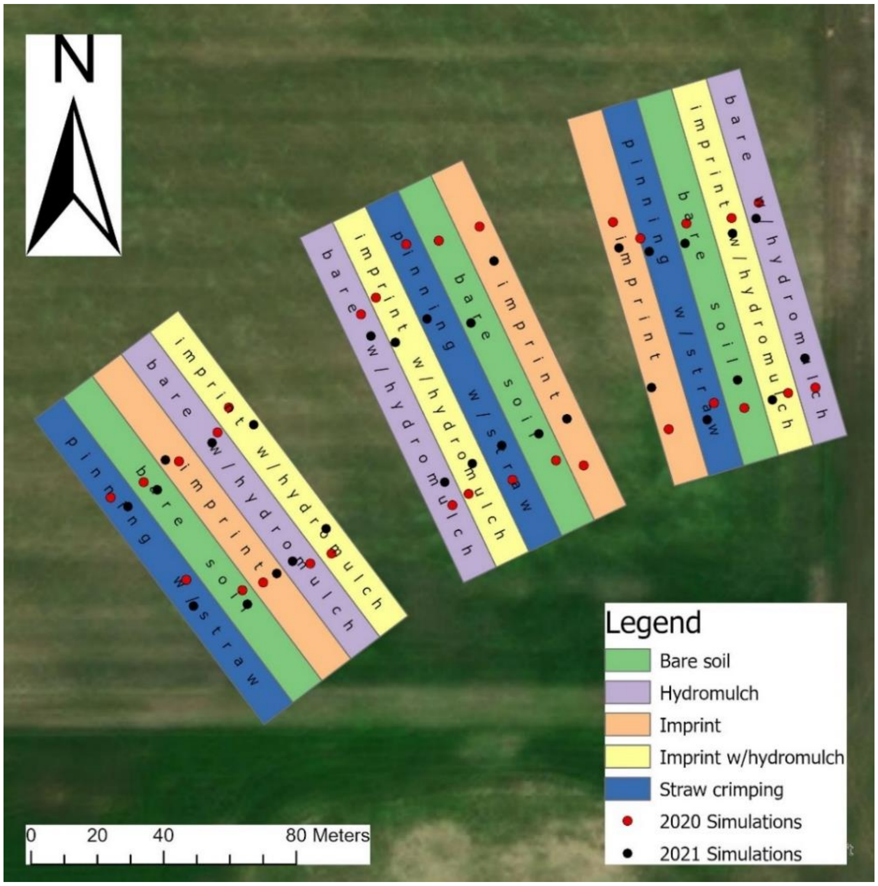

Figure 1. Study design and location of rainfall simulations. Created by Jarrett Lardy and Nate Derby.

Site Preparation

On 11 September 2020, plot establishment was completed with the assistance of reclamation specialists (H2 Enterprises, Keenesburg, CO). Prior to treatment installation the study site was managed for 12 yr as no-till and the 2020 crop was barley (K. Dragseth, personal communication, 2021). After multiple passes with a speed disk, residue cover was reduced to 20%. Then, the entire site was broadcast seeded (King Kutter® Inc., S-500 seed spreader, Winfield, AL) with oats at 11.2 kg pure live seed (PLS) ha^{-1} and a native seed mix (North Dakota Department of Trust Lands, n.d.) applied at 42.6 kg PLS ha^{-1}, which was double the recommended rate. The native seed mix contained three cool-season grasses of Rosana western wheatgrass (*Pascopyrum smithii* (Rydb.) Á. Löve) at 9 kg ha^{-1}, Revenue slender wheatgrass (*Elymus trachycaulus* (Link) Gould ex Shinners) at 5.6 kg ha^{-1}, and Lodorm green needlegrass (*Nassella viridula* (Trin.) Barkworth) at 4.5 kg ha^{-1} and one warm-season grass of Pierre side-oats grama (*Bouteloua curtipendula* (Michx.) Torr.) applied at 2.2 kg ha^{-1}. Seeds were purchased from Agassiz Seed & Supply (West Fargo, ND). After seeding, the entire site was tine harrowed to improve soil to seed contact followed by the application of treatments. Each bock has a bare soil control plot shown in Figure 2A.

Straw Crimping

Crimped straw plots had straw spread using a straw applicator (Haybuster®, Balebuster 2100, DuraTech Industries International Inc., Jamestown, ND) at a rate of 1 Mg (one bale) block, totaling three bales for the entire study. After the straw was spread it was crimped into the soil surface, shown in Figure 2B. Straw was crimped parallel to the slope using a 2.4 m wide crimper having 0.6-cm coulter blades spaced 15 cm apart, which allowed for straw to stand above the soil surface up to 15 cm.

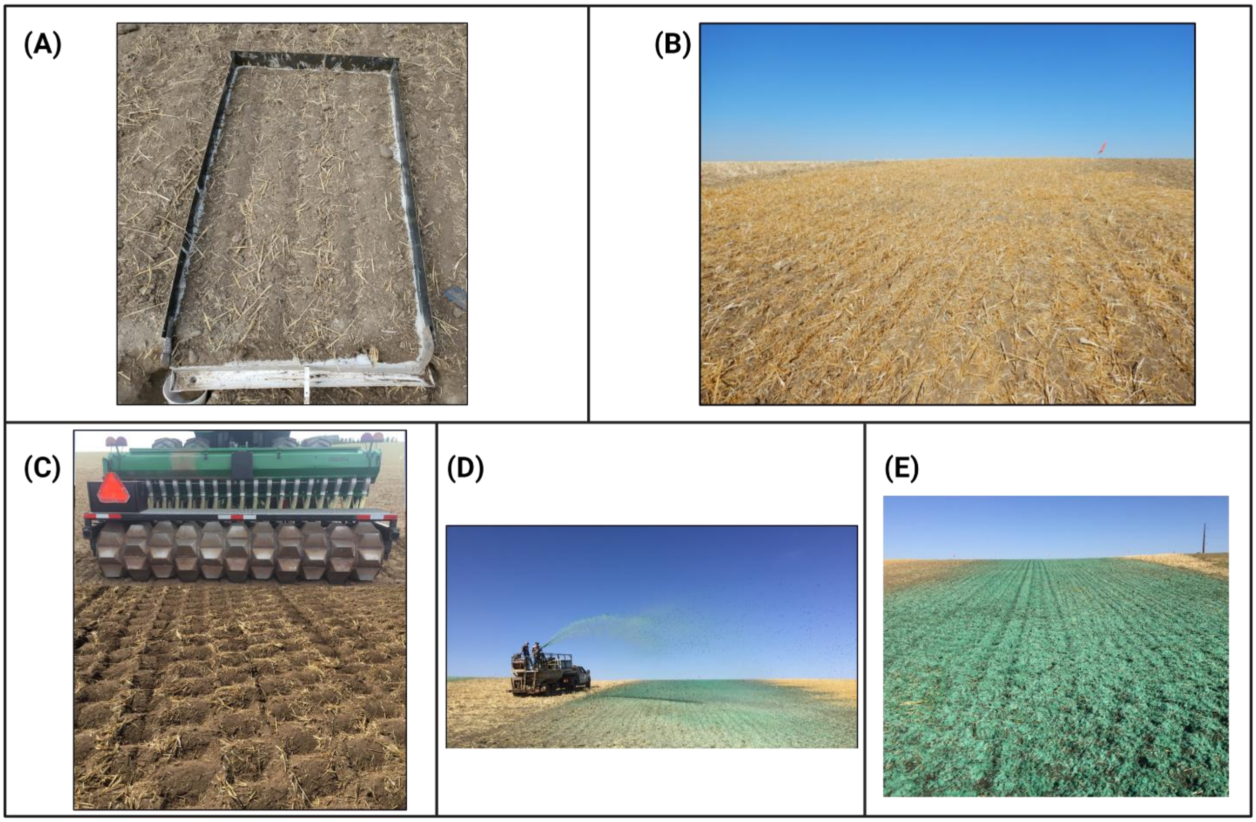

Figure 2. Land preparation treatments used for this study included A) control: bare soil, B) straw crimping, C) imprinting, D) hydromulch, and E) imprinting with hydromulch.

Land Imprinting

The imprinter was custom made by H2 Enterprise and was 3.7 m wide leaving 88 imprints each rotation. Each imprint was 20 cm wide, 28 cm long, and 9 cm deep with slopes of about 42 degrees. This imprinter is capable of leaving 20,000 imprints ha^{-1}. In front of the imprinter were ripper shanks (20 cm long and 2.5 cm wide spaced 7.5 cm apart) set to a 10 cm depth to break up the surface soil and allow for distinct imprints to form. Imprinting was done parallel to the slope until the entire plot was imprinted (Figure 2C).

Hydromulch and Imprinting with Hydromulch

Hydromulch (Figure 2D) with and without imprinting (Figure 2E) were performed. The hydromulch was a 100% biodegragable and non-toxic wood fiber hydromulch made from recycled wood fibers with Flexterra® HP-FGM™ tackifier (Profile®, Buffalo Grove, IL). The hydromulch plots with and without imprinting received the same rate of hydromulch. Thus, each strip-plot received 3,800 L of water with 136 kg of hydromulch applied with a commercial hydromulcher (Finn®, T120 Hydroseeder®, Fairfield, OH), totaling 22,800 L of water and 816 kg of hydromulch for the entire study. Water used for this study was locally sourced from the Missouri River and had a total solids content of 300 mg L^{-1} in 2020 and 150 mg L^{-1} in 2021. The combination of hydromulch and imprinting was done to evaluate if the sealing effect of hydromulch could be mitigated though the use of imprints.

Rainfall Simulation

The rainfall simulator was 1.8 m by 2.4 m and 3 m tall (Humphry et al., 2012; USDA-ARS, n.d.). A single TeeJet Technologies® cone nozzle (FL-15VS) was placed in the center of the simulator. The rain simulator was calibrated before simulations for 30 min using thirty 100-mL cups with a 6-cm diameter in a 5x6 grid formation to determine the coefficient of uniformity (Cu) (Eq 1) which was determined to be 93.6% at a pressure of 29.0 kPa (Christiansen, 1942) and within the range (greater than 80%) recommended by Mhaske et al. (2019). Perfect rainfall uniformity is equal to 100% (Mhaske et al., 2019). Coefficient of uniformity was calculated by

$$Cu = 1 - \frac{\sum_{i=1}^{n} |R_i - M|}{nM} \tag{1}$$

where *Cu* is the coefficient of uniformity (%), R_i is the amount of water in each cup (mm), *M* is the mean amount of water in all cups (mm), and *n* is the number of cups.

A downslope trench (0.25 m wide, 2 m long, and 0.25 m deep) was dug to collect runoff. Steel landscape edging (0.3 cm thick and 15 cm tall) were used to make the rainfall treatment boundaries (1.0 by 1.9 m dimensions). Rain fall simulation was performed in a 1.8 by 0.9 m area running lengthwise to the slope. Edging was pressed into the soil using hammers. Along the frame's inside edges a seal of bentonite (Enviroplug, No. 16, Wyo-Ben; Billings, MT) was utilized to keep water from exiting the sides of the rainfall areas. The downslope side was open-ended to allow runoff to flow into a collection device, shown in Figure 2A.

Similar to Kibet et al. (2014) and Babcock & McLaughlin (2013), the collection device consisted of a runoff collection trough system with a shield over the trough that allowed runoff to flow into a bucket to then be pumped out using a peristaltic pump, allowing runoff to be quantified while rain simulation occurred. A 90-degree angle of 22-ga sheet metal that was 0.9 m long and 7.6 cm for each width was inserted into a clean face of the hole 2.54 cm below ground surface. Positioned under the 90-degree angle sheet metal was a trough constructed from a commercial aluminum gutter (5KHD16RTW, Menards, Fargo, ND) fitted with end caps. At the left-hand side of the gutter a 2.54 cm hole was made. Attached to the underside of the hole, a 1.9 cm diameter PVC pipe, 4.5 cm long, was glued to funnel runoff water to enter a 2-L plastic bucket positioned below the hole. The trough was positioned under the lip of the 90-degree angle sheet metal and was set in place at a 5-degree angle towards the left-hand side of the hole. Above the trough and bucket a clear, acrylic shield (0.3 cm thick, 30 cm wide, 2.2 m long) was placed to prevent any simulated rainfall from entering directly into the runoff collection assembly. Each rain event was 30 min in duration with pressures ranging from 21-34 kPa from which 379 L of water was applied to each treatment area, which equated to a 1 in 25-yr rain event ("PF Map: Contiguous US," 2017). Tarps were also added to the sides of the simulator frame to control wind influences on the simulated rainfall pattern.

Sampling

For the duration of each rainfall simulation, total runoff was recorded as the peristaltic pump (Masterflex®, 7520-00, Cole-Parmer Inst. Co., Barrington, IL) moved runoff to graduated cylinders for quantification. Following runoff quantification, runoff was added to a rinsed and empty 121-L garbage bin. Initiation time of runoff was recorded here as well. Once all runoff was collected the water in the bin was mixed using a drill fitted with a 41-cm drywall mud/paint mixer for 1 min. Immediately after mixing two 230-mL samples were taken and after all rainfall simulations were transported to the laboratory at North Dakota State University and stored at 4.5 °C until analysis. Samples were allowed to equilibrate to room temperature, shaken to agitate sediment, and 30-mL subsamples were removed to quantify total sediment by mass after being dried at 105 °C for 24 hr. Sediment load was then calculated as mass per total runoff for each plot area, with the known solids from the water tank subtracted out. Total runoff was converted to equivalent depth of the runoff treatment area (0.9 m x 1.8 m). Cumulative runoff was recorded as each cylinder was measured and emptied while rain simulation occurred.

Soil samples (6.5 cm depth) were taken just outside the rainfall treatment area and from within the treatment area after rainfall was completed. Samples were dried at 105 ˚C for 24 hr and gravimetric water content determined. Three soil bulk density (Bd) samples were taken adjacent to the rainfall treatment areas and these samples were placed in one bag and dried at 105 ˚C for 24 hr as one sample for each treatment area. Residue cover was also determined using a meter stick and counting residue presence or absence every 1 cm, this was done at three locations outside each rainfall area and percent residue cover determined. In 2021, residue cover included vegetative cover for the growing season.

Plant data was collected in August of 2021, outside of the rainfall simulation areas. All plots were accidentally mowed prior to sampling, which left behind stubble approximately 15 cm tall. This made species identification difficult in some cases and us unable to collect total biomass production. Due to the drought conditions and accidental mowing, relative cover was chosen to assess plant cover, which was completed using 0.25 m^2 Daubenmire frames to estimate plant cover for plot. At each plot, five frames were estimated and then averaged.

Statistical Analysis

A mixed linear model was used to evaluate land preparation methods (straw crimping, imprinting, hydromulching, hydromulching with imprinting, and bare soil control), landscape slope (2 and 5%), and their interactions on time elapsed until runoff, total runoff, sediment load, gravimetric water outside of simulation area, gravimetric water inside of simulation area, residue cover, soil Bd, and relative plant cover using Proc Mixed in SAS 9.4 (SAS, Version 9.4, Cary, NC). Blocks were used as a random effect. Means were separated using Tukey-Kramer's range post hoc test with an alpha level of 0.05. Years were analyzed separately.

Results and Discussion

Slope and its interaction with land preparation method was not significant for all parameters except a slope main effect for time elapsed to runoff in 2020 and gravimetric water outside of the simulation area in 2021 (Table 3). The slope effect on time to initial runoff in 2020 is consistent with other studies, which found steeper slopes to initiate runoff earlier than shallower slopes (Cuomo & Della Sala, 2013). As an example, the initial time of runoff occurred earlier on 84% slopes than gentler 36% slopes (Cuomo & Della Sala, 2013). This same principle may explain why the 5% slopes had less gravimetric water than 2% slopes in 2021 outside the rain simulators. The gentler slope may have delayed runoff and accumulated more infiltration over the season (NDAWN- Williston, 2022), as compared to the 5% slope.

In contrast to slope, the land management practices had a significant effect on all measured parameters in 2020 and most parameters in 2021 (Table 3). The following sections describe the effects in detail.

Table 3. ANOVA table including mean values (with standard deviations) for variables of interest. Corresponding treatments were control: bare soil; straw: crimped straw into the soil surface; imprint: imprinting; mulch: hydromulch; and Im/mulch: combination of imprinting and hydromulch.

Year	Effect	Level	Time Elapsed to Runoff	Total Runoff	Sediment Load	Gravimetric Water outside simulator	Gravimetric Water inside simulator	Bulk Density	Residue Cover	Cover of All Plants
			min	cm	g L^{-1} of total runoff	g g^{-1}	g g^{-1}	g cm^3	%	%
2020	Treatment	Control	17.8 (4.1) a	0.47 (0.37) bc†	2.54 (1.09) a	0.02 (0.006) a	0.23 (0.014) abc	1.01 (0.03) ab	36.7 (14.9) b	N/A
		Straw	20.7 (3.9) a	0.36 (0.37) bc	2.37 (1.38) a	0.02 (0.002) a	0.24 (0.023) ab	1.04 (0.07) a	82.8 (11.0) a	
		Imprint	24.4 (4.0) a	0.06 (0.05) c	2.32 (0.41) ab	0.02 (0.003) a	0.24 (0.018) a	1.01 (0.04) a	27.8 (25.3) b	
		Mulch	4.6 (1.2) b	3.06 (0.78) a	0.70 (0.14) b	0.05 (0.015) b	0.19 (0.021) bc	0.93 (0.04) c	97.2 (4.4) a	
		Im/mulch	8.8 (5.7) b	1.42 (1.22) b	0.81 (0.26) b	0.04 (0.006) b	0.18 (0.043) c	0.93 (0.06) bc	88.9 (10.5) a	
		p-value	<0.01	<0.01	0.01	<0.01	0.01	0.01	<0.01	
	Slope	2%	16.9 (8.6) a	1.23 (1.37)	1.76 (1.13)	0.03 (0.016)	0.21 (0.037)	0.99 (0.06)	66.2 (30.9)	
		5%	12.9 (7.8) b	0.92 (1.22)	1.69 (1.19)	0.03 (0.012)	0.22 (0.031)	0.98 (0.07)	67.1 (34.7)	
		p-value	0.04	0.26	0.79	0.37	0.45	0.90	0.88	
	Treatment × Slope	p-value	0.45	0.99	0.16	0.95	0.99	0.38	0.58	
2021	Treatment	Control	4.5 (0.8) b	2.97 (0.45) a	2.50 (0.55) a	0.08 (0.029)	0.20 (0.023) a	1.02 (0.07)	50.0 (11.0) b	50.8 (10.0)
		Straw	9.7 (3.5) a	1.19 (0.62) b	1.29 (0.46) b	0.08 (0.013)	0.28 (0.012) b	1.02 (0.09)	86.1 (12.7) a	49.6 (5.9)
		Imprint	5.0 (0.8) b	2.73 (0.30) a	1.95 (0.73) ab	0.08 (0.020)	0.20 (0.050) a	1.05 (0.08)	50.6 (9.3) b	53.0 (7.0)
		Mulch	5.5 (2.1) b	2.07 (0.70) ab	1.35 (0.42) b	0.09 (0.027)	0.26 (0.043) ab	1.02 (0.06)	78.9 (13.8) a	47.7 (4.9)
		Im/mulch	5.9 (3.0) b	2.40 (1.08) a	1.27 (0.45) b	0.08 (0.011)	0.22 (0.053) ab	0.97 (0.07)	77.2 (6.5) a	49.8 (10.2)
		p-value	0.01	0.01	0.01	0.71	0.01	0.34	<0.01	0.77
	Slope	2%	6.5 (3.6)	2.40 (0.83)	1.55 (0.64)	0.09 (0.017) a	0.24 (0.046)	0.98 (0.05)	64.9 (17.7)	47.6 (5.3)
		5%	5.8 (1.9)	2.14 (0.96)	1.79 (0.75)	0.07 (0.018) b	0.23 (0.055)	1.05 (0.07)	72.2 (19.2)	52.8 (8.8)
		p-value	0.50	0.48	0.21	0.01	0.70	0.17	0.37	0.21
	Treatment × Slope	p-value	0.19	0.57	0.73	0.37	0.98	0.88	0.10	0.79

†Different letters indicate statistical differences within column within effect (i.e., treatment) identified by Tukey's HSD test at α = .05.

Time Elapsed Until Runoff

In 2020, treatments which initiated runoff first were the hydromulch with and without imprinting and were statistically different from the control (Table 3; Figure 3A). Straw treatments and hydromulch treatments were also significantly different from each other, with hydromulch treatments beginning runoff 16 min before straw treatments. Babcock & McLaughlin (2013) found similar results with both low (1,970 kg ha^{-1}) and high (2,960 kg ha^{-1}) applications of hydromulch as compared to straw treatments. They observed runoff in low and high hydromulch treatments to begin 11.5 and 15 min before straw treatments, respectively. Also in 2020, the trials experienced a slope effect, attributed to the increase in angle of the hillslope.

In 2021, straw crimping was the only treatment to significantly increase the amount of time observed until runoff (9.7 min) compared to the control (4.5 min) (Table 3; Figure 3B). The similarity among hydromulching, imprinting, and the control in 2021 may be attributed to the decomposition of hdromulch treatments and the settling of imprints over time, which was also observed by MacDonald & Robichaud (2007). However, the straw was still relatively in place, as supported in the residue cover (Table 3).

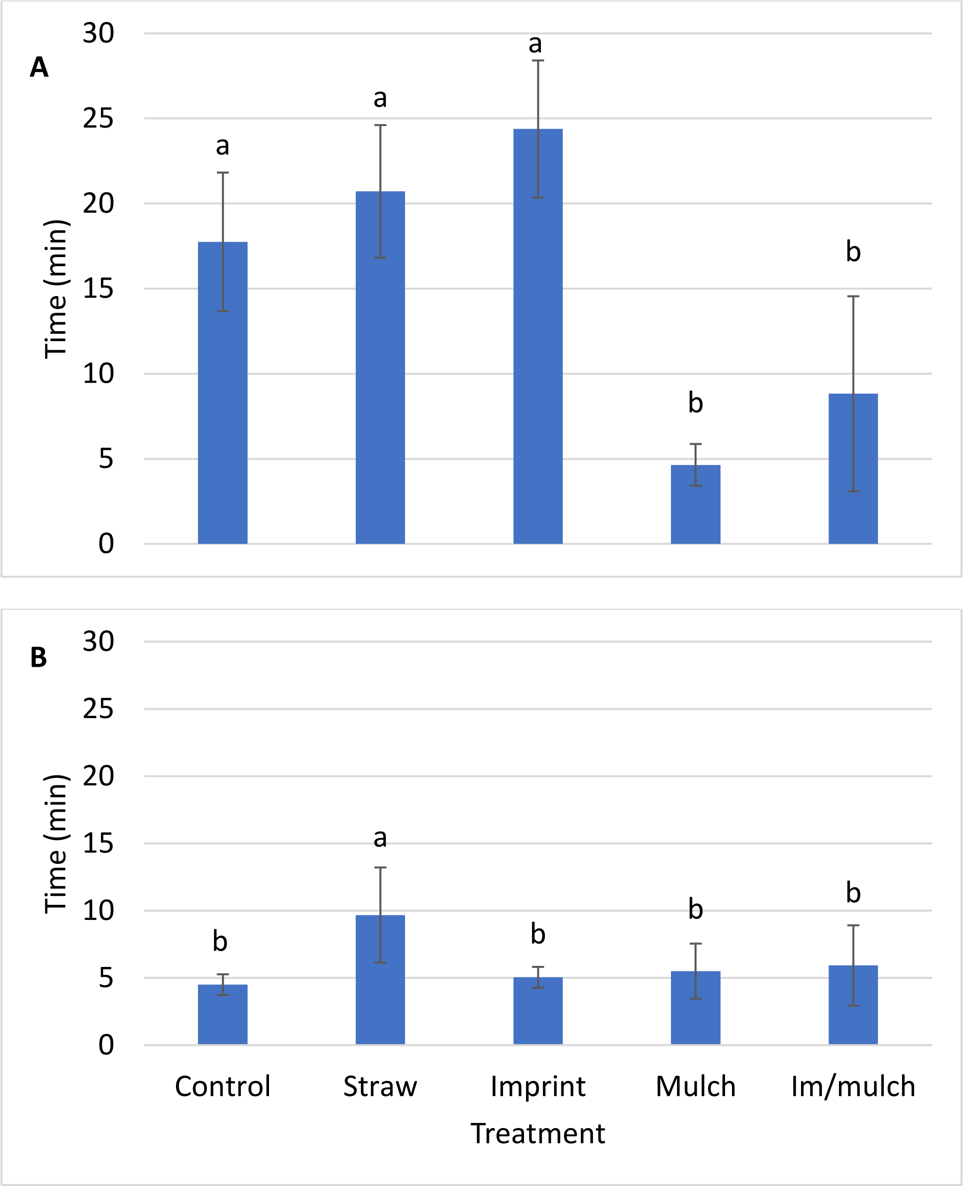

Figure 3. Time elapsed until runoff initiation (A) 2020 and (B) 2021. Error bars indicate standard deviations. Same letters within each year indicate statistical significance $p \leq 0.05$. Corresponding treatments were control: bare soil; straw: crimped straw into the soil surface; imprint: imprinting; mulch: hydromulch; and Im/mulch: combination of imprinting and hydromulch.

Total Runoff

In 2020, hydromulch treatments had significantly greater runoff (3.06 cm) compared to the control (0.47 cm) (Table 3; Figure 4A). All other treatments did not differ from the control. The combination of imprinting with hydromulch did produce significantly less runoff than hydromulch alone, suggesting that imprinting had a desirable effect of partially alleviating runoff (Table 3).

In 2021, crimped straw treatments significantly reduced runoff (1.19 cm) when compared to the control (2.97 cm) (Table 3; Figure 4B). All other treatments did not significantly differ from the control. Adams (1966) observed in a 107 cm natural rainfall, season-long field study in Texas that a 5 cm depth of straw cover, when replaced each subsequent year and held to the soil surface with a woven wire fence, reduced runoff after a year, yielding 16 cm of runoff compared to the bare soil control yielding 32 cm of runoff on 4% slopes.

The hydromulch appeared to partially degrade and reduce residue cover from 2020 to 2021 (Table 3), which likely contributed to runoff in the hydromulch treatments behaving more like the control in 2021. Degradation has been cited as a drawback to using hydromulch (MacDonald & Robichaud, 2007). A similar explanation can be used for the imprint trials, as the imprints were not visually apparent in 2021 (visual observations), likely due to high winds in excess of 160 km hr^{-1} during the winter of 2020-2021 (Table 3) redistributing soil and residue. The climactic characteristics of the study area highlight the need for more permanent cover, such as crimping straw versus simply surface applying hydromulch or straw.

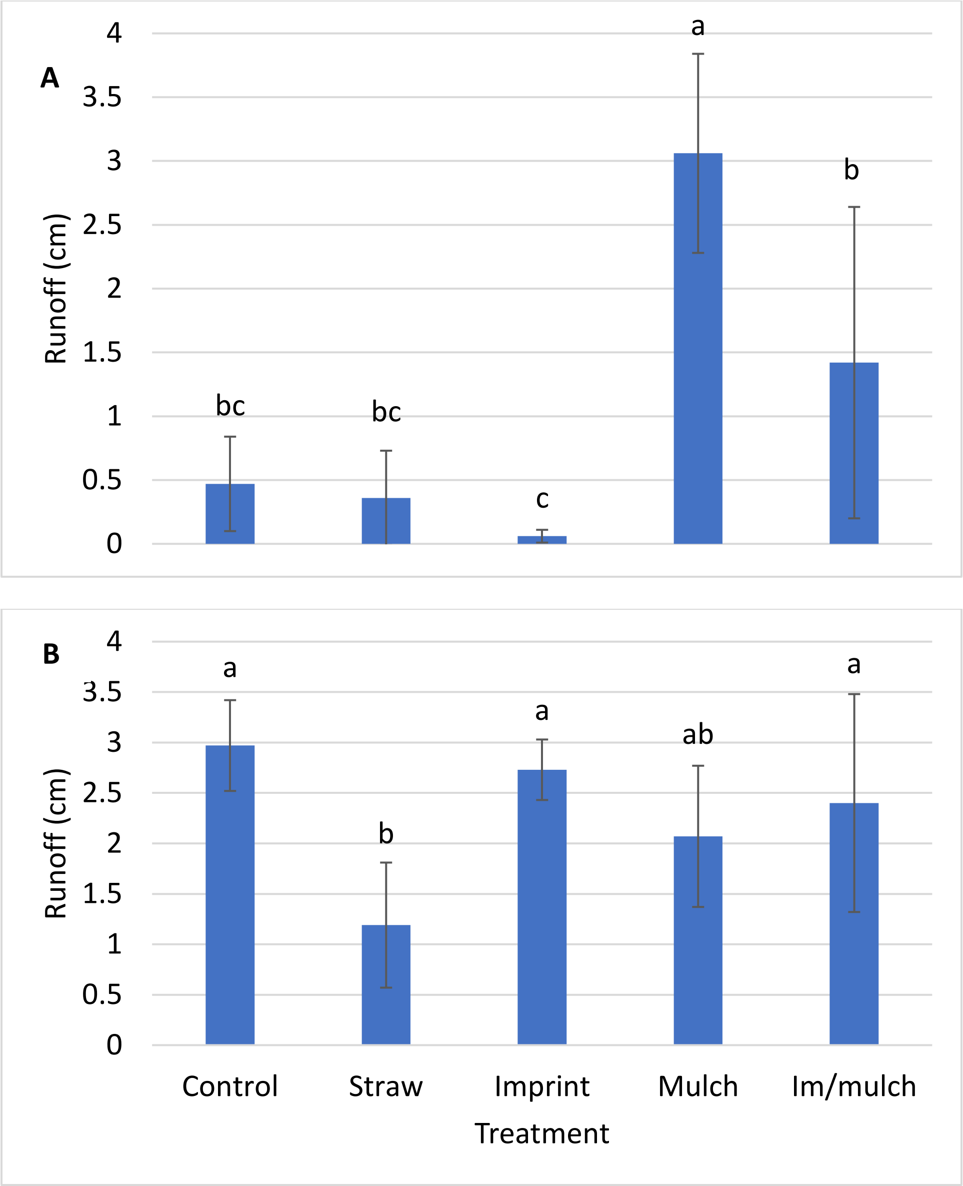

Figure 4. Mean equivalent depth of total runoff in (A) 2020 and (B) 2021. Error bars indicate standard deviations. Same letters within each year indicate statistical significance p≤0.05. Corresponding treatments were control: bare soil; straw: crimped straw into the soil surface; imprint: imprinting; mulch: hydromulch; and Im/mulch: combination of imprinting and hydromulch.

Sediment Load

Hydromulch yielded a sediment load of 0.70 g L^{-1} and the combination of imprinting and hydromulch yielded 0.81 g L^{-1}, which were both significantl reductions in sediment load when compared to the control which yielded 2.54 g L^{-1} in 2020 (Table 3; Figure 5A). Other studies found both hydromulch and crimped straw reduce sediment load (Babcock & McLaughlin, 2013; Ricks et al., 2020). Under simulated rainfall, Ricks et al. (2020) determined crimped straw treatments and wood fiber hydromulch behaved similarly and lost significantly less sediments (155 kg ha^{-1} and 199 kg ha^{-1} of soil, respectively) than a bare soil control (4,000 kg ha^{-1}) on 33% slopes. Babcock & McLaughlin (2013) also determined, under simulated rainfall that there was no difference in total sediment loss on an 32.5% slope when comparing straw and hydromulch treatments, yielding about 53 and 41 kg ha^{-1} total sediment loss, respectively. However, sediment load for our study found only hydromulch treatments (0.70 g L^{-1}) and the combination of hydromulch and imprinting (0.81 g L^{-1}) to significantly differ from the control. The crimped straw treatment (2.37 g L^{-1}) was similar to the control (2.54 g L^{-1}), contrary to both Ricks et al. and Babcock & McLaughlin (Table 3).

In 2021, treatments had similar results to 2020 for sediment load (Table 3; Figure 5B) with the exception being the crimped straw treatment that was also significantly less than the control (Figure 5B). Hydromulch and the combination of land imprinting and hydromulch both exhibited significant reductions in sediment load when compared to the control. Another study conducted in Minneapolis, MN, on about 35% slopes concluded that soil loss was ten times greater in bare control plots when compared to disk-anchored wheat straw (Benik et al., 2003). These results highlight the need for cover on a wide variety of slopes after soil disturbance to reduce soil erosion.

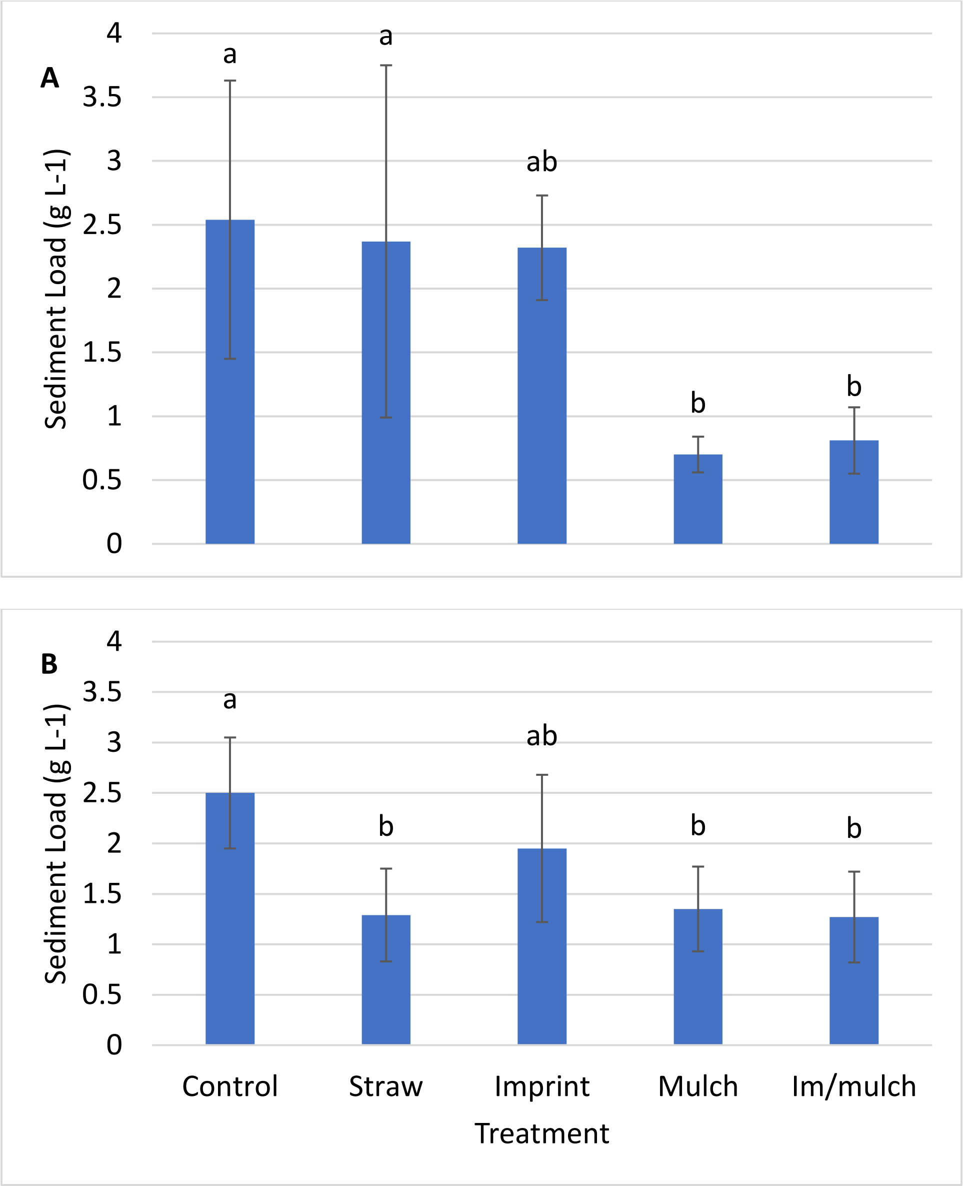

Figure 5. Mean sediment load in (A) 2020 and (B) 2021. Error bars indicate standard deviations. Same letters within each year indicate statistical significance $p \leq 0.05$. Corresponding treatments were control: bare soil; straw: crimped straw into the soil surface; imprint: imprinting; mulch: hydromulch; and Im/mulch: combination of imprinting and hydromulch.

Gravimetric Water Content

As expected in 2020, the gravimetric water outside the simulator plots that received hydromulch were statistically wetter, often twice as wet as the other treatments and the control (Table 3). This is attributed to the water that was used during the application of hydromulch.

During 2021, no land preparation treatment effect was observed, but a slope effect was evident. This is attributed to both the degradation of the treatments applied over time and the role that different slope has in water movement as previously discussed.

Inside the simulator, gravimetric water content was often lower in the hydromulch treatments with and without imprinting (Table 3), which was likely due to the sealing effect of the hydromulch in 2020. As a contrast, in 2021, the straw treatments were the only treatments to significantly increase the gravimetric water after simulations. This suggests that the crimped straw is still providing a path for water infiltration and conservation, nine months later. It is well known that straw aids in conserving soil water (Mollard et al., 2014; Mollard et al., 2016).

Residue Cover

As expected, in 2020, residue cover was highest for treatments that received any type of cover, being straw or hydromulch with or without imprinting (Table 3). Imprinting and the control both had statistically similar residues. However, in 2021 residue cover increased in both the control and imprint at nearly the same rate, possibly as plants began to establish or due to the redistribution of straw due to winds. Treatments that received hydromulch experienced degradation, as previously mentioned.

Bulk Density

In 2020, Bd varied across the treatments. Land imprinting (1.01 g cm^{-3}) and straw crimping (1.04 g cm^{-3}) had significantly greater Bd than treatments receiving either hydromulch with and without imprinting (both at 0.93 g cm^{-3}) (Table 3). Given the relatively low values reported, this difference is not likely due the machinery, with no reasonable explanation to this result being found.

In 2021, there were no treatment differences for Bd, possibly due to the decomposition of materials and settling of soil. Coarse materials readily settle, which may contribute to Bd being similar among all treatments (Mohammadshirazi et al., 2017).

Percent Plant Cover

Percent plant cover did not differ among treatments in 2021 (Table 3), which was attributed to the drought and the mowing that occurred prior to evaluations. During droughts, cool-season annual grasses typically emerge, and even increase during droughts in the northern mixed grass prairie (Hild et al., 2001). A possible reason is that annual species have higher successful establishment rates than their perennial counterparts in semiarid grasslands, particularly after disturbances (Kinucan & Smeins, 1992).

Further research should be conducted along catenas. Our study only had a small sampling of slopes (2% and 5%). Other research on the restoration of degraded arid and semi-arid lands for spatially and temporally variable lands call for the use of banded vegetation as a restoration tool (Valentin et al., 1999). Banded vegetation acts as a type of waddle or tree row depending on size, preventing erosion perpendicular to sloped surfaces across a variety of gradient changes. Crimping straw perpendicular to the slope of the ROW would be an example of banding residue rather than vegetation. Banded vegetation is found in natural environments and may provide a method to reduce runoff by catching water, as well as providing cover to prevent soil erosion.

Similarly, the use of loose rocks, or lunas, are a low-tech solution and have been shown to improve soil moisture immediately adjacent to their downslope placement and control erosion, which may aid vegetation establishment on slopes (Nichols et al., 2012). Additionally, South African grasslands have used nurse rocks to aid the establishment of shrub and woody species, as height of rocks both shades and protects soil from excessive evapotranspiration loss and wind erosion (Fujita & Mizuno, 2015). This may become important in semiarid rangelands as increasing the heterogeneity of the landscape in such ways may increase establishment success of a variety of plants of interest, not just grasses.

Conclusions

Covering the soil can aid in reducing soil losses via runoff. The use of soil-covering methods will be dictated by available resources and budgets. Wheat straw, which was crimped into the soil and is common in the study area, may be the most viable and effective option as it can be locally sourced and reduced runoff up to nine months after application. Additionally, it was the only treatment to increase gravimetric water content within the rainfall simulation areas when compared to the control in 2021, indicating the ability to infiltrate and conserve water. Although the imprinting trials were effective in the short-term at controlling runoff, their effects did not persist to the following growing season during severe drought conditions with winds periodically exceeding 160 km hr^{-1}. Unfortunately, the vegetation establishment objective of our study was not conclusive. Further evaluation of seeding preparation strategies is needed since establishment of plants is paramount to reclamation success.

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CHAPTER 3: EFFECTS OF SOIL BULK DENSITY AND WATER CONTENT ON PENETRATION RESISTANCE

Abstract

Oil and gas extraction has expanded over the past 15 years in the Williston Basin of the northern Great Plains. Infrastructure installation often disturbs soils, resulting in soil compaction (i.e., increased bulk density (Bd) and penetration resistance (PR)). This creates difficulties for reclamation specialists attempting to revegetate disturbed areas. A laboratory study was performed to determine relationships of soil Bd, gravimetric water content (Θg), and a suite of other physiochemical properties to PR. Seven topsoils from the Williston Basin were evaluated with the goal of building a simple model and database for reclamation specialists to use when assessing post-disturbance soils. Penetration resistance had a strong linear association with Bd. However, increases in Θg mediated the range of PR as BD increased. A step-wise regression model to predict PR identified Bd, Θg, electrical conductivity, pH, texture, clay speciation, and organic matter as significant factors. Predicted PR ranged from <1 to 8 MPa and closely matched measured values (r2 = 0.91; RMSE = 0.59 MPa). Soil Bd and Θg explained 84% of the models predict for PR. This study provides important tools for reclamation specialists that aid in understanding the risks associated with trafficability on soils with varying water contents. It also highlights the importance of keeping the soil at water contents high enough post-reclamation so that root penetration into compacted soils.

Introduction

The primary method by which oil and natural gas is moved from the point of extraction to processing is by pipelines (US EIA, 2021). Compaction is the most common issue after pipeline construction due to repeated loads applied to the soil (Tekeste et al., 2019). However, other problems include loss of topsoil, mixing of top and subsoil, decreases in organic matter, drainage issues, reduced soil water content, and establishment of weeds and invasive species (Culley et al., 1982; Naeth et al., 1987). Compaction often results in changes to chemical, physical, and biological processes including temperature, aeration, soil-water relations, pore size, bulk density (Bd), and penetration resistance (PR) (Panayiotopoulos et al., 1994; Soane et al., 1980). Soil PR refers to the amount of force needed to move a penetrometer into and down the soil profile. Soil PR is a function of texture, soil water content, and Bd (Vaz et al., 2001). Soil PR > 2 MPa (Murdock et al., 1993) limits root elongation and their access to water and plant nutrients (Colombi et al., 2017; Colombi et al., 2018). Measuring PR is the most commonly used test to determine root growth potential when root force cannot be measured (Bengough & Mullins, 1990). Thus, PR is a useful measurement to monitor pre- and post-construction of pipelines, particularly in semi-arid regions where soils are susceptible to rapid drying, hardening of soils, and poor vegetation establishment (Weaich et al., 1992). Knowing PR before seeding may be beneficial to determine if other land preparation methods are needed.

Within right-of-ways (ROWs), compaction often severely limits vegetation establishment and crop yields by limiting root growth and air and water movement (Arshad et al., 1996; Ehlers et al., 1983; Greene et al., 1994; Soane et al., 1980; Soane & van Ouwerkerk, 1994a; Soane & van Ouwerkerk, 1994b). Compaction affects a wide variety of properties when a load is applied to a soil (Horn et al., 1995). Decreases in porosity and water infiltration increases interparticle bonds or soil strength via friction and increasing PR (Mirreh & Ketcheson, 1972; Saffih-Hdadi et al., 2009). Dry soils during droughts have relatively high PR since soil water directly affects soil strength (Bengough et al., 2011; Rajaram & Erbach, 1999; Whitmore & Whalley, 2009). The severity and frequency of compaction issues are expected to increase as machinery weights increase across industries interacting with soil (Batey, 2009; Keller et al., 2019).

Vegetation establishment is essential for the reclamation process due to its ability to stabilize and secure soils, aid in infiltration, and reduce runoff due to the interception of raindrop kinetic energy and slowing of runoff velocity (Li & Pan, 2018). Soil measurements are typically not performed on ROWs to determine if soil is too compacted for seeding (C. Martin, personal communication, Stealth Energy Group LLC., 2022). After installation of a pipeline, an environmental assessment could prove to be beneficial to determine if conditions are conducive to seeding and successful vegetation establishment. Vegetation establishment success is expected to increase when soil physical properties such as Bd, PR, and soil water content are taken into consideration at the time of seeding. The goal of this study is to develop tools for reclamation specialists to use when beginning reclamation projects. Thus, the objectives of this study were to 1) determine the relationships among Bd, PR, and gravimetric water content (Θg) and 2) use these relationships and other common soil metrics to predict PR.

Materials and Methods

Soil Collection and Characterization

For this study, seven common topsoils (upper 15 cm) from the Bakken region in North Dakota were collected. Their general characteristics are reported in Table 4. The soils were air-dried, ground, and sieved to < 2 mm. Texture was determined following Gee & Bauder (1986), EC and pH using 1:1 soil:water slurries, and OM by loss on ignition (UW Soil and Forage Lab, 2004). Clay mineralogy was determined by XRD (Code 9 XRD, Activation Laboratories Ltd, Ancaster, ON, Canada). Clay fractions were dominated with smectite and illite and contained lower amounts of kaolinite and chlorite (Table 4).

Table 4. Physical and chemical properties of each soil.

Name	Series†	EC‡	pH‡	Sand	Silt	Clay	Texture§	Smectite	Illite	Kaolinite	Chlorite	Organic Matter‡
		dS m^{-1}		---------g kg^{-1}--------				-------------% of clay fraction------------				%
A1	Williams, Zahl	0.49	8.02	590	215	195	SL	68	22	4	5	1.8
D1	Shambo	0.29	4.39	583	247	170	SL	24	57	13	6	3.0
T1	Zahl, Bowbells	0.57	7.64	346	405	249	L	60	29	7	4	3.0
W1	Zahl	0.42	7.98	515	333	152	L	53	34	8	5	1.9
W2	Shambo	1.40	7.61	622	233	145	SL	51	27	15	7	3.0
W3	Williams, Bowbells	0.18	5.51	401	447	152	L	11	78	6	4	3.2
W4	Wabek, Appam	0.28	7.87	488	365	147	L	44	44	7	5	3.5

†Williams (Fine-loamy, mixed, superactive, frigid Typic Argiustolls), Zahl (Fine-loamy, mixed, superactive, frigid Typic Calciustolls), Shambo (Fine-loamy, mixed, superactive, frigid Typic Haplustolls), Bowbells (Fine-loamy, mixed, superactive, frigid Pachic Argiustolls), Wabek (Sandy-skeletal, mixed, frigid Entic Haplustolls), Appam (Sandy, mixed, frigid Typic Haplustolls).

‡ EC and pH determined using 1:1 soil:water slurries, Organic Matter determined by loss on ignition.

§SL: Sandy Loam; L: Loam

Water Content

Each soil was brought to six different Θg contents by adding 0.08, 0.12, 0.16, 0.2, 0.24, or 0.28 kg of water to 1.8 kg of soil. Each soil was mixed in bags and stored at 4.5 ˚C for > 72 hr. Soils were mixed three times during the 72 hr period to facilitate equilibration.

Compaction

After equilibration, soils were compacted in an aluminum cylinder with a known volume (5.6 cm height and 5.0 cm inner diameter). Three cm of soil was placed into the cylinder and compacted with a 511 g steel rod (2.8 cm diameter). This process was repeated until the soil was within 1 cm of the top of the cylinder. After which, soil was compacted using a hydraulic jack fitted with a solid stainless-steel piston with a diameter of 5.0 cm and height of 1.6 cm (Figure 6A) to acquire a gradient of soil Bd. Samples were then weighed, the depth from the top of the cylinder to the surface of the soil was recorded, and Θg accounted for to calculate Bd. For each water content, a minimum of eight samples were compressed. More samples were compressed if PR values were repeated to gain a wide variety of samples for each water content.

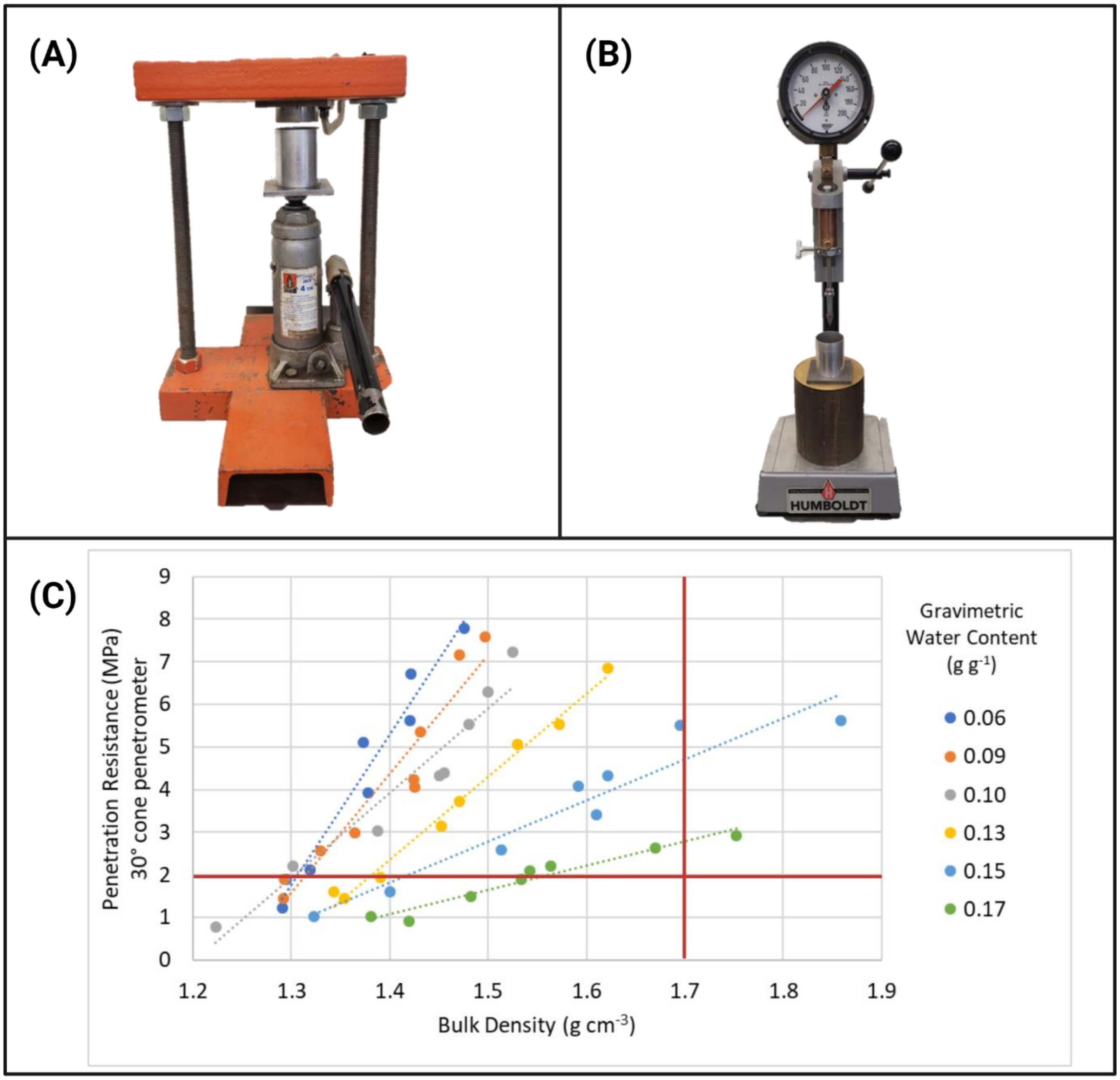

Figure 6. (A) Apparatus used to compact soils; (B) Penetrometer fitted with 30° cone; (C) Example data (W4) showing penetration resistance as a function of bulk density and gravimetric water content. Bulk density of 1.7 g cm^{-3} limits root growth (Arshad et al., 1996). PR of 2 MPa limits root growth (Murdock et al., 1993).

Assessment of Penetration Resistance (PR)

Immediately after compacting a sample, the PR was determined using a penetrometer (H-4133; Humbolt Manufacturing; Elgin, IL) refitted with an industry standard 30° cone having a height of 2.1 cm and a basal area of 1.16 cm^2 (FieldScout SC 900 Soil Compaction Meter; Spectrum Tech., Aurora, IL; Figure 6B). The cone tip was inserted 5 cm into the soil and gauge reading recorded. The penetrometer reported data in pounds in^2 (PSI), so the collected data was multiplied by 5.7 to scale data based on the basal area of the cone to convert to MPa. After PR was determined, the soil was removed from the cylinder and oven-dried at 105 °C for 24 hr. Bulk density and Θg were then determined for each sample.

Statistical Analysis

Linear regression was used to determine the relationships between Bd and PR for each Θg and soil series individually. A step-wise regression was then used to identify significant factors to predict PR across all Θg for each soil individually and across all seven soil series (JMP 15.0.0, SAS Institute, Inc., Cary, NC). Factors assessed in the step-wise regression across all seven soil series included Bd, Θg, EC, pH, sand, silt, clay, clay mineralogy, and OM. The percent contribution of each factor to the model's explained variance was determined by multiplying each factors F-value with its degrees of freedom (df) and the model's mean square error to get its sum of squares for regression, then dividing by the whole model's sum of squares for regression, and multiplying by 100. The percent contribution of Bd and Θg was 84%.

Results and Discussion

Among all soils, PR values ranged from <1 to near 8 MPa indicating a wide range of compaction that would have little or no negative impacts on root growth to inhibiting root growth completely. For each Θg, PR has a strong linear association with Bd, where 83% of the relationships having an $r^2 > 0.90$ (Table 5). All relationships having an r^2 of < 0.90 were soils at either the lowest or highest Θg. In an Australian study of sandy soils, as Θg is reduced, PR increased exponentially, possibly explaining the variability of this study's data, which was a linear model as Θg is reduced (Henderson et al., 1988). An example graphical relationship is shown in Figure 6C.

Table 5. Linear and step-wise regressions predicting penetration resistance (PR) as a function bulk density (Bd) and gravimetric water content (Θg) for each relationship, and step-wise regression predicting PR using all data collected and data within Table 4.

Name	Avg. Θg	Penetration Resistance	r^2	RMSE	Bd at 2 MPa
	g g^{-1}	MPa			g cm^{-3}
A1	6.1	= 16.54Bd-20.92	0.24	1.05	1.39
	8.4	= 18.23Bd-23.77	0.82	0.56	1.41
	10.5	= 15.77Bd-20.66	0.97	0.17	1.44
	12.4	= 16.06Bd-21.69	0.96	0.27	1.48
	15.2	= 8.09Bd-10.85	0.99	0.07	1.60
	17.1	= 3.42Bd-4.25	0.79	0.14	1.84
	All	= -14.0 – (39.95* Θg) + (14.15*Bd) + (-172.17*(-0.12* Θg)*(-1.53*Bd))	0.49	0.50	
D1	5.2	= 29.86Bd-39.30	0.88	0.76	1.39
	7.6	= 21.69Bd-27.91	0.95	0.41	1.39
	10.0	= 18.66Bd-24.20	0.97	0.35	1.41
	12.0	= 16.51Bd-21.78	0.92	0.66	1.44
	14.7	= 12.29Bd-16.92	0.99	0.25	1.54
	16.4	= 7.36Bd-10.34	0.96	0.20	1.69
	All	= -17.6 – (50.06* Θg) +(17.57*Bd) + (-195.91*(-0.11* Θg)*(-1.54*Bd))	0.78	0.48	
T1	8.3	= 27.75Bd-33.51	0.95	0.49	1.28
	10.6	= 20.56Bd-24.25	0.96	0.44	1.28
	10.7	= 22.98Bd-27.79	0.96	0.37	1.30
	13.2	= 18.11Bd-21.72	0.98	0.35	1.31
	15.8	= 10.16Bd-11.82	0.99	0.22	1.37
	18.3	= 5.27Bd-6.36	0.93	0.23	1.60
	All	= -14.7 – (43.44* Θg) +(17.00*Bd) + (-233.49*(-0.13* Θg)*(-1.41*Bd))	0.77	0.36	
W1	6.8	= 28.73Bd-38.68	0.93	0.72	1.42
	9.4	= 18.72Bd-25.33	0.96	0.35	1.46
	11.4	= 18.61Bd-26.32	0.95	0.42	1.53
	12.5	= 23.87Bd-35.83	0.95	0.50	1.59
	16.4	= 3.61Bd-5.10	0.80	0.18	1.98
	17.7	= 0.56Bd-0.40	0.22	0.06	NA†
	All	= -13.3 – (72.82* Θg) +(15.78*Bd) + (-181.11*(-0.12*Θg)*(-1.63*Bd))	0.81	0.56	
W2	10.3	= 20.44Bd-28.16	0.91	0.61	1.48
	11.3	= 15.42Bd-20.97	0.98	0.30	1.49
	12.3	= 20.62Bd-30.18	0.95	0.46	1.56
	13.8	= 17.42Bd-25.59	0.97	0.39	1.59
	14.0	= 13.12Bd-18.91	0.96	0.36	1.60
	16.7	= 5.27Bd-7.23	0.91	0.17	1.76
	All	= -12.9 – (64.39* Θg) +(15.06*Bd) + (-166.17*(-.13* Θg)*(-1.65*Bd))	0.89	0.53	
W3	5.3	= 40.94Bd-52.31	0.95	0.49	1.33
	8.2	= 22.68Bd-27.75	0.91	0.70	1.31
	10.0	= 21.71Bd-27.22	0.96	0.47	1.35
	12.0	= 23.13Bd-30.14	0.99	0.29	1.39
	14.3	= 16.13Bd-20.93	0.93	0.65	1.43
	19.0	= 3.40Bd-3.93	0.85	0.22	1.76
	All	= -19.9 – (44.19* Θg) +(19.85*Bd) +(-203.34*(-0.12* Θg)*(-1.46*Bd))	0.69	0.57	
W4	6.3	= 35.36Bd-44.20	0.96	0.54	1.31
	8.7	= 27.97Bd-34.79	0.92	0.67	1.32

Table 5. Linear and step-wise regressions predicting penetration resistance (PR) as a function bulk density (Bd) and gravimetric water content (Θg) for each relationship, and step-wise regression predicting PR using all data collected and data within Table 4 (continued).

Name	Avg. Θg	Penetration Resistance	r^2	RMSE	Bd at 2 MPa
	10.0	= 19.82Bd-23.83	0.93	0.61	1.31
	13.3	= 19.42Bd-24.82	0.99	0.24	1.38
	15.1	= 9.67Bd-11.72	0.91	0.54	1.43
	17.2	= 5.67Bd-6.86	0.95	0.18	1.57
	All	= -17.2 – (53.30* Θg) +(19.01*Bd) + ((-250.11*((-0.12* Θg)*(-1.46*Bd))	0.71	0.54	
All	All	= -6.7 – (54.08* Θg) +(16.99*Bd) +(-181.02*(Θg -0.12)*(Bd-1.53)) –(0.02*sand%) –(0.01*silt%) –(0.18*kaolinite) +(1.89*OM%)	0.91	0.59	

†NA; not available due to slope of regression line

As expected, the PR of 2 MPa, which is the threshold where root growth first becomes limited (Murdock et al., 1993), was variable across soils and Θg. Using a Bd of 1.75 g cm^{-3} as another threshold for root growth limiting conditions for sandy loam soils (Arshad et al., 1996) (applicable to the A1, D1, and W2 soils in our study), soils A1 and W2 exceeded this limit when Θg was at highest (Table 4). Similarly, for loamy soils, root growth limiting conditions may begin at Bd of 1.70 g cm^{-3} (Arshad et al., 1996) (applicable to the four remaining T1, W1, W3, and W4 soils). Soils W1 and W3 exceeding 1.70 g cm^{-3}, again at their highest Θg (Table 4). This highlights inconsistencies with broad labeling of where “limitations” associated with Bd occur across similar textures, as it fails to account for how water content influences PR and Bd.

In general, PR values reached their maximum for each soil with the lowest Θg. Vepraskas et al. (1984) noted similar results, with the maximum PR values expressed when Θg was between 0.02-0.03 g g^{-1}. Additionally, each soil type experienced lower PR values as Θg increased. Across all Θg, each soil was able to be characterized with one equation using step-wise linear regression with Bd, Θg, and their interaction (the last line in Table 5 for each soil) with r^2 values of 0.49 to 0.89 and RMSE values 0.36 to 0.54 MPa.

Lastly, on the last line of Table 5, an overall step-wise linear regression model was determined for all soil types, Bd, and Θg. This model used each of the soil properties from Table

4 as input factors to predict PR. Soil Θg, Bd and their interactions accounted for 84% of the model’s explained variance in predicting PR with each of the other factors accounting for <5% each. Another study found soil water content, soil particle roughness, and soil Bd to be the most important variables in a three-variable model using step-wise regression (Stitt et al., 1982).

Saffih-Hdadi et al. (2009) observed soils in compression tests to have both elastic and plastic phases. In their study, soils with low Bd are more prone to collapse and thus would allow a PR needle to move more easily through the soil. It is worth noting that similar results reported in terms of PR have limitations from one penetrometer to another, but the relationships noted will remain the same (Vepraskas, 1984). Additionally, plants have genotypic adaptations when encountering compaction, as such, plastic and tolerant genotypes, in sorghum (*Sorghum bicolor* L. Moench) for example, may avoid production of fine roots due to their high energy cost and decreased efficiency (Correa et al., 2022).

Unfortunately, due to lack of research on specific texture classes and mixtures of clay mineralogy, broad generalizations are commonly used by reclamation specialists to avoid excessive compaction in soils. While construction and installation of pipelines should occur on dry or possibly frozen lands to prevent compaction (Desserud et al., 2020; Neilsen et al., 1990), the reclamation process should occur with timely rain events. Studies also have reached similar conclusions where seeding should seek “Opportunistic exploitation of wet years” improving establishment success (Bakker et al., 2003). In semi-arid regions, such as within the Williston Basin, conducting reclamation during seasons of precipitation (spring and summer) may be the best management practice.

Implications

At most levels of Θg, PR was >2 MPa when Bd values were less than 1.5 g cm^{-3}. Bulk density reached greatest values at the greatest Θg, yet at high Θg still had low PR values. Reclamation success may be optimized with a model such as ours, showing potential water contents and Bd combinations that allow for potential conditions beneficial to improving root elongation. Penetration resistance can be managed by maintaining elevated Θg which can then reduce PR <2 MPa, even when Bd values are elevated. This relationship points towards the need for increasing and conserving soil water, such as by reducing evaporation via soil covers (e.g., straw, hydromulch). The results of this study are also applicable to other oil and gas related activities such as well pad and access road reclamation.

Conclusions

The main objective of this study was to identify how PR varies as a function of Bd and Θg for a variety of soils in the Williston Basin. For long-term reclamation success, pipeline installation should occur on dry soils, since they are more difficult to severely compact. However, seeding should be timed for moist soil conditions since PR is reduced. Seeding around periods of natural rainfall events or paired with irrigation will increase the chance of desirable vegetation establishment with robust root systems.

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GENERAL CONCLUSIONS

The overall goal of this research was to provide land management and reclamation specialists with improved knowledge on reducing runoff and erosion and information about plant growth limitations as PR changes with Bd and Θg. Straw crimping was shown to be an effective method to reduce runoff and erosion but in the short term was not any better than bare soil. With vegetation establishment being the overall goal, the study did not determine any “improved” method for vegetation establishment, which was likely due the difficulties of reclamation during prolonged drought.

The field-study results can be coupled with the laboratory study to assess ROWs for seeding. As an example, determining soil Bd and Θg allow for prediction of PR, which for this study is limited to loamy and sandy loam soil textures. Nonetheless this prediction can be used for viability of seeding on soils impacted by pipeline installation, and also reclamation of well pads and access roads. This laboratory data can provide users with three major conclusions. The first being that when soils are dry, increases in Bd are minimized, which suggests that the ideal time for soil disturbance is at times of low water content. The second conclusion is that when soils are wet, Bd is easily increased meaning that during and shortly after heavy rainfall events, soil disturbance should be minimized. However, seeding when the soil is wet allow for plant roots to more readily elongate and facilitate plant establishment. Lastly, PR can be predicted with reasonable confidence when Bd and Θg are measured.