FINAL REPORT FOR LINK ET AL TITLED "EFFECTS OF CROPPING SEQUENCE, TILLAGE, AND MANURE APPLICATION ON PIPELINE RECLAMATION IN WESTERN NORTH DAKOTA"

ABSTRACT

Oil and natural gas (ONG) production is expected to increase internationally over the next few decades due to its reliability and cost effectiveness. Increased volume of ONG resources being extracted and transported will require installing pipelines to support the ONG infrastructure network. Pipeline installation leads to the mixing of topsoil and subsoil, which results in changes to soil properties and long-term losses in plant productivity on reclaimed right-of-ways (ROWs). The research objectives of this study were to: 1) determine the effectiveness of five cropping sequences on restoring lost crop yields on a reclaimed pipeline ROW, and 2) investigate the effects of applying manure and deep tillage on a reclaimed pipeline ROW. Research was conducted on a reclaimed water pipeline ROW in Williston, North Dakota (USA), which was installed in the spring of 2015. Crop yields were assessed annually following each growing season between 2015 and 2020. Soil pH, electrical conductivity (EC), inorganic carbon (IOC), organic matter (SOM), penetration resistance (PR), and microbial community composition were collected to determine the impact of reclamation on those soil properties. The reclaimed ROW showed significantly lower levels of SOM compared to undisturbed sites, while pH, EC, and PR were elevated. Crop yields on the ROW produced approximately 80% of the yields of the undisturbed sites six years following reclamation. Manure and deep tillage applications had no significant effect on crop yields. The diverse cropping sequence that planted field peas (*P. sativum*) immediately following reclamation produced the highest relative yields overall,

while the cropping sequence that planted field peas two years after reclamation produced the lowest yields; continuous wheat relative yields were between these two treatments. These results demonstrate the long-term effects of pipeline reclamation activities on soil properties while providing insight into effective management practices for mitigating reclamation activity effects on crop yield.

INTRODUCTION

Oil and natural gas (ONG) exploration has greatly increased in recent decades due to the advent of horizontal drilling technology making difficult to access shale oil and gas financially viable to extract (Kelsey et al., 2015). However, increases in ONG production has put a strain on the existing infrastructures used to extract and transport these resources, creating a need to install more ONG pipelines and well pads to relieve strain on the network (Feijoo et al., 2018) and create avenues to transport this resource to new communities. The pipeline infrastructure in the United States is expected to significantly expand by the year 2040 to meet current and future energy demands driven by 1) the newfound availability unconventional ONG resources and 2) the reliability of ONG as an energy resource regardless of factors that normally impact the efficacy of renewable energy resources (Energy Information Administration, 2013).

Impacts of the expansion of ONG infrastructure will be felt most in regions where ONG resources are being extracted. The Williston Basin, an ONG bearing geologic formation underlying western North Dakota, eastern Montana, and southern Saskatchewan, has experienced extensive land use change over the last two decades during the region's most recent oil boom. Using oil well databases obtained from the Montana Board of Oil and Gas, the North Dakota Industrial Commission, and the South Dakota Department of Environment and Natural Resources and analyzed using GIS software, it has been estimated that 13,000 ha of land in the Williston Basin was directly converted to a land use associated with ONG production between 2000 and 2015 (Preston & Kim, 2016). Land conversion related to ONG extraction in the Williston Basin disproportionally impacted land managed as grassland and agroecosystems, with approximately 50% of the land converted previously being managed as such (Preston & Kim, 2016). Annual lost revenue from agricultural land conversion in North Dakota is approximately $4 million, which will increase as the ONG infrastructure footprint in the Williston Basin is expected to expand by 270% by 2050 (Preston & Kim, 2016).

The construction activities related to installing pipelines typically are conducted in a systematic fashion with the following procedures: topsoil stripping, grading, pipeline welding as needed, x-raying the pipe for faults, pressure testing, pipeline installation, backfill, topsoil replacement, and reclamation (Aaron DeJoia, personal communication, Pilgrim Construction Company, Colorado Springs, CO, 2021). Pipeline ROW width can vary depending on the diameter of the pipe being used but typically range from approximately 18 to 30 m wide (Aaron DeJoia, personal communication, Pilgrim Construction Company, Colorado Springs, CO, 2021). Topsoil surveys may be conducted to determine topsoil depth, or publicly available soil maps are used to determine topsoil salvage depths. Topsoil is stripped from the ROW during construction and is stored within the limits of disturbance and protected against erosion and subsoil mixing.

Most lands surrounding installed pipelines have three distinct sections, each comprising approximately one-third of the total ROW width, which can be classified as the spoil side, the trench line, and the working side. The spoil side is the area of topsoil and/or subsoil storage, the trench line is the area where the pipeline is installed, and the working side is where most of the vehicular traffic is conducted (Aaron DeJoia, personal communication, Pilgrim Construction Company, Colorado Springs, CO, 2021). Subsoil is then excavated from the pipeline trench until the depth sufficient for pipeline installation is reached. Subsoil is either stored opposite of the topsoil piles or adjacent with a physical barrier protecting against topsoil/subsoil mixing. Once the pipeline has been tested and installed, the reclamation process can begin. Reclamation is defined as "the construction of topographic, soil, and plant conditions after disturbance, which may not be identical to the pre-disturbance site, but which permits the degraded land mass to function adequately in the ecosystem of which it was and is a part" (Munshower, 1993). Reclamation generally consists of backfilling subsoil over the pipeline trench and seeding the ROW in a manner consistent with the intended land use.

Crop yield losses on reclaimed ROW's result from impacts of construction and reclamation activities on soil chemical and physical properties. The process of scrapping topsoil from the ROW destroys soil aggregates, thus releasing previously physically protected carbon (T) and nitrogen (N). Released soil C and N is protected while stockpiled but may be released when stockpiled topsoil is respread, resulting in losses to mineralization (Mason et al., 2011; Soon et al., 2000a) and immobilization (Soon et al., 2000b). Losses in soil C and N from mineralization and soil mixing have also been associated with decreases in total soil microbial abundance (Gasch et al., 2016).

Topsoil and subsoil are commonly mixed during construction and reclamation, meaning topsoil rich in soil organic matter (SOM) is mixed with subsoil, which in the study region is often more alkaline. Soil mixing effectively dilutes SOM through the soil profile, resulting in decreases in SOM in the topsoil when reclamation is complete (Culley et al., 1982). Alkaline material in the form of carbonates that are incorporated into the topsoil through soil mixing can limit soil nutrient availability, including increased P sorption to the soil (Soon et al., 2000a) and carbonate dissolution increasing topsoil pH (Coiffait-Gombault et al., 2012). Heavy machinery traffic on the exposed subsoil of the ROW often applies sufficient force to cause a failure of soil structure, thus collapsing soil pores and resulting in an increase in soil bulk density (Bd) (Olson & Doherty, 2012; Lupardus et al., 2019). A combination of these factors leads to losses in soil productivity on reclaimed ROWs (de Jong & Button, 1973; Culley et al., 1982; Neilsen et al., 1990; Soon et al., 2000a).

A crucial factor in improving reduced yields on reclaimed ROWs is understanding how reclamation activities have altered the soil system. Previous research on the impacts of pipeline reclamation projects has focused on soil physical and chemical properties, as soil compaction and changes in soil chemical properties resulting from soil mixing are common problems on ROWs (de Jong & Button, 1973; Culley et al., 1982; Neilsen et al., 1990; Soon et al., 2000a; Tekeste et al., 2019). Research is limited regarding the effects of pipeline reclamation projects on soil microbes, and the reported effects are mixed. Losses in organic C and N associated with topsoil from soil mixing have been shown to decrease soil microbial abundance on reclaimed ROWs (Gasch et al., 2016). Increases in topsoil organic carbon following carbonate incorporation into the topsoil from soil mixing have been shown to increase soil microbial abundance on reclaimed ROWs (Soon et al., 2000a). Better understanding the effects of pipeline reclamation projects on the soil microbial community can provide insights into how this soil component plays into a successful reclamation project (Farrell et al., 2020), therefore further research ought to be conducted to meet this end.

With regards to reclaimed ROWs, research regarding crop performance post-reclamation is limited. The majority of studies that pertain most closely to the northern Great Plains region have investigated corn (*Zea. mays*) (Culley & Dow, 1988; Neilsen et al., 1990; Shi et al., 2015; Tekeste et al., 2020), barley (*Hordeum vulgare*) (Soon et al., 2000a), soybeans (*Glycine max*)

(Culley et al., 1982), and winter wheat (*Triticum aestivum*) (Culley & Dow, 1988), all of which have shown depressed yields on pipeline ROWs compared to adjacent undisturbed land. Although immediate yield declines are quite common post construction, previous research suggests that crop yields are partially restored over time through soil nutrient pools naturally rejuvenating (Soon et al., 2000b). However, these yields rarely if ever return to pre-disturbance levels (Culley & Dow, 1988). Thus, reclamation goals should address soil nutrient and bulk density (Bd)/compaction concerns, which can potentially be achieved through the application of diverse cropping sequences. For example, planting crops that restore soil N pools through fixing atmospheric N can boost soil N content and choosing crops that have a taproot or robust root system can break up soil compaction and produce high yields despite soil disturbance (Culley et al., 1982; Culley & Dow, 1988).

Research is also limited on land preparation strategies prior to seeding. Applying deep tillage on reclaimed pipeline ROWs can improve soil growing conditions by breaking up soil compaction and decreasing Bd and penetration resistance (PR) (McConkey et al., 2012). Pipeline ROWs where deep tillage has been applied to lower elevated soil Bd and PR have been shown to produce greater corn and soybean yields than those that do not (Tekeste et al., 2020). Addressing issues related to reductions in soil nutrient contents on reclaimed ROWs can be addressed through applying organic amendments like manure and compost that provide readily mineralizable C and N to soil microbes (Larney et al., 2003). Applying organic amendments can also provide a surplus of nutrients, which has been shown to increase the stable pool of SOM over the long-term (Larney et al., 2012). A combination of these treatments could potentially resolve compaction and soil nutrient issues on reclaimed ROW’s, thereby providing additional tools for stakeholders to apply to achieve reclamation goals. Therefore, this paper studies the effects of five six-year cropping sequences on restoring depressed crop yields on a reclaimed pipeline ROW in western North Dakota. Three tillage treatments, including no-till, deep tillage, and surface manure application followed by deep tillage, were also assessed in this study. The objectives of this paper are three-fold: 1) measure the effects of pipeline reclamation activities on soil properties; 2) assess the effectiveness of five cropping sequences in recovering lost crop yields on a reclaimed pipeline ROW over time; and 3) determine if deep tillage and surface manure application followed by deep tillage can improve crop yields on a reclaimed pipeline ROW. Although the below study was performed on a rural water pipeline, given that the installation procedures are identical, the results of our study are transferable to pipelines installed to support ONG industries.

METHODS

This study was conducted at the Williston Research Extension Center (WREC) (48°13’88.7”N, 103°73’83.1”W) from May 2015 to September of 2020. The soils on the study site were classified as Williams-Bowbells loams, 0-3% slopes (USDA-NRCS, 2022). The Köppen-Geiger Climate Classification for the study region is BSk, denoting a semi-arid climate with a mean annual temperature less than 18°C (Kottek et al., 2006). Departures from 30-year average air temperature, 30-year total precipitation, and 26-year average Penman PET are reported for each month across all six growing seasons in this study in Table 8.

Table 1: Growing season 30-year average air temperature and rainfall at Williston, ND (National Oceanic and Atmospheric Administration Regional Climate centers, xmACIS, 1991-2020). The 26-yr potential evapotranspiration (PET) values were obtained from the Williston, ND reporting station within the North Dakota Agricultural Weather Network (NDAWN, 2015-2020).

		------------------Year------------------					
Month		2015	2016	2017	2018	2019	2020
	30-yr average air temperature (1986-2015)	Departure from 30-yr average					
		--------------------------------°C--------------------------------					
April	43.1	1.5	1.8	1.1	-7.5	0.3	-4.8
May	54.1	-1.3	2.2	3.4	6.4	-3.2	1.4
June	63.8	2.6	3.6	2.9	3.5	0.8	2.8
July	70.3	2.1	1.1	6.6	0.1	-0.4	0.6
August	68.8	1.8	1.3	-0.9	-0.4	-0.8	3.9
September	57.9	2.9	1.6	0.4	-3.2	0.6	0.6
	30-yr average rainfall (1986-2015)	Departure from 30-yr average					
		-------------------------------------mm----------------------------					
April	27.7	-20.8	21.8	-15.0	-15.5	-9.40	-25.4
May	56.9	-10.7	-10.9	-32.0	-18.8	-28.7	-33.5
June	65.5	-17.3	-18.8	-32.8	10.9	2.03	-24.6
July	64.8	-25.4	-4.06	-44.7	11.4	17.3	-2.29
August	37.6	-15.0	-26.2	57.2	-20.6	12.2	-26.9
September	26.9	29.5	63.0	19.6	10.2	178	-22.4
	26-yr average potential evapotranspiration (1990-2015)	Departure from 26-yr average					
		-------------------------------mm----------------------------					
April	120	18.3	-4.57	-16.3	-17.0	-3.30	3.56
May	158	-0.51	8.13	28.2	1.02	-15.5	4.06
June	164	7.62	28.7	45.5	-1.02	0.00	18.5
July	188	1.27	-21.8	33.8	-16.0	-25.7	-4.83
August	177	-0.51	12.7	-25.7	-21.1	-26.2	35.1
September	132	0.00	-24.1	-21.8	-31.5	-42.2	13.2

In the spring of 2015, a 0.9-m diameter water pipeline was installed by North Dakota's Western Area Water Supply Authority. The pipeline was oriented north to south and ran for 2.4 km under agricultural land that was previously managed as a long-term no-till dryland system. The soils at the site were mapped as Williams-Bowbells loams, 0 to 3 percent slopes (USDA-NRCS, 2022). The construction ROW extended approximately 30 m wide, resulting in approximately 7.2 ha of agricultural land being disturbed. The ROW was prepared by scraping the top 30 cm of soil (defined as the topsoil layer) and storing it in piles adjacent to the ROW. Subsoil (defined as the soil 30 cm or deeper in the soil profile) was excavated to prepare the trench for the pipeline. Subsoil was repacked into the trench following pipeline installation and topsoil was respread across the ROW, completing the reclamation process in May of 2015. The site was returned to no-till dryland management in the growing season immediately following reclamation.

The study site was divided into three unique disturbance zones: the pipeline trench, the roadway on the ROW west of the pipeline trench, and a section of undisturbed agricultural land located 75 m west of the roadway which was used as a control site. Research plots measuring 15 m by 5 m were established on each disturbance. A total of five 6-year cropping sequence treatments (T) were tested (Table 9). The cover crop mix was composed of field pearl millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor*), sudan grass (*Sorghum x drummondii*), turnip (*Brassica rapa*), radish (*Raphanus sativus*), burseem clover (*Trifolium alexandrinum*), sunflower (*Helianthus*), soybean (*Glycine max*), cow field pea (*Vigna unguiculata*), flax (*Linum usitatissimum*), hairy vetch (*Vicia villosa*), phacelia (*Phacelia tanacetifolia*), mammoth red clover (*Trifolium incarnatum*), and Italian ryegrass (*Lolium multiflorum*). This cover crop mix was used in a previous experiment at the Williston Research Extension Center and was implemented in this experiment as the mix was already available to the research team. Durum wheat and safflower were planted across all plots in 2019 and 2020, respectively, to gauge the effects of each treatment on crop yields (Table 9).

Table 2: Description of the levels of main effects of analysis. Below the descriptions of all main level effects are more details descriptions of the Cropping Sequence (T) and Sub-Treatment (S) effect levels.

Effect	**Levels**					
(**Y**) Year	2015	2016	2017	2018	2019	2020
(D) Disturbance	Undisturbed		Roadway		Pipeline	
(T) Cropping Sequence	T1	T2	T3	T4	T5	
(**S**) Sub-Treatment	S1	S2	S3			

Cropping Sequence Code (T)	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
T1	HRSW	Durum	Durum	Durum	Durum	Safflower
T2	HRSW	Peas	Barley	Safflower	Durum	Safflower
T3	Peas	Barley	Safflower	Durum	Durum	Safflower
T4	CC Mix	Durum	CC Mix	Durum	Durum	Safflower
T5	HRSW	CC Mix	Durum	CC Mix	Durum	Safflower

Sub-Treatment Code (S)	**Tillage**
S1	No-Till
S2	Deep-Tillage
S3	Deep Tillage with Manure

All plots were divided into three 5 m * 5 m subplots to apply tillage sub-treatments (S) (Table 9) in April of 2017 prior to planting. Subplots were randomly applied with one of the three sub-treatments. No-till plots (S1) served as the sub-treatment control. Subplots where deep tillage (S2 and S3) was applied were ripped to a depth of 60 cm. Subplots where deep tillage and manure (S3) were applied had beef cattle (*Bos taurus*) manure spread by hand prior to ripping at a rate of 28 Mg ha^{-1}. Manure provided the system with organic C at a rate of 8000 kg ha^{-1} and first year plant available N at a rate of 91 kg ha^{-1}. Treatments were fertilized with N, P, and K starting in the 2016 field season using soil samples from the previous growing season to determine application rates. Inoculum was applied to promote rhizomatous bacteria growth for T2 and T3 when field peas were planted. Nitrogen-N, phosphorous (P), and potassium (K) were applied as recommended for each crop at the start of the growing season. A 45 kg ha^{-1} N credit was applied to plots planted with field peas the year prior when performing fertility calculations.

Plots planted with annual cash crops were harvested annually to the full length of the plot (15 m in 2015 and 2016, and 5 m in 2017 through 2020) using a 1.5-m wide plot combine. Harvested grains and seed were air-dried for 72 hr and percent moisture content was determined. Dried grain was then passed through a dockage tester to remove subpar grain and foreign material from the sample. The processed grain was weighed, and the weight was divided by the size of the area harvested to determine the grain yield. Percent protein content was determined for HRSW, durum, barley, and field peas using near-infrared spectroscopy, and oil content was determined for safflower using nuclear magnetic resonance spectroscopy. Cover crop biomass was harvested by hand from a 1-m^2 area from each plot, dried at 60 °C for 48 hr and weighed.

All soils data were collected following harvest in September of the years listed. Soil PR data was collected using a static cone penetrometer in 2016, 2017, and 2019 (CTS-1000, Amity Technology, Fargo, ND). Samples used to determine soil texture were collected in 2017. Samples collected in 2020 were analyzed to determine SOM, soil inorganic carbon (IOC), electrical conductivity (EC), and potential hydrogen (pH). Soil organic matter content was determined through loss-on-ignition, IOC was determined through finding calcium carbonate equivalent percentage, EC was determined through the 1:1 soil/water method, pH was determined through the 1:1 soil/water method. Microbial community composition was determined through phospholipid fatty acid analysis (PLFA) (Microbial ID, Newark, DE). Soil samples were collected using a truck mounted Giddings hydraulic soil coring machine using a tube approximately 5-cm in diameter (Giddings Machine Company, Windsor, CO). Soil OM, IOC, EC, pH, microbial community composition, and texture data were collected from the 0-15 cm depth, and soil PR data were collected for the 0-30 cm depth. Soil OM, IOC, EC, and pH samples were collected for all treatments and sub treatments on each disturbance on three of the four replicants, and PLFA samples were collected from three reps of T1, T2, and T5 on the S2 and S3 soil treatments.

DATA ANALYSIS

Relative crop yields and protein content on reclaimed sites were analyzed by dividing the yield of a plot on the pipeline or roadway by the yield on corresponding undisturbed plot, providing a ratio of pipeline/undisturbed or roadway/undisturbed yield. Soil metrics for each plot were left unadjusted.

Pearson correlation was used to determine if different metrics on the roadway and the pipeline were correlated with each other. Data compared with Pearson correlation were all collected in 2020 to directly compare safflower yield, EC, pH, IOC, OC, total microbial abundance, gram+/gram- ratio, AMF abundance, gram- abundance, eukaryote abundance, fungi abundance, gram+ abundance, and actinomycete abundance. The absolute value of Pearson's r correlations are described as follows: very weak (r=0.00-0.19), weak (r=0.20-0.39), moderate (r=0.40-0.59), strong (r=0.60-0.79), and very strong (r=0.80-1.00). Linear regression analysis was performed between metrics to determine if correlations were significant. Correlations were considered significant if p determined by linear regression was < 0.05.

Data analysis was conducted using the R statistical analysis software (R Core Team, 2021). Kruskal-Wallis non-parametric tests were used to determine if significant differences existed within and between the levels described in Table 9. Soil metrics were only assessed between disturbances in the year that they were collected. Wilcoxon Rank-Sum tests were used following a significant Kruskal-Wallis test to determine which levels significant differences existed between. Kruskal-Wallis and Wilcoxon Tests were run using the rstatix package (Kassambara, 2020). Results were considered statistically significant at the level $p<0.05$.

RESULTS

DATA CORRELATIONS

Correlations between crop yield and soil properties on the roadway in 2020 are reported in Table 10. Safflower yield and soil EC were not correlated with any other analyzed soil properties on the roadway. Soil pH was moderately positively correlated AMF abundance (r=0.604) and moderately negatively correlated with SOC (r=-0.577). Soil inorganic carbon was strongly negatively correlated with SOC (r=-0.797). Total microbial abundance was strongly negatively correlated with actinomycete abundance (r=-0.666). The gram+/gram- ratio was strongly negatively correlated with AMF abundance (r=-0.634), gram- bacteria abundance (r=-0.755), moderately negatively correlated with eukaryote abundance (r=-0.477) and strongly positively correlated with actinomycete abundance (r=0.914), and moderately positively correlated with gram+ bacteria abundance (r=0.584). Arbuscular mycorrhizal fungi was moderately negatively correlated with actinomycete abundance (r=-0.561) and moderately positively correlated with gram- bacteria abundance (r=0.511). Gram- bacteria abundance (r=-0.498) and eukaryote abundance (r=-0.513) were moderately negatively correlated with actinomycete abundance.

Fungi abundance was strongly negatively correlated with gram+ bacteria abundance (r=-0.615) and actinomycete abundance.

Table 10: Pearson's r correlations between safflower yield (Yield), EC, pH, IOC, OC, total microbial abundance (Total), gram+/gram- ratio (G+/G-), AMF abundance (AMF), gram- abundance (G-), eukaryote abundance (Euk), fungi abundance (Fungi), gram+ abundance (G+), and actinomycete abundance (Act) on the roadway in 2020.

	Yield	EC	pH	IOC	OC	Total	G+/G-	AMF	G-	Euk	Fungi	G+	Act
Yield	-												
EC	-0.088	-											
pH	0.192	-0.161	-										
IOC	-0.230	0.145	0.434	-									
OC	0.086	-0.066	-0.577*	-0.797**	-								
Total	0.099	-0.393	0.046	-0.084	0.264	-							
G+/G-	0.073	-0.045	-0.048	-0.106	0.079	-0.424	-						

AMF	0.384	-0.068	0.604 *	0.156	-0.267	0.422	-0.634 *	-					
Gram-	-0.104	0.180	0.027	-0.026	-0.019	-0.019	-0.755 **	0.511 *	-				
Euk	-0.152	-0.097	-0.314	-0.007	0.040	0.438	-0.477 *	0.113	0.265	-			
Fungi	0.043	-0.118	0.002	0.167	-0.138	0.398	-0.413	0.158	-0.224	0.172	-		
G+	-0.149	-0.197	-0.070	-0.029	0.199	0.063	0.584 *	-0.347	-0.335	-0.296	-0.615 *	-	
Act	0.111	0.158	0.006	-0.168	0.068	-0.666 *	0.914 **	-0.561 *	-0.498 *	-0.513 *	-0.577 *	0.413	-

*=p<0.05; **=p<0.001

Correlations between crop yield and soil properties on the pipeline in 2020 are reported in Table 11. Safflower yield was moderately negatively correlated with EC (r=-0.546) and IOC (r=-0.571), and moderately positively correlated with OC (r=0.581) and actinomycete abundance (r=0.408). Soil EC was moderately negatively correlated with soil pH (r=-0.532) and moderately positively correlated with IOC (0.539). Soil inorganic carbon was very strongly negatively correlated with OC (r=-0.862), strongly negatively correlated with the gram+/gram- ratio (r=-0.617) and actinomycete abundance (r=-0.670), strongly positively correlated with AMF abundance (r=0.710), moderately positively correlated with total microbial abundance (r=0.563) and eukaryote abundance (r=0.608). Soil organic carbon was strongly negatively correlated with AMF abundance (r=-0.652), moderately negatively correlated with total microbial abundance (r=-0.468) and eukaryote abundance (r=-0.568), and moderately positively correlated with actinomycete abundance (r=0.646). Total microbial abundance was strongly negatively correlated with actinomycete abundance (r=-0.787) and the gram+/gram- ratio (r=-0.664), strongly positively correlated with AMF abundance (r=0.703) and eukaryote abundance (r=0.623). The gram+/gram- ratio was strongly negatively correlated with AMF abundance (r=-0.647), gram- bacteria abundance (r=-0.652), eukaryote abundance (r=-0.612), and fungi abundance (r=-0.621), very strongly positively correlated with actinomycete abundance (r=0.919), and moderately positively correlated with gram+ bacteria abundance (r=0.499). Arbuscular mycorrhizal abundance was strongly negatively correlated with actinomycete abundance (r=-0.690), and moderately positively correlated with gram- bacteria abundance (r=0.503) and eukaryote abundance (r=0.512). Gram- bacteria abundance was moderately negatively correlated with actinomycete abundance (r=-0.491). Eukaryote abundance was strongly negatively correlated with actinomycete abundance (r=-0.695), moderately negatively correlated gram+ bacteria abundance (r=-0.555), and strongly positively correlated with fungi abundance (r=0.645). Fungi abundance was strongly negatively correlated with gram+ bacteria abundance (r=-0.760) and actinomycete abundance (r=-0.667).

Table 11: Pearson's r correlations between safflower yield (Yield), EC, pH, IOC, OC, total microbial abundance (Total), gram+/gram- ratio (G+/G-), AMF abundance (AMF), gram- abundance (G-), eukaryote abundance (Euk), fungi abundance (Fungi), gram+ abundance (G+), and actinomycete abundance (Act) on the pipeline in 2020.

	Yield	EC	pH	IOC	OC	Total	G+/G-	AMF	Gram-	Euk	Fungi	Gram+	Act
Yield	1.000												
EC	-0.546*	1.000											
pH	-0.052	-0.532*	1.000										
IOC	-0.571*	0.539*	0.136	1.000									
OC	0.518*	-0.299	-0.281	-0.862**	1.000								
Total	-0.378	-0.013	0.285	0.563*	-0.468*	1.000							
G+/G-	0.353	-0.170	-0.045	-0.617*	0.576*	-0.664*	1.000						

AMF	-0.440	0.190	0.425	0.710**	-0.652*	0.703*	-0.647*	1.000					
Gram-	-0.155	0.289	-0.223	0.467	-0.276	0.338	-0.652*	0.503*	1.000				
Euk	-0.460	0.220	0.213	0.608*	-0.568*	0.623*	-0.612*	0.512*	0.057	1.000			
Fungi	-0.138	-0.105	0.104	0.223	-0.372	0.432	-0.621*	0.147	-0.141	0.645*	1.000		
Gram+	-0.057	0.238	-0.114	-0.064	0.167	-0.132	0.499*	0.015	0.049	-0.555*	-0.760*	1.000	
Act	0.408	-0.226	-0.060	-0.670*	0.646*	-0.787**	0.919**	-0.690*	-0.491*	-0.695*	-0.667*	0.305	1.000

***=**p<0.05; **=p<0.001

SOIL CARBON, pH, EC, AND TEXTURE

Evidence of soil mixing resulting from pipeline installation was evident six years following reclamation, as is shown in Table 12. Soil OM levels were significantly greater on the undisturbed and the roadway sites compared to the pipeline. Soil IOC, pH, and EC were elevated on both disturbed sites compared to the undisturbed, and the pipeline had significantly greater levels of IOC, pH, and EC than the roadway. Clay content was significantly lower on the pipeline than the undisturbed, and clay content on the roadway was not significantly different from either other disturbance. Silt content on both disturbed sites was significantly greater than the undisturbed, and sand content on both disturbed sites was significantly lower than on the undisturbed. We did not find a significant effect of cropping sequence or tillage on measured soil properties.

Table 12: Differences in soil organic matter (SOM), inorganic carbon (IOC), pH, electrical conductivity (EC), and soil texture (%Clay, %Silt, and %Sand) between disturbed sites from the 0-15 cm depth interval. OM, IOC, pH, and EC data were collected in 2020, and soil texture data were collected in 2017.

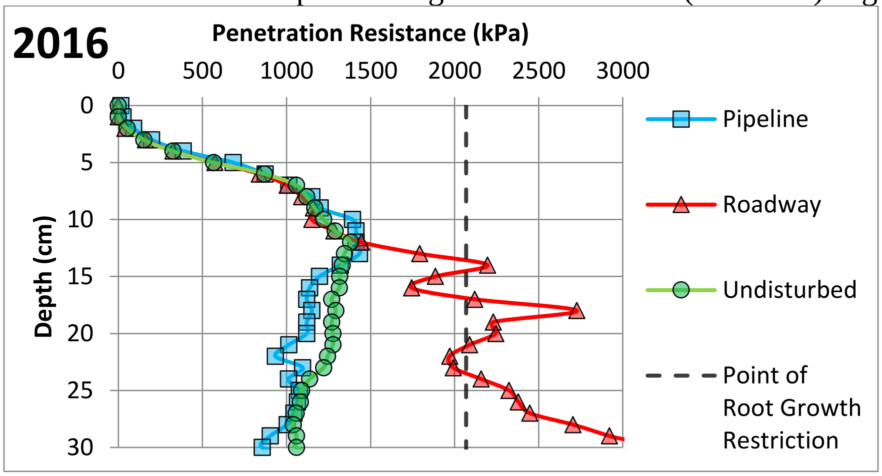
	OM	IOC	pH	EC	Clay	Silt	Sand
Disturbance (D)	--------%--------			dS m^{-1}	------------%--------------		
Undist.	2.03 A*	0.01 C	6.16 C	0.175 C	17.9 A	36.4 B	44.7 A
Road.	1.92 A	0.12 B	8.00 B	0.283 B	17.1 AB	38.6 A	43.9 B
Pipe.	1.29 B	0.57 A	8.13 A	0.366 A	16.6 B	43.5 A	40.2 B

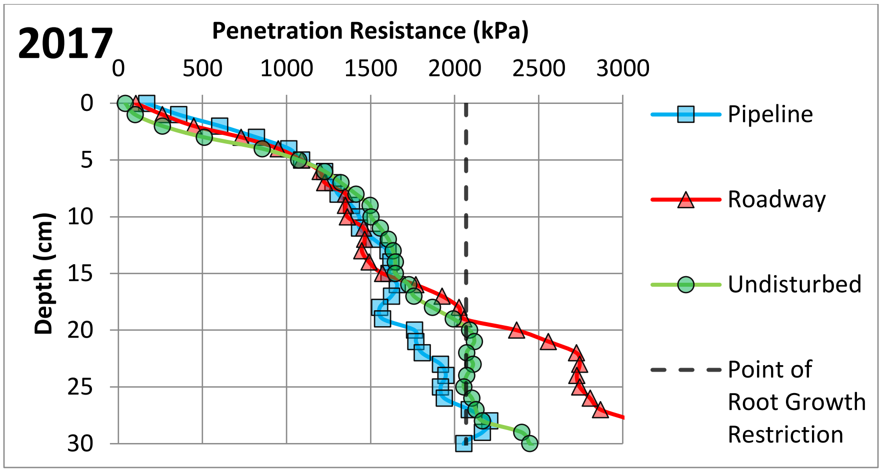
* Medians for metrics that do not share the same capital letter within columns are significantly different from each other at p<0.05.

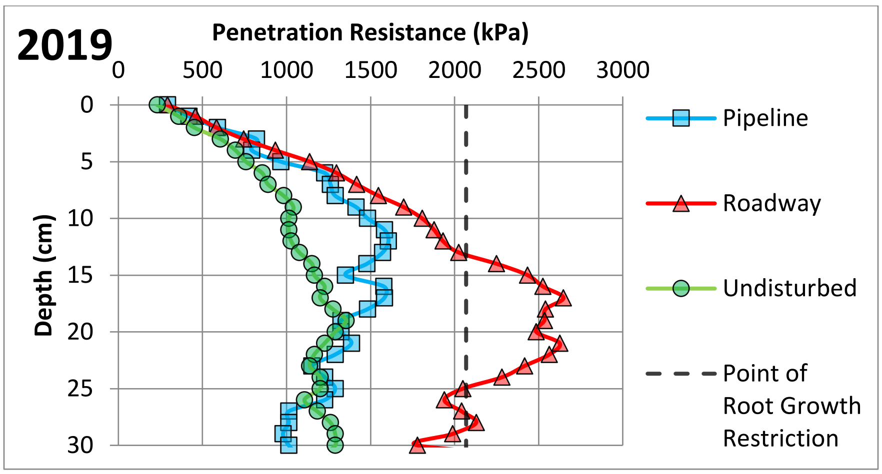
SOIL PENETRATION RESISTANCE (PR)

Examining the graphical representations of PR data provides insights into growth limitations caused by soil compaction (Figure 6). In 2016 and 2019 the median PR on the undisturbed and pipeline disturbances did not exceed the 2068 kPa level where root growth is restricted (Bengough & Mullins, 1991). The roadway exceeded 2068 kPa at the 13 to 14 cm depth level in both 2016 and 2019. All three disturbances had essentially the same median PR values to a depth of 15 cm in 2017, with the undisturbed and the roadway not exceeding 2068 kPa until a depth of 20 cm was reached. The pipeline reached 2068 kPa at a depth of approximately 25 cm in 2017.

Figure 6: Median soil penetration resistance (PR) graphed from the 0-30 cm depth interval on each disturbance in 2016, 2017, and 2020. Penetration resistance in reported in kilopascals (kPa). The PR level at which plant root growth is restricted (2068 kPa) is graphed for reference.







SOIL MICROBIAL COMMUNITY COMPOSITION

Pipeline construction and reclamation activities resulted in significant changes to the microbial community on the ROW (Table 13). Total microbial abundance was greater on the undisturbed than the disturbed sites, and greater on the roadway than the pipeline. Gram positive (Gram+) bacteria, fungi, and actinomycetes were significantly lower on the pipeline compared to the undisturbed and the roadway. Eukaryote abundance was significantly reduced on the ROW compared to the undisturbed. Gram negative (Gram-) bacteria abundance was significantly lower on the pipeline than the undisturbed, but abundance on the roadway was not significantly different from either other disturbed site. Total arbuscular mycorrhizal fungi (AMF) abundance was not significantly different across disturbance levels. There was no significant effect of cropping sequence or tillage sub-treatment on the soil microbial community.

Eukaryote % and the Gram+/Gram- ratio were greater on the undisturbed than the disturbed sites, and greater on the roadway than the pipeline. AM fungi % and Gram- % were significantly greater on the pipeline and the roadway than the undisturbed, and significantly greater on the roadway than the undisturbed. Gram+ % was greater on the undisturbed site than the disturbed sites. The ratio of fungi to bacteria was significantly greater on the roadway than the undisturbed, while that ratio on the pipeline was not significantly different from either other disturbance. No significant differences were observed in concentrations of fungi and actinomycetes between disturbances.

Table 13: Total microbial abundance is reported in nmole g-1. Microbial groups are reported as a percent of the total microbial abundance. First quartile (Q1), third quartile (Q3), and median are reported for each dataset are reported.

	Undisturbed			**Roadway**			**Pipeline**		
Group	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**
			-----Microbial abundance (nmol g^{-1})-----						
Total	64.04	85.1	71.0 A†	49.1	69.2	58.8 B	40.9	52.72	43.4 C
AMF*	1.99	3.50	2.49 A	2.23	3.50	2.72 A	1.94	2.96	2.12 A
Gram-	23.2	32.00	25.6 A	18.1	26.2	22.6 AB	16.0	21.36	17.6 B
Gram+	25.6	31.61	28.4 A	17.1	24.1	21.2 A	13.7	18.15	15.1 B
Fungi	2.44	4.90	3.68 A	2.03	4.48	2.42 A	1.40	2.49	1.80 B
Eukaryotes	1.07	2.16	1.66 A	0.75	1.33	0.95 B	0.30	0.54	0.48 B
Actinomycetes	9.41	11.94	10.4 A	7.35	10.6	9.92 A	6.34	7.33	6.97 B
			-----Microbial abundance (% of total abundance)-----						
AMF	3.04	3.82	3.56 C	4.49	5.16	4.80 B	4.79	5.45	5.13 A
Gram-	35.4	36.5	35.9 C	36.5	38.1	37.2 B	39.3	40.3	39.7 A
Gram+	38.3	39.7	39.0 A	34.1	36.1	34.8 B	33.1	34.2	34.1 B
Fungi	3.72	5.45	4.75 A	3.73	6.95	5.18 A	3.26	5.79	4.19 A
Eukaryotes	1.65	2.32	2.17 A	1.39	1.99	1.65 B	0.72	1.20	0.88 C
Actinomycetes	13.5	15.5	14.7 A	14.6	17.1	15.7 A	14.1	16.5	15.4 A
F/B Ratio[€]	0.09	0.13	0.11 B	0.11	0.17	0.13 A	0.12	0.17	0.13 AB
G+/G- Ratio[$]	1.22	1.32	1.30 A	1.06	1.19	1.13 B	0.98	1.06	1.04 C

† Medians that do not share the same capital letter are significantly different from other medians in the same row at $p<0.05$.

- ∗ Arbuscular mycorrhizal fungi.
- ₡ Ratio of fungi to bacteria measured in nmole kg^{-1}.
- $ Ratio of Gram+ bacteria to Gram- bacteria in nmole kg^{-1}.

MAIN EFFECTS AND EFFECT INTERACTION ON RELATIVE CROP YIELDS

Results of Kruskal Wallis tests assessing relationships between main effects and main effect interactions on relative crop yields are reported in Table 14. Year and cropping sequence both had a significant effect on relative crop yield while no significant effect was observed for disturbance or sub-treatment. All two-way, three-way, and four-way main effect interactions had a significant effect on relative crop yield, except for disturbance by sub-treatment (D x S). Crop protein content was not significantly affected by pipeline reclamation for any crops in any year of the study, therefore crop protein content will not be reported in this paper.

The 2015 growing season produced the lowest relative yields out of all years in the study with median yields on disturbed sites being approximately 40% of those on undisturbed sties (Table 14). Relative yields nearly doubled the following year to approximately 78% of the undisturbed. Relative yields produced by disturbed sites in 2016 were not significantly different from relative yields produced in 2019 and 2020. The 2017 and 2018 growing seasons produced median relative yields significantly greater than any other growing season, which were at 92% and 94% of the undisturbed, respectively.

Overall, T1 produced significantly lower relative yields than T3, but did not produce significantly different yields than T4 or T5 (Table 14). T2 produced significantly lower relative yields than all other treatments when aggregated across all years of the study. Both T2 and T3, the two cropping sequences that incorporated cover crop-durum rotations, produced relative yields that were not significantly different from each other.

Table 14: Kruskal-Wallis results for tests assessing the effect of pipeline reclamation on relative crop yield on all main effects. First quartile (Q1), third quartile (Q3) and median are reported for each main effect level. Medians within the same main effect that do not share the same letter are significantly different at p<0.05. Significance of Kruskal-Wallis test results for main effect interactions are reported at the bottom of the table.

Main Effects	Q1	Q3	Median
(**Y**) Year			
2015	0.26	0.58	0.40 C
2016	0.61	0.88	0.78 B
2017	0.67	1.14	0.92 A
2018	0.77	1.24	0.94 A
2019	0.68	0.94	0.80 B
2020	0.68	1.01	0.81 B

p-value: 2.20E-16 ***†			
(T) Cropping Sequence			
T1	0.70	0.95	0.80 B
T2	0.51	0.84	0.69 C
T3	0.74	1.12	0.90 A
T4	0.72	1.08	0.86 AB
T5	0.62	1.09	0.86 AB
p-value: 1.54E-07 ***			
(**D**) Disturbance			
Roadway	0.64	1.03	0.82
Pipeline	0.68	1.05	0.83
p-value: 0.385 NS			
(**S**) Sub-Treatment			
No-Till	0.72	1.09	0.89
Deep Tillage	0.67	1.10	0.83
Deep Tillage with Manure	0.71	1.05	0.85
p-value: 0.396 NS			
Main Effect Interactions	p-value		
Y x C	2.20E-16	***	
Y x D	2.67E-16	***	
Y x S	8.75E-05	***	
C x D	5.83E-06	***	
C x S	2.82E-06	***	
D x S	0.574	NS†	
Y x C x D	2.20E-16	***	
Y x C x S	2.07E-06	***	
Y x D x S	0.03	*	
C x D x S	3.42E-03	**	
Y x C x D x S	1.61E-02	*	

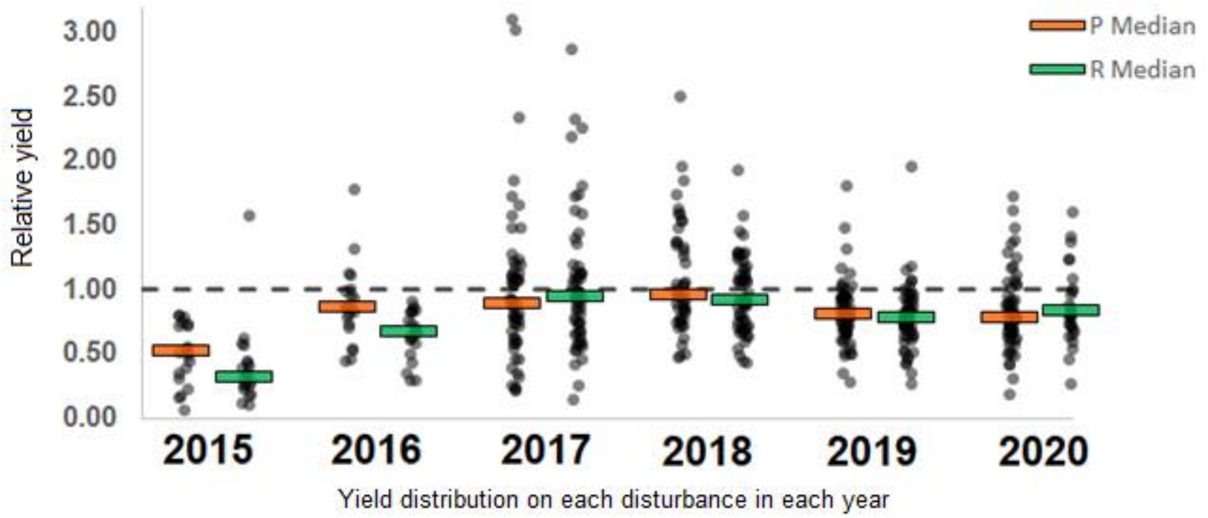
† NS=Not Significant; *=p<0.05, **=p<0.01; ***=p<0.001

T1, T3, and T5 produced relative yields in 2016 that were not significantly different than the relative yields they produced in 2019 and 2020 (Table 15). T4 produced relative yields in 2016 that were significantly greater than relative yields produced in 2019 and not significantly different from relative yields produced in 2020 (Table 15). Production of high relative yields in the second growing season following reclamation suggests rapid crop yield restoration for T1, T3, and T5. Median crop yields for T1, T3, and T5 in 2016, 2019, and 2020 ranged from 0.73 to 1.01, providing a range for expected relative yields post-reclamation.

Treatments T2 and T3, the two treatments that implemented field peas had significantly lower relative yields than other cropping sequences in the same year that field peas were planted (Table 15). This corresponds to T2 relative yields in 2016 and T3 relative yields in 2015. Relative yields of barley in the year following field pea planting were significantly greater than preceding relative field pea yields for both T2 and T3. Despite similarities at the individual growing season level T2 produced significantly greater relative yields than T3 when aggregated across all years of the study. On an individual year basis, T3 produced significantly greater relative yields than T2 in 2016, 2019, and 2020. T4 produced relative yields in 2016 and 2020 that were not significantly different from each other, suggesting early reclamation success comparable to T1, T3, and T5. Relative yields produced by T4 in 2016 and 2020 fall within the expected yield restoration range of T1, T3, and T5, being 0.90 and 0.93 respectively.

Mann-Whitney U Test results for the Year by Disturbance (Y x D) interaction level show relative yields were significantly greater on the pipeline than the roadway in 2015 and 2016 (Table 15). Similar relative yields between disturbed sites were observed in 2019 and 2020 following two growing seasons affected by abnormal weather conditions. Reduced relative yields on the roadway compared to the pipeline followed by homogenous relative yields by the end of the study would suggest the disturbed sites behaved similarly over the long-term following a short-term delay in roadway yield restoration. A visualization of this is provided in Figure 7 below.

Figure 7: Results of the Mann-Whitney U Test for the Cropping sequence by sub-treatment (CxS) interaction level. Reported values are relative crop yields on the pipeline (P) and roadway (R) relative to corresponding undisturbed site yields.



No significant differences were detected among tillage Sub-Treatments (S) within years (Table 15). Relative yields within S3 were homogenous among all four years the effect was present. S2 and S3 produced significantly lower relative yields in 2019 and 2020 compared to 2018.

No significant differences were detected between disturbances (D) within any cropping sequence (T). Relative yields produced by T2 were significantly lower within each disturbance among all other treatments. T5 on the roadway produced relative yields that were not significantly different from T2 on the roadway, however this is likely due to outliers in the dataset drawing the distribution of T2 observations down (data not shown).

S2 produced significantly lower relative yields than S1 and S3 within T4. No other significant differences were detected among tillage sub-treatments within cropping sequences. T2 produced significantly lower relative yields than all other cropping sequences when tillage with manure was implemented.

Significant Kruskal-Wallis test results show an interaction effect between tillage treatment and year (YxS) and tillage treatment and cropping sequence (CxS) (Table 15). Mann-Whitney U-Test results showed that T2 and T3 did not vary significantly from T1 relative yields within any year (Table 14). Mann-Whitney U Test results of the CxS interaction showed one significant difference between tillage treatments within cropping sequences, with T4 x S1 producing significantly greater relative yields than T4 x S2. Results of the Mann-Whitney U Tests at the YxCxS interaction level show that 2017 was the only year where there were significant differences in relative yield between T4 x S1 (median value: 1.85) and T4 x S2 (median value: 0.87). It is not readily apparent why these sub-treatments are significantly different. Due to the only significant difference at the YxCxS level being between T4 x S1 and T4 x S2 in 2017, we are not confident in further exploring this interaction level.

Table 15: Results of the Mann-Whitney U Test for the Year by Cropping Sequence (Y x C), Year by Disturbance (Y x D), Year by Sub-Treatment (Y x S), Cropping Sequence by Disturbance (C x D), and Cropping Sequence by Sub-Treatment (C x S) interaction levels. Reported values are relative crop yields between disturbed and undisturbed sites. First quartile (Q1), third quartile (Q3), and median (Med) values for each effect level are reported.

Y x C	**2015**			**2016**			**2017**			**2018**			**2019**			**2020**		
C[$]	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**
T1	0.37	0.56	0.42 C*a†	0.62	0.84	0.73 Ba	0.62	1.15	0.96 ABbc	0.78	1.29	1.01 Aa	0.78	0.90	0.84 ABa	0.75	0.96	0.88 ABab
T2	0.42	0.74	0.56 BCa	0.35	0.48	0.43 Cb	0.50	0.84	0.64 Bc	0.93	1.20	1.08 Aa	0.51	0.81	0.69 Bb	0.51	0.80	0.67 Bc
T3	0.13	0.33	0.23 Bb	0.77	0.84	0.80 Aa	0.87	1.13	1.02 Aab	0.70	1.46	1.13 Aa	0.77	0.99	0.91 Aa	0.80	1.14	1.00 Aa
T4	0.35	0.63	0.57 Da	0.76	1.00	0.90 Ba	0.88	1.62	1.35 Aa	0.75	1.08	0.92 Ba	0.70	0.85	0.77 Cb	0.71	1.16	0.93 ABab
T5	0.25	0.77	0.48 Ca	0.79	1.18	1.01 ABa	0.96	1.48	1.15 Aab	0.81	1.13	1.00 Aa	0.59	0.98	0.84 Bab	0.64	0.95	0.80 Bbc
Y x D	**2015**			**2016**			**2017**			**2018**			**2019**			**2020**		
D	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**
Roadway	0.25	0.44	0.40 D	0.57	0.83	0.66 C	0.68	1.15	1.04 A	0.73	1.14	0.97 A	0.68	0.91	0.79 B	0.71	1.01	0.87 AB
Pipeline	0.34	0.74	0.51 C	0.73	1.00	0.89 B	0.63	1.14	1.00 AB	0.78	1.36	1.10 A	0.69	0.95	0.83 B	0.66	0.98	0.84 B
Y x S	**2017**			**2018**			**2019**			**2020**								
S[¢]	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**						
S1	0.76	1.13	1.00 A	0.76	1.31	1.05 A	0.68	0.93	0.81 B	0.73	0.93	0.84 B						
S2	0.60	1.13	0.86 AB	0.79	1.32	0.97 A	0.67	0.92	0.79 B	0.66	1.13	0.79 B						
S3	0.67	1.21	0.95 A	0.76	1.06	0.91 A	0.71	0.95	0.83 A	0.65	0.97	0.77 A						
C x D	**T1**			**T2**			**T3**			**T4**			**T5**					
D	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**			
Roadway	0.68	0.93	0.81 A	0.49	0.92	0.69 B	0.72	1.08	0.87 A	0.72	1.10	0.83 A	0.57	1.08	0.87 AB			
Pipeline	0.72	0.96	0.80 A	0.51	0.80	0.65 B	0.75	1.18	0.91 A	0.73	1.05	0.90 A	0.69	1.14	0.86 A			
C x S	**T1**			**T2**			**T3**			**T4**			**T5**					
S	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**	**Q1**	**Q3**	**Med**			
S1	0.75	0.92	0.85 BC	0.54	0.94	0.80 C	0.82	1.13	0.98 A	0.79	1.20	0.94 ABa	0.72	1.34	0.89 ABC			
S2	0.74	1.11	0.80 AB	0.53	0.91	0.69 C	0.82	1.18	0.92 A	0.67	0.99	0.77 BCb	0.89	1.15	0.94 AB			
S3	0.74	1.07	0.84 A	0.53	0.78	0.68 B	0.74	1.09	0.93 A	0.76	1.05	0.93 Aa	0.67	1.04	0.88 A			

∗ Treatment medians that do not share the same capital letter are significantly different from medians within the same row at $p<0.05$.

† Treatment medians that do not share the same lowercase letter are significantly different from medians in the same column within treatment interactions at $p<0.05$.

$ T1 = HRSW-durum-durum-durum-durum-safflower; T2 = HRSW-field peas-barley-safflower-durum-safflower; T3 = field peas-barley-safflower-durum-durum-safflower; T4 = CC Mix-durum-CC Mix-durum-durum-safflower; T5 = HRSW-CC Mix-durum-CC Mix-durum-safflower.

¢ S1 = no-till; S2 = deep tillage; S3 = deep tillage following surface manure application.

Significant differences at the Year by Disturbance by Treatment (Y x C x T) interaction level only existed in 2015 and 2016 (Table 16). Significant differences within treatments between disturbances in 2015, however T1, T2, and T4 had significantly greater relative yields on the pipeline than the roadway in 2016 (Table 9). T3 and T5 saw similar relative yields between disturbed sites when planted in barley and the cover crop mix respectively, while T1 and T4 were planted in durum and T2 was planted in field peas. T1 and T4 produced relative yields on the roadway that were not significantly different between 2015 and 2016, and T2 produced relative yields on both disturbed sites that were not significantly different between 2015 and 2016.

Table 16: Comparing relative yields between pipeline and roadway disturbances within cropping sequences in 2015 (top) and 2016 (bottom) (YxCxT interaction). Median yields for each treatment on undisturbed sites are reported in kg ha-1. First quartile (Q1), third quartile (Q3), and median for each effect level are reported. All Pipeline and Roadway values are reported as relative yields compared to the reported Undist. yield in the same row.

2015		**Pipeline**				**Roadway**			
Trt	**Undist. Yield**	Q1	Q3	Median		Q1	Q3	Median	
T1$	1840	0.508	0.556	0.541	EF*	0.245	0.449	0.334	CD
T2	1300	0.678	0.759	0.737	CDE	0.309	0.492	0.382	BCD
T3	1390	0.156	0.362	0.251	F	0.128	0.23	0.159	D
T4	4130	0.304	0.481	0.375	DEF	0.370	0.494	0.398	ABCD
T5	1640	0.624	0.803	0.777	CDEF	0.253	0.319	0.269	D

2016		**Pipeline**				**Roadway**			
Trt	**Undist. Yield**	Q1	Q3	Median		Q1	Q3	Median	
T1	3420	0.806	0.885	0.846	BC†	0.585	0.649	0.619	ABC
T2	3140	0.461	0.539	0.501	EF†	0.308	0.380	0.334	D
T3	4810	0.773	0.849	0.817	BCD	0.793	0.841	0.836	A
T4	2820	0.987	1.05	1.01	A†	0.721	0.793	0.749	A
T5	3170	1.06	1.44	1.22	AB	0.628	0.860	0.741	AB

* Different capital letters denote significant differences ($p<0.05$) between median values within columns.

† Median pipeline values are significantly greater than median roadway values within the same treatment in 2016.

$ T1 = HRSW-durum-durum-durum-durum-safflower; T2 = HRSW-field peas-barley-safflower-durum-safflower; T3 = field peas-barley-safflower-durum-durum-safflower; T4 = CC Mix-durum-CC Mix-durum-durum-safflower; T5 = HRSW-CC Mix-durum-CC Mix-durum-safflower.

DISCUSSION

EFFECT OF PIPELINE RECLAMATION ON SOIL PROPERTIES

Lower crop yields on the disturbed sites compared to the adjacent undisturbed site can be partially attributed to differences in soil properties between disturbances. Soil organic matter was positively correlated with safflower yields on the pipeline (Table 11). Soil organic matter levels on the pipeline trench were approximately 65% of those on the undisturbed site. Soil organic matter losses on reclaimed ROW's generally occur when 1) organic material stored in soil aggregates is released during topsoil scraping and released when topsoil is respread (Mason et al., 2011) and when 2) organic matter rich topsoil is mixed with subsoil, resulting in topsoil organic matter being diluted throughout the soil profile (Culley et al., 1982). Similar levels of organic material losses resulting from organic material releases during topsoil striping would have been similar between the roadway and the pipeline due to topsoil scraping and storage being the same for all topsoil removed from the ROW. Significantly lower SOM levels on the pipeline compared to the roadway suggest that soil mixing occurred to a greater degree on the pipeline trench compared to the rest of the ROW.

Levels of IOC, EC, and pH were significantly greater on the ROW than the undisturbed site, with levels of these properties being significantly greater on the pipeline disturbance than the roadway disturbance. Soil pH and IOC were positively correlated on the roadway (Table 10) and soil EC and IOC were positively correlated on the pipeline (Table 11). Crop yield on the pipeline was moderately negatively correlated with soil EC (r=-0.546) and IOC (r=-0.571). Elevated levels of IOC, EC, and pH have commonly been observed on reclaimed pipeline ROWs (Culley et al., 1982). The highest levels of soil pH and IOC on reclaimed pipelines has been shown to be on the pipeline disturbance, corresponding with the area where the greatest amount of disturbance and soil mixing occurred (Ivey & McBride, 1999).

Increases in IOC and pH on reclaimed ROWs are commonly driven by the incorporation of sulfates (Soon et al., 2000b) and carbonates (Culley et al., 1982) originating in the subsoil into the topsoil through soil mixing. Pipeline construction activities can excavate soil to a depth where a subsoil alkaline calcareous matrix is at least partially removed and mixed with topsoil, resulting in potentially drastic increases in topsoil calcium carbonate ($CaCO_3$) content (Coiffait-Gombault et al., 2012). Increases in topsoil pH on reclaimed ROWs has been correlated with increases in topsoil Ca content (Soon et al., 2000b), with topsoil Ca being at least partially attributed to the dissolution of incorporated $CaCO_3$. Increases in soil pH on reclaimed pipeline ROWs can limit plant available nutrients in the soil. Observations of low shoot P in barley planted on a fertilized reclaimed pipeline ROWs suggests that elevated pH on reclaimed ROWs limits the availability of fertilizer P to plants (Soon et al., 2000b). Overall crop health and productivity are negatively associated with elevated pH and reduced P on reclaimed pipeline ROWs (Shi et al., 2015). Elevated soil pH on reclaimed pipeline ROWs has not been shown to limit the availability of N and K to plants, suggesting that limited P availability despite fertilizer application remains an issue in managed agriculture land on reclaimed ROWs.

Soil mixing during the reclamation process has been shown to result in increased soil EC through the introduction of previously leached ions like sodium (Na) into the topsoil (Soon et al., 2000b).

The incorporation of Na into the topsoil following reclamation activities has been shown to be of concern in semi-arid regions due to the prevalence of subsoil horizons rich in salts (Day et al., 2015). Soil EC being elevated on reclaimed ROWs should be of concern in regions where salts tend to accumulate in the subsoil. Despite EC being elevated on the ROW, mean EC levels recorded on all sites was not sufficient to result in significant crop yield losses (Francois & Bernstein, 1964; Cedrá et al., 1982; Maas & Hoffman, 1977). Electrical conductivity was moderately positively correlated with IOC on the pipeline (r=0.539), meaning these factors are likely both elevated due to soil mixing that occurred on the pipeline (Soon et al., 2000b).

No correlations were found between the examined soil properties and crop yield on the roadway. A significant omission from this dataset is meaningful Bd data, which has been shown to be a driving factor in depressed yields on reclaimed ROWs in other studies due to soil compaction limiting crop root growth and soil water and nutrient movement (Neilsen et al., 1990; Tekeste et al., 2020). Penetration resistance data collected on this reclaimed ROW shows elevated levels of PR on the roadway compared to the undisturbed and pipeline sites, suggesting that compaction could be a cause for yield losses on the roadway. The persistence of elevated PR on the roadway five growing seasons post reclamation poises a long-term management concern. Conclusions cannot be drawn as Bd data could not be collected to substantiate these claims.

Similar PR levels between the undisturbed and pipeline suggests that soil repacking and respreading practices on the trench did not result in significant soil compaction. Other studies have recorded subsoil conditions that exhibit levels of soil porosity and PR like those on adjacent undisturbed sites (Soon et al., 2000b). Limiting elevated PR on reclaimed pipeline ROWs can be tied to soil properties that affect PR. Soil PR is at least partially related to soil Bd and soil water content (Taylor & Gardner, 1963). Best management practices, including performing reclamation activities at times when soil water is limited (Neilsen et al., 1990), have been shown to limit soil compacted on reclaimed pipeline ROWs.

Soil mixing on the pipeline ROW resulted in a significant change in soil texture. Silt and sand contents were significantly greater and lower respectively on the ROW compared to the undisturbed, and clay content was significantly lower on the pipeline than the undisturbed. Texture changes did not lead to a change in soil texture classification, as the mean soil texture on all three disturbances is categorized as loams (USDA-NRCS, 2022). Changes in soil texture on reclaimed ROWs are generally not correlated with changes in other soil properties, with the exception being Culley & Dow (1988) who related increases in clay content with an increase in cation exchange capacity (CEC) on a reclaimed ROW. Increased sand content and decreased clay content has been related to decreased soil water holding capacity (Olorunfemi et al., 2016). Significant increases in sand content have been observed alongside decreases in soil water, however soil water decreases were attributed to increases in soil PR and Bd (Olson & Doherty, 2012). Significant differences in soil texture remain a legacy effect of soil mixing but the effects of soil texture changes on CEC and water content will likely be marginal.

Pipeline reclamation activity significantly affected the soil microbial community across the ROW. Total microbial abundance was significantly reduced on the ROW compared to the undisturbed location, with the pipeline exhibiting lower microbial abundance than the roadway.

Pipeline reclamation activities have been shown to lead to a decrease in total soil microbial abundance (Gasch et al., 2014). Losses of nutrient sources to organic matter dilution and increased mineralization to disturbance have been associated with decreases in total microbial abundance on reclaimed ROWs (Gasch et al., 2016). Reductions in microbial activity on reclaimed pipeline ROWs have been linked to limited available phosphorus in the soil (Soon et al., 2000a). Increased soil Bd resulting from repeated vehicle traffic has been identified as a factor limiting microbial abundance on reclaimed ROWs due to reduced soil aeration, nutrient availability, and moisture content (Rowell & Florence, 1993; Block et al., 2020). Elevated PR was observed on the roadway disturbance, suggesting that reduced microbial abundance on that disturbance could be driven by issues related to lack of soil pore space and available water and nutrients. In addition to soil compaction, microbial communities can be negatively affected by a lack of soil nutrients, including organic material (Alexander, 1961).

Relative arbuscular mycorrhizal fungi (AMF) abundance was elevated on the ROW compared to the undisturbed. Total abundance of AMF was not significantly different across all disturbances. Arbuscular mycorrhizal fungi abundance was positively correlated with soil properties that were shown to be elevated on the ROW, specifically pH on the roadway (r=0.604) and IOC on the pipeline (r=0.710). A critical property of AMF is that it can colonize plant roots and form bridges between the plant root system and nutrients in the soil matrix (Wang, 2017). High relative AMF abundance on reclaimed pipeline ROWs has been associated with increased plant community recovery as a result of the symbiotic relationship AMF forms with plants in the rhizosphere (Farrell et al., 2020). Relative AMF abundance has been shown to increase to roughly pre-disturbance levels on reclaimed pipeline ROW's approximately five years following reclamation, suggesting inherent resiliency (Gasch et al., 2016). Elevated relative AMF abundance on the ROW provides crops planted there a means to accessing limited soil nutrients, providing a pathway to yield restoration.

It is important to note that total AMF abundance was negatively correlated with crop yields on the pipeline in this study. AMF has a varying relationship with SOC, and this is influenced by the fate of cellulose, an important byproduct of plant residue decomposition to AMF growth. AMF growth can be hindered in systems where the uptake of cellulose is rapid, limiting this nutrient source (Ravnskov et al., 1999). In a system where the microbial community is relying on rapidly decomposing plant residue, increased competition amongst these organisms could limit the ability for AMF to have a positive effect on crop yields on reclaimed pipeline ROWs. Gram-negative and gram-positive bacteria communities were both affected by reclamation. Relative gram-negative bacteria abundance was significantly lower on the roadway than the undisturbed and significantly lower on the pipeline than both other sites, and relative gram-positive bacteria abundance was significantly lower on both disturbed sites compared to the undisturbed. Changes in relative gram-negative and gram-positive bacteria community abundance resulted in the gram+/gram- ratio being significantly lower on both disturbed sites compared to the undisturbed. Lower gram+/gram- ratios on the ROW were correlated with decreases in actinomycete abundance (Table 9; Table 10). Decreases in actinomycete abundance on reclaimed pipeline ROWs in semi-arid regions have been noted where total microbial abundance associated with reductions in SOM (Gasch et al., 2016). Significant changes in SOM across disturbances can partially explain the changes in the gram+/gram- ratio. Gram-negative bacteria have been shown to be associated with simple plant derived C sources, while Gram-positive bacteria were associated with more complex and recalcitrant SOM C sources (Fanin et al., 2019; Kramer & Gleixner, 2008). Levels of SOC in this study follow the same pattern of decreasing levels from the undisturbed to pipeline disturbances as the gram+/gram- ratio, reinforcing the idea that limits in SOM are driving the gram+/gram- ratio down. A low gram+/gram- ratio on the ROW can pose challenges in terms of naturally restoring lost SOM, as gram-positive bacteria has been shown to play an important role in converting labile C and N to a more complex SOM associated form (Enggrob et al., 2020).

Relative eukaryote abundance was significantly lower on the roadway than the undisturbed and significantly lower on the pipeline than both other disturbances. Decreases in relative eukaryote abundance on reclaimed ROWs have been associated with a lack of available water and sunlight, as these resources are critical to this microbial group's success (Block et al., 2020). Reductions in relative eukaryote abundance may not be due to persistent reductions in soil water content but are likely influenced by limited water and sunlight resources available to eukaryotes while soil is stockpiled during construction and reclamation (Block et al., 2020).

CROPPING SEQUENCE EFFECTS

Cropping sequence and year were both shown to have a significant effect on relative crop yields on the ROW in this study. Relative yields were significantly greater in 2017 and 2018 than all other years in the study (Table 15). Homogenized relative yields in 2017 and 2018 can be attributed to the effects of abnormal rainfall events on the study area. Rainfall has been shown to be the most significant environmental factor affecting reclaimed pipeline ROWs in semi-arid regions (Xiao et al., 2016). The study site was impacted by drought in 2017, with the average monthly precipitation being 31 mm less than the 30-year average for the months of April through August (Table 8). Reduced precipitation likely acted as a greater limiting factor in relation to crop growth compared to soil conditions in the pipeline ROW leading to homogenous poor crop yields across the landscape. The 2018 growing season also saw three significant rain events that produced approximately 105 mm of rainfall on the study site within the span of 17 days. Rain events were accompanied by winds over 74 kph and the final rain event on July 9th produced hail at the study site that was likely yield reducing. The July 9th rain event also resulted in a subsidence over the pipeline trench that impacted approximately half of all pipeline sites. The subsidence was approximately one to two meters wide and approximately 0.15 m deep. Crops yields appeared to be depressed within the subsidence, however crops were able to be harvested within the affected plots outside the subsidence. The effects of significant rainfall and potential hail damage on crop productivity varied. Median undisturbed safflower yields in 2018 were approximately 400-500 kg ha^{-1} greater than undisturbed safflower yields in 2020, whereas median undisturbed durum yields were comparable to or slightly less than durum yields in 2019. Despite varying effects on crops, relative yields were not significantly different between treatments in 2018 suggesting a field-wide homogenization effect imposed by weather conditions. When disregarding the first growing season post-reclamation and the two years affected by adverse climate conditions, disturbed sites produced yields in the range of 78% and 81% of undisturbed sites.

Trends observed in relative crop yield depression and restoration over time on the reclaimed pipeline ROW in this study agree with the findings of pipeline reclamation studies conducted on similarly fine-textured soils (Culley et al., 1982; Neilsen et al., 1990; Soon et al., 2000b; Shi et al., 2015). The greatest levels of yield suppression on pipeline ROWs occurred during the first growing season following reclamation when soil disturbance is the most pronounced (Soon et al., 2000b; Shi et al., 2015). Lower nutrient availability has been associated with depressed crop yields on reclaimed ROWs in the first few growing seasons following reclamation, even on sites managed as agroecosystems with annual applications of fertilizer guided by soil fertility tests (Soon et al., 2000b; Shi et al., 2015). Reductions in plant available N associated with SOM dilution and increased mineralization (Mason et al., 2011) along with increased soil compaction caused by reclamation-related heavy vehicle traffic have been associated with suppressed crop yields in the short-term following reclamation (Neilsen et al., 1990). Soil nutrient availability on reclaimed pipeline ROWs has also been shown to be limited by elevated topsoil pH resulting from alkaline subsoil material, namely $CaCO_3$ (calcium carbonate), being mixed with the topsoil (Soon et al., 2000a). Low soil P levels and high soil Ca, the latter being associated with elevated topsoil carbonates, on reclaimed pipeline ROWs have been associated with poor plant growth and establishment (Espeland et al., 2017). Decreases in soil water on reclaimed pipeline ROWs are also of importance, as soil water is thought to be the primary limiting factor in crop production in the upper Great Plains (Farahani et al., 1999). Increases in soil Bd and PR resulting from repeated vehicle traffic destroy soil structure and reduce soil porosity, resulting in lower soil water content (Culley et al., 1982; Olson & Doherty, 2012) and water use efficiency (Ebrahimi et al., 2022). Restoration of relative crop yields on pipeline ROWs has been shown to occur rapidly following reclamation resulting from multiple factors. Precipitation following reclamation is believed to have a positive effect on crop yield on disturbed ROW's by washing introduced carbonate rich substrate from the topsoil (Soon et al., 2000a). Ameliorating the soil N pool by the lowering the often-elevated C/N ratio on reclaimed pipeline ROWs through the decomposition of organic and inorganic C sources and residual fertilizer (Soon et al., 2000b) can also improve crops yields over time (Neilsen et al., 1990).

Regardless of the year they were implemented, field peas experienced severely depressed yields on the roadway and the pipeline compared to the undisturbed (Table 15). There are no existing studies relating to field pea yields on reclaimed pipeline ROW, legumes, namely soybeans, have been shown to experience reduced yields following pipeline reclamation. Culley and Dow (1988) found that soybean yields on a reclaimed pipeline ROW were approximately 67% of those on adjacent undisturbed cropland. Observed depressed soybean yields on reclaimed pipeline ROWs have been associated with changes in physical soil properties, namely increased soil Bd and PR (Tekeste et al., 2020), reduced soil aggregation (Ebrahimi et al. 2022), and increases in soil clay content (Ramsay & MacKenzie, 1978; Culley et al., 1982). The only study to observed increases in relative soybean yields over time on reclaimed ROWs did not provide an explanation as to why this may have occurred (Culley et al., 1982), and as soil clay content remained elevated on the pipeline compared to the undisturbed site 10 years following reclamation it stands to reason that it remains a factor affecting crop yields (Culley & Dow, 1988). Soil physical properties likely remain a factor that impacts legume productivity on reclaimed ROWs over time, however, further research ought to be conducted to better understand increases in legume yield on reclaimed ROWs over the short term.

Culley and Dow (1988) found that crop yield restoration on disturbed sites leveled off approximately five years post-reclamation when disturbed yields reached 72% of undisturbed yields. Considering that this study found that relative yields reached approximately 80%, a relative crop yield range of 70-80% are a likely long-term result of natural yield recovery on reclaimed pipeline ROW's. Culley and Dow (1988) and this study were conducted on different soil types and in different climate regions, which will allow for some differences in time to recovery. Despite the inability to determine if 70-80% relative yields can be expected from reclaimed pipeline ROWs at this time, this is a potential trend that warrants further exploration.

Over the timescale of this entire study, relative yields on the roadway and the pipeline were not significantly different from each other. Homogenous yields between the pipeline trench and working sides on reclaimed ROWs are commonly reported (Culley & Dow, 1988; Neilsen et al., 1990; Tekeste et al., 2020). Despite significant differences in soil properties between the roadway and the pipeline (Table 12), it is possible that the nature of these disturbances ultimately resulted in similar negative effects on crop productivity. Crop yield on reclaimed pipeline ROWs in semi-arid regions has been shown to be driven most by changes in the levels of available N, SOM, and soil pH (Shi et al., 2015). Low levels of SOM on the pipeline would drive the lack of nutrient availability on that disturbance (Table 12), while elevated soil compaction on the roadway would limit the crops access to soil nutrients through the destruction of soil pores and aggregates (Batey, 2006). Elevated soil pH levels across the ROW would further limit soil nutrient availability and result in crop stress. These results suggest that, in the long term on pipeline ROWs, similarly depressed yields caused by different factors can be expected across the ROW.

Relative yields were significantly lower on the roadway than the pipeline in 2015 and 2016. This discrepancy in yields can at least partially be attributed in elevated soil PR on the roadway compared to the pipeline. Differences in soil PR between disturbed sites are shown in Figure 6. A compacted soil layer on the roadway would also result in lower water infiltration rates, meaning that the natural leaching of soluble substrates that has been associated with early reclamation success (Soon et al., 2000b) would occur over a longer timescale if at all. Sufficient precipitation, which can be partially attributed to substantial rainfall in 2018, may have provided enough rainfall to leach carbonates and saline material down to the subsoil.

The lack of significant differences between the HRSW-durum-durum-durum-durum-safflower (T1), HRSW-CC Mix-durum-CC Mix- durum-safflower (T4), and CC Mix-durum-CC Mix-durum-durum-safflower (T5) treatments suggests that cover crops did not play a significant role in the reclamation process. The implementation of cover crops was intended to improve subsequent crop yields by limiting soil water usage while building soil organic nutrient levels between years where cash crops were planted (Obour et al., 2021). Research regarding the effects of cover crops on subsequent crop yield has produced inconsistent results concerning the impacts of cover crop mixes on water use, soil biological activity, and subsequent crop yields (Florence & McGuire, 2020). Cover crops proved to not be robust against disturbance as relative yields were similar with wheat in 2015 (Table 15). Effects that cover crops potentially had on soil water availability, microbial activity, and nutrient levels did not result in significantly different crop yields than treatments were cash crops were continuously planted, meaning lost revenue was not justified in this experiment.

Significantly greater relative yields aggregated over the duration of this study were found on the field peas-barley-safflower-durum-durum-safflower (T3) treatment compared to the HRSW-field peas-barley-safflower-durum-safflower (T2) treatment despite both treatments incorporating the same crops. It is important to note that the pipeline subsidence that occurred following significant rain events in 2018 largely affected plots where T2 was implemented. Crops within the subsidence were noticeably smaller than those within the plot but outside of the subsidence. This subsidence likely had an impact on pipeline yields in T2 in 2019 and 2020 but this does not account for the depressed yields T2 plots exhibited on the roadway in those years, however, as the subsidence only extended approximately one to two meters across the width of the pipeline. Consistent cropping sequence effects of T2 between the roadway and the pipeline despite the subsidence suggest the depressed crop yields on T2 are valid.

The differences between yields produced by T3 and T2 could relate to the timing of the implementation of field pea. Cropping systems that incorporate legumes have been shown to increase the N carrying capacity of soils while also increasing the mineralizable fraction of soil C (O'Dea et al., 2015). An analysis of published data regarding leguminous crop's contributions to N in agroecosystems showed field peas contribute an average of approximately 15 kg ha^{-1} of atmospherically fixed N in the Northern Great Plains (Walley et al., 2007). Numerous factors affect the ability of field peas to positively contribute to the soil N pool, such as low yields resulting in greater N accretion in the soil (Peoples & Craswell, 1992). Greater quantities of fertilizer N are more likely to remain in the soil in fields planted to field peas, as field peas in the Northern Great Plains region derive approximately 55% of their N from fixation (Walley et al., 2007). The combination of low relative field pea yield and low initial soil N values likely resulted in significant additions to the soil N pool following harvest in 2015. Subsequently, mineralized N would then be available to the subsequent barley crop, resulting in the significant increase in relative yield observed in T3 in 2016. Greater field pea yields produced by T2 in 2016 would then leave less soil N for the subsequent barley crop in 2017, negatively effecting yield. Drought experienced in 2017 would also negatively affect the positive effects of field pea in T2. Soil N benefits provided to wheat by field pea are reduced during drought years (Miller and Holmes, 2005), meaning soil N accrued in 2016 while field pea was implemented would not be as readily available to the subsequent barley crop.

Both T3 and T2 did not see a positive yield effect of safflower on subsequent durum yields (Table 4). Previous studies in the upper Great Plains are inconclusive regarding the effects of oilseed crops on subsequent wheat, with both positive effects (Beckie & Brandt, 1997) and no effect (Miller et al., 2002) being reported. The positive effects of safflower on the subsequent crop are largely associated with reduced pest pressure benefits associated with practicing crop rotations. Safflower, while providing pest pressure relief, adds stress to the subsequent crop in terms of soil water. Safflower can access deep soil water resources due to its deep taproot (Rafey & Prasad, 1991). Any potentially negative effects that safflower's usage of soil water had on subsequent durum crops did not result in significant differences between relative yields of T2 and T3 and T1 in any years where durum followed safflower (Table 15). These results suggest that, while safflower may not provide a beneficial effect to the subsequent crop, incorporating it in a cropping sequence ultimately may not result in significantly different relative yields than continuous durum.

Relative yield gains on T2 effectively stopped in 2017 following field pea planting. Disregarding anomalous results in 2018, the relative yields within T2 capped around a median value of 0.66 to 0.69, as relative yields were not significantly different between 2017, 2019, and 2020. Explanations for the lack of reclamation success within T2 are not readily apparent, and directly contrast with the success of T3. Nutrient cycling concerns are a potential issue as N additions from field peas in 2016 may not have been as impactful as they would have been in 2015.

Relative yields were not significantly different between T1 and T3 in 2016, 2019, and 2020. Relative yields were elevated on T3 compared to T1 in all three years previously mentioned, however, resulting in significantly greater relative yields on T3 than T1 when aggregated over all six years of the study. Greater yields over time on T3 than T1 may be related to the ability of field pea to fix atmospheric N_2. Spring soil N levels have been shown to be greater on sites where field pea was planted the previous year compared to wheat in fertilized agroecosystems (Miller et al., 2006). Wheat grown on field pea stubble has been shown to produce greater yields than wheat grown on wheat stubble due to additions to soil N provided by field pea, even in systems where annual N fertilizer was applied (Miller and Holmes, 2005). T1 was shown to be more effective over the short term as it produced significantly greater relative yields than T3 in 2015. Legumes have been shown to perform poorly on reclaimed pipeline ROWs due to lower soil N levels and increased soil compaction (Culley et al., 1982; Culley & Dow, 1988). For some producers, it may prove worthwhile to take a slight loss in productivity in the long term in exchange for greater yields immediately following reclamation. T1 and T3 may provide either short- or long-term benefits to stakeholders producing crops on reclaimed pipeline ROWs, however, the data presented in this study are limited and further research ought to be conducted relating to potential long-term effects of early field pea planting on relative yield.

SUB-TREATMENT EFFECTS

Deep tillage (S2) and deep tillage with surface manure application (S3) did not result in significantly different relative yields compared to no-till (S1) plots when aggregated across the four years of the study following the implementation of these sub-treatments in 2017 (Table 14). Combined effects of tillage treatments with study year and disturbance also did not produce significant effects (Table 15).

Lack of significant yields resulting from manure application could be related to the fact that plots were fertilized with commercial fertilizers annually prior to planting. Plots fertilized prior to planting have been shown to produce corn yields comparable to plots treated with manure on reclaimed pipeline ROW's (Neilsen et al., 1990). Even if a positive effect of manure would have been noted, Neilsen et al. (1990) found that positive yield effects of manure application on a reclaimed pipeline ROW did not extend beyond the third growing season after it was applied. Manure application, therefore, does not seem to be an economical amendment in reclaimed pipeline ROWs managed as agroecosystems with annual fertilizer applications.

Deep tillage treatments have been shown to loosen compacted layers on reclaimed ROWs (Tekeste et al., 2020), however in our study Bd and PRs remained elevated (Figure 7) and crop yields remained depressed (Table 15) on the ROW. While deep tillage can break up compaction, thus improving aeration and water infiltration rates (Batey, 2006), it may not solely ameliorate soil conditions on reclaimed pipeline ROWs. The application of deep tillage on reclaimed pipeline ROWs has been shown to improve crop yields compared to applying no tillage treatment, however this did not restore crops yields to their pre-disturbance levels (Tekeste et al., 2020). A negative impact of soil compaction that deep tillage does not address is the destruction of soil aggregates. Loss of soil structure and destruction of soil aggregates has been observed on reclaimed pipeline ROWs where deep tillage was applied (Ebrahimi et al., 2022). The application of deep ripping following surface manure application allows for some manure to be incorporated into the subsoil but still allowing for most the organic material to remain in the topsoil. Applying organic material to the soil system such that most of it will be incorporated into the subsoil would allow for further deep soil aggregation. Leskiw et al. (2012) found that injecting pelletized organic material into the subsoil at a rate of 20 Mg ha^{-1} following deep tillage on a reclaimed pipeline ROW resulted in soil Bd values in the subsoil comparable to an adjacent undisturbed site. Although not a focus of our study, further research into injecting organic materials into the compacted topsoil and subsoil on a reclaimed pipeline ROW may be warranted.

MANAGEMENT IMPLICATIONS

The findings of this study provide important insights into management decisions that can be made regarding reclaimed pipeline ROWs. Significant yield losses in the first growing season following reclamation are effectively unavoidable and ought to be planned for. Fields could potentially be put into green fallow to conserve soil water and allow for organic soil nutrient pools to naturally restore themselves before planting a crop on the ROW while limiting financial risk involved with planting a crop. The long-term success of planting field pea immediately following pipeline reclamation was a significant finding of this study and indicated that sacrificing yield in the short term to build nutrient pools over the long term may be a worthwhile pursuit for stakeholders. Continuous durum provided generally stable yields over the course of the study, presenting this as an option for producers looking to maintain a more stable revenue stream during the reclamation process. Continuous durum would also create potential challenges for producers as it can drain the soil nutrient pool over time while also increasing the chances for pest and disease pressure. Incorporating cover crop mixes into cropping sequences did not result in increased crop yields in subsequent years, and since cover crops are less monetizable than other cash crops tested in this study, it stands that cover crops may not be a viable to management tool.

While there was no control to compare to, it can be speculated that applying fertilizer annually likely played a critical role in minimizing yield reductions on the ROW. Available soil nutrients on the ROW were likely lesser than on the undisturbed due to soil pH values being elevated above 8.0 and SOM values being significantly lower on the ROW than the undisturbed. Providing consistent sources of N and P to the soil system in the form of fertilizer has been shown to significantly increase crop yields compared to applying no fertility treatment (Neilsen et al., 1990). However, application of fertilizers to non-cropped areas (rangeland or native areas) should be done with caution and thus one should seek information or professional advice on this topic before any applications occur.

Soil pH levels above 8.0 likely led to reduced P availability due to increased P sorption to soil particles (Soon et al., 2000b). It is concerning that soil P deficiency would exist in a system where proper soil testing was done to determine soil P levels and subsequent soil P fertilizer was applied based on crop fertility recommendations, as this represents an ineffective use of time and resources. Developing P fertility recommendations that better consider high soil pH values may improve crop yields on pipeline ROWs.

CONCLUSIONS

Depressed yields on reclaimed pipeline ROW's are unavoidable, however strategies are available to producers and stakeholders to ameliorate disturbed lands. The greatest levels of yield reduction on reclaimed pipeline ROW's occur immediately following reclamation when disturbance is most pronounced. In this study, natural recovery of approximately 80% of undisturbed yields is achievable within six years following reclamation. A delay in the recovery time of yields on disturbed sites on ROW might occur due to increased PR in those zones. Increased PR is not necessarily a yield suppressant on pipeline ROW's, however, management factors that address this issue ought to be considered. Manure application is not necessary to restore lost yields when fertilizer is applied annually, however applying manure immediately following reclamation to boost nutrient pools and promote soil aggregation should be considered.

Allowing for natural recovery to occur appears to be a viable long-term option as monocropping wheat consistently produced yields within the range of 80% of the undisturbed on disturbed sites between two to five years following reclamation. Planting field peas immediately following reclamation produced greater yields over time despite poor yields in the first year. However, the same effect was not noted for second year field pea planting. Cover crop mixes, regardless of when they were incorporated, did not have a significant effect on yield. Safflower did not have a positive or negative effect on relative crop yields and produced relative yields on par with durum, however its usage of soil water ought to be considered.

Further research is needed regarding methods for fully reclaiming lost yields on pipeline ROW's. Reclamation levels of approximately 80% relative yields appear to be a reasonable long-term expectation for reclamation success. Identifying options to get to 100% reclamation would be greatly beneficial to producers and stakeholders. Additionally, further research into the application of manure or other organic treatments to the subsoil ought to be pursued, as rebuilding soil structure following reclamation could contribute to restoring lost yields.

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