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Pipeline Impacts and Recovery of Dry Mixed-Grass Prairie Soil and Plant Communities

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ABSTRACT

Agricultural practices have historically dominated disturbance on North American grasslands. Disturbances from oil and gas have become increasingly common and problematic for grassland conservation. With growing demand for oil and gas, industry is actively implementing minimal disturbance techniques during construction to reduce impacts on grasslands. This study aimed to determine impacts of a large-diameter pipeline right of way (ROW) on dry mixed-grass prairie to determine if and how far these impacts extended beyond the ROW and the effect of time on grassland recovery on and off ROW. Soil and vegetation on the ROW and on transects extending 300 m on either side of the ROW were assessed over a 10-yr period, starting the yr of construction, at six sites along a pipeline route in southern Alberta, Canada. There were significant impacts to soil and vegetation on the ROW and within 5 m of the ROW in the first yr. The trench was most impacted, followed by work and storage areas. Within 2 yr, soil and plant communities were on a trajectory toward reference prairie conditions. Ten yr following construction, only soil pH and bare ground were greater, and litter was less, on the trench than on work and storage areas, and relative to reference prairie. While native grass richness, dominance, and cover were similar on and off ROW, abundance of some native forb species was less on ROW. Non-native species cover was $< 2\%$ in all yr and locations. Although ruderal weed species were abundant on ROW the yr following construction, they disappeared by the following yr. Use of minimal-disturbance construction techniques reduced the size and intensity of the disturbance footprint, allowing for even sensitive arid habitat to recover within a short period of time. Similar approaches to other grassland disturbances can increase ecosystem resiliency.

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Introduction

Agricultural practices have been the dominant disturbance on North American grasslands; more recently oil and gas wells, pipelines, and associated roads have become problematic for grassland conservation. The growing energy production demand over the past few decades has resulted in increased habitat fragmentation and pressures on biological diversity (Braun et al. 2002; Copeland et al. 2009; Ludlow et al. 2015). While low-intensity disturbances can benefit grasslands by increasing diversity, large-scale and intense disturbances can have long-term detrimental effects (Collins and Barber 1985; Sampson and Knopf 1994). Linear disturbances such as pipelines and roads have unique impacts on grasslands relative to isolated disturbances (Jones et al. 2014; Daniel 2015). Linearity creates high edge-to-area ratios, which increase cumulative edge effects, including non-native species invasion onto and off the disturbance (Forman and Alexander 1998; Ries et al. 2004; Hansen and Clevenger 2005).

Demand for pipelines is increasing relative to other methods of transporting natural resources, as they have greater volume capacity, higher security, and lower energy costs relative to rail or highway transportation (Xiao et al. 2014, 2016). However, pipelines may significantly impact native prairie ecosystems. Through pro-

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cesses such as topsoil and subsoil mixing, pipelines can alter soil properties including electrical conductivity, pH, salinity, soil water content, texture, and temperature on the right of way (ROW) (de Jong and Button 1973; Naeth 1985; Ivey and McBride 1999; Olson and Doherty 2012; Shi et al. 2014; Xiao et al. 2014; Xiao et al. 2016). Activities such as trenching, welding, and vehicular traffic can result in elevated metal concentrations (Shi et al. 2014). Through soil compaction, bulk density can increase across the ROW, decreasing porosity and organic carbon content (Naeth et al. 1987; Batey and McKenzie 2006; Olson and Doherty 2012). During construction, native vegetation and topsoil are usually removed, facilitating introduction and potential spread of non-native and invasive plant species. These species can form monocultures, resulting in landscape fragmentation and altered wildlife habitat through loss of species important for food and shelter (Sousa 1984; Hobbs and Heunneke 1992; Smith and Knapp 1999; Craine et al. 2001; Parker 2005; Olson and Doherty 2012; Xiao et al. 2014, 2016; Gasch et al. 2016). In fescue grasslands, non-native plant species persisted for at least 40 yr on ROW (Desserud et al. 2010). Impacts of pipelines may be greater, and recovery times longer, in arid and semiarid environments.

Impacts from linear disturbances can impact adjacent plant communities directly by creating gaps and changing plant composition (Sousa 1984; Hansen and Clevenger 2005) and indirectly by altering environmental conditions, such as light and water content limitations (Parendes and Jones 2000; Hansen and Clevenger 2005). Opportunistic entry for invasive plant species was observed on a pipeline through an ecological reserve, where exotic annuals spread into surrounding grassland, coastal sage, and oak woodland native plant communities (Zink et al. 1995). Some grasslands were more susceptible to invasion by non-native species near roads and railways than forested environments (Hansen and Clevenger 2005). High abundance of non-native species observed near transportation corridors in various habitat types suggests corridor edges act as microhabitats (Forcella and Harvey 1983; Tyser and Worley 1992; Hansen and Clevenger 2005).

Linear disturbance effects vary with distance from the disturbance edge. Most research focused on industrial edge effects and buffer zones in forest and wetland environments predominantly for wildlife and watershed protection (Ries et al. 2004; Environment Canada 2009; Henderson 2011). In one study vegetation recovery was inhibited within 10 m from a pipeline work area (Hansen and Clevenger 2005); in another it was negatively impacted 10−15 m from a railway edge, while effects on soils were negligible (Jinxing et al. 2008). In Hawaii, wind-blown soil from a military training point and roads did not affect surrounding rare and common plants at distances > 40 m (Gleason et al. 2007). Effects of pipelines on vegetation were found up to 300 m in east China (Shi et al. 2014) and up to 25 m in arid and semiarid regions of Uzbekistan (Jones et al. 2014). Changes in soil thermal regime and vegetation on pipeline ROW may extend off ROW under climate warming (Smith and Riseborough 2010).

The critical shortage of pipelines to move oil and gas from source to end users in Canada and the United States has led to a recent increase in demand for their development (Hussain 2018; Aliakbari and Stedman 2019). More than 433 000 km of pipelines exist in Alberta (Alberta Energy Regulator 2019), and their potential impacts are widespread across the Great Plains region. The longer-term effects of pipeline disturbances on comparatively susceptible dry mixed-grass prairie need to be investigated to protect and conserve the integrity of grassland communities. The purpose of this study was to determine the impact of a large-diameter pipeline ROW on dry mixed-grass prairie soil and plant communities; to determine if and how far these impacts extend beyond the ROW; and the effect of time on grassland recovery on and off ROW.

Materials and methods

Research area

The research was conducted in southeastern Alberta in the dry mixed-grass subregion of the grassland natural region from 2009 to 2018. The climate is warm and dry, with cold winters, warm summers, and low precipitation (Environment Canada 2017). High evaporation due to high summer temperatures and wind speeds results in water deficits. Based on 1981−2010 climate normals, mean growing season (May to September) temperature was 16.0°C and winter (November to February) temperature was −9.2°C. Mean annual precipitation was 307 mm, with snow contributing 19%. Brown chernozemic soils are dominant, with a 10- to 15-cm thick A horizon (Adams et al. 2013). Solonetzic soils are found where sodium-rich bedrock is at or near the soil surface, or in areas with saline and sodic ground water discharge. Short and midheight, drought-tolerant grasses dominate the vegetation. The most common plant community is *Stipa comata* (needle and thread grass)–*Bouteloua gracilis* (blue grama grass) with *Agropyron smithii* (western wheat grass) and *Agropyron dasystachyum* (northern wheat grass).

The study area is along the TC Energy (formerly TransCanada) Keystone pipeline (diameter 76.2 cm), which transports crude oil from Alberta to the United States. To accommodate the installation of a large-diameter pipe, the ROW was 30 m wide and consisted of standard trench, storage, and work areas. During construction, 4 m of trench area were stripped with the trench placed in the center 2 m. The pipe was buried with a minimum cover of 1.2 m. Size of work and storage areas varied by site to accommodate travel lanes, grade requirements to provide a safe work surface, and soil storage. The trench has the greatest disturbance followed by work areas, where vehicle, equipment, and foot traffic are common, and then storage, where soil stockpiles are placed during construction. In general, the topsoil layer (0−0.15 m) was removed from the trench and stored in 0.80-m high stockpiles. Subsoil (0.16−2.10 m) was removed, leveled (≈0.30 m high), and used as a work lane for equipment travel. This was specific for species-at-risk areas, and in other sections of the pipeline, topsoil and subsoil would have been stored separately in stockpiles 2−4 m high. Where grading was not required, vehicles would travel partially on a low-profile topsoil ramp ≈0.3 m high and on the prairie.

Construction and reclamation of study sites occurred February to May 2009. Construction methods to reduce impact on the prairie included following existing disturbance corridors; construction under frozen conditions; minimizing the construction footprint and extent of topsoil removal; topsoil salvage and replacement in the same season; and geotextiles, soil ramps, and matting to protect the sod layer. Seeding and straw crimping occurred May to July 2009. The primary seed mix contained 8 native grasses (*Agropyron dasystachyum*, Hook. Scribn. & J.G. Sm., northern wheatgrass, *Agropyron smithii* Rydb. (western wheatgrass), *Agropyron trachycaulum* (Link) Malte ex H.F. Lewis (slender wheatgrass), *Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths (blue grama grass), *Koeleria macrantha* (Ledeb.) J. A. Schultes (june grass), and *Stipa comata* Trin. & Rupr. (needle and thread grass)) and 2 native forbs (*Astragalus canadensis* L., Canada milk vetch and *Vicia americana* Muhl. ex Willd., wild vetch), common in mixed-grass prairie. Seed was sown at 10 kg/ha.

Experimental design

Six research sites represented landscapes typical of the surrounding prairie. Sites were southeast to northwest of each other and ≈1 km apart, except for Site 6, which was 21 km from the

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others. Three sites were in community pastures under the same management, including no ROW fencing. At these sites, the ROW consisted of 7 m of storage area to the west (23% of ROW) and 19 m of work area to the east (63%). The other three sites were on private land; ROWs were fenced until 2014 and had variable grazing regimes. These ROW had 10 m of storage area (30% of ROW) with 4–15 m of work area (13–50%); location of storage and work areas relative to the trench varied, and work areas were on one or both sides of the trench.

The Government of Canada has recommended a setback distance of 300 m from a pipeline ROW to protect federally listed plant species at risk (Henderson 2011). Three segments of the pipeline were randomly selected at each site and used as start points for perpendicular transects that ran from the trench center to 300 m from the ROW edge in both directions. There were 36 transects (6 sites × 3 transect locations × 2 directions). Sampling locations along each transect included trench, storage, and work areas and various distances from the ROW edge up to 300 m. Sampling locations were considered experimental units. Specific distances sampled varied somewhat for soil and vegetation and among yr and are described later. Using careful planning and a relatively large number of plots over hundreds of meters of undulating landscape, potential issues related to spatial autocorrelation for plots in 0-, 5-, 10-, 20-, and 30-m distances were minimized with our design.

Soil assessment

Soils were assessed and sampled in May 2010, May 2013, and July 2018. Soil penetration resistance was measured using a cone penetrometer (2.3-cm length, 1.2-cm diameter) in 2010 and 2013. Measurements were taken on ROW, at intervals up to 50 m from the ROW edge and in 2013 at a 300-m reference. Three to five measurements were taken at 5-, 10-, 15-, and 20-cm depths at each sampling location and considered subsamples.

Soil was sampled on and off ROW with a 5-cm diameter Dutch auger each yr. Three subsamples were taken at each sampling location and composited. Sampling on ROW in 2010 and 2018 was at 0–10 cm and 11–20 cm and in 2013 at 0–5 cm and 6–15 cm. The upper sampling depths are hereafter called "surface"; the lower depths are called "at depth." Off ROW samples were taken 10 m and 20 m from the ROW edge. At-depth samples were not taken off ROW in 2010.

Samples were kept cool until submitted to a commercial laboratory for analyses. Particle size analysis was determined by the hydrometer method (Carter 1993); total carbon, total organic carbon, and total nitrogen by LECO combustion (Nelson and Sommers 1982); and total inorganic carbon by calculation. Soil pH, electrical conductivity, sodium adsorption ratio, base saturation, and soluble salts were determined via saturated paste (Carter 1993).

Vegetation assessment

Vegetation assessments were conducted annually on and off ROW from 2009 to 2014 and in 2018. Assessments were conducted mid to late July. Data were collected annually on trench, storage, and work areas. In 2009, 2010, 2012, and 2013 vegetation data were collected off ROW, at every m for a distance of 5 m, then every 5 m to 20 m, every 10 m to 50 m, and every 50 m to 300 m. In 2011, vegetation data were collected at 10, 20, 30, and 50 m; in 2014 at 5, 10, 20, and 100 m; and in 2018 at 10 and 20 m from the ROW edge. A 20 cm × 50 cm quadrat was placed with the short end along the transect at each sampling location. Ocular estimates were made of percent ground cover (bare, litter, vegetation) and canopy cover by species in each quadrat. Plant identification and nomenclature followed Moss (1994) and Tannas (2003a, 2003b).

Data analyses

Plant species were classified as native and non-native according to the Alberta Conservation Information Management Sys-

Table 1
Select surface soil properties on pipeline rights-of-way areas 1 yr (2010), 4 yr (2013), and 9 yr (2018) after construction.

			Total Organic C %	Total Number %	pH	EC dS/m	SAR	Ca mg/kg	Mg mg/kg	Na mg/kg
2010	Storage	Mean	1.98^{a}	0.18^{a}	7.49^{b}	0.49^{B}	0.30abc	64.52^{B}	18.55^{AB}	10.52^{ab}
		SD	0.93	0.08	0.56	0.24	0.27	37.81	12.83	9.46
	Trench	Mean	1.42^{a}	0.13^{a}	7.99a^{a}	0.53^{B}	0.74^{a}	63.26^{B}	18.27^{B}	23.55^{a}
		SD	0.53	0.04	0.43	0.11	1.32	13.92	4.09	33.32
	Work	Mean	1.91^{a}	0.15^{a}	7.22^{b}	0.47^{AB}	0.28^{b}	58.76^{B}	18.25^{AB}	10.41^{b}
		SD	0.85	0.06	0.55	0.25	0.35	34.90	11.59	16.00
	10 m	Mean	2.45^{b}	0.23^{b}	7.07^{b}	0.48	0.16c	62.67	17.92	5.16^{b}
		SD	1.06	0.09	0.74	0.36	0.15	73.17	19.98	4.58
	20 m	Mean	2.36^{b}	0.23^{b}	7.10^{b}	0.40	0.15c	49.10	13.46	3.87^{b}
		SD	1.04	0.09	0.74	0.12	0.09	21.84	5.14	2.55
2013	Storage	Mean	1.83^{a}	0.19	7.32^{a}	0.48^{B}	0.16	63.27^{B}	17.15^{B}	6.78
		SD	0.74	0.10	0.54	0.20	0.39	36.35	8.71	16.30
	Trench	Mean	1.43^{a}	0.20	7.46^{aB}	0.52^{B}	0.59	58.49^{B}	17.01^{B}	15.63
		SD	0.59	0.09	0.45	0.16	1.80	21.98	7.68	39.34
	Work	Mean	1.97^{ab}	0.20	7.12^{ab}	0.43^{A}	0.13	51.18^{B}	14.76^{B}	4.18
		SD	1.08	0.08	0.56	0.13	0.13	23.27	5.37	3.98
	10 m	Mean	2.64^{b}	0.27	6.77^{b}	0.43	0.16	51.09	15.60	6.36
		SD	1.00	0.13	0.65	0.19	0.34	29.20	8.28	15.49
2018	Storage	Mean	2.00	0.19	7.16^{ab}	0.70^{A}	0.14	99.99^{abA}	26.06^{A}	5.99
		SD	0.56	0.05	0.52	0.34	0.23	45.38	8.41	9.86
	Trench	Mean	1.73	0.16	7.43^{aB}	0.72^{A}	0.29	100.48a^{a}	27.76^{A}	11.06
		SD	0.56	0.05	0.36	0.10	0.73	21.36	5.37	25.36
	Work	Mean	1.93	0.18	7.04^{b}	0.61^{B}	0.13	86.70^{abA}	22.59^{A}	5.07
		SD	0.59	0.05	0.58	0.24	0.19	38.86	6.92	7.01
	10 m	Mean	1.91	0.18	7.03^{b}	0.60	0.16	82.52^{ab}	22.97	6.14
		SD	0.69	0.06	0.67	0.19	0.28	31.58	9.03	10.38
	20 m	Mean	1.95	0.18	6.83^{b}	0.62	0.70	73.42^{b}	23.04	21.88
		SD	0.53	0.05	0.57	0.41	3.32	30.23	8.61	99.77

EC, Electrical conductivity; SAR, sodium adsorption ratio; C, carbon; Ca, calcium; Mg, magnesium; Na, sodium; SD, standard deviation of the mean. Means that do not share a common lowercase letter are different within yr. Means that do not share a common uppercase letter are different between yr.

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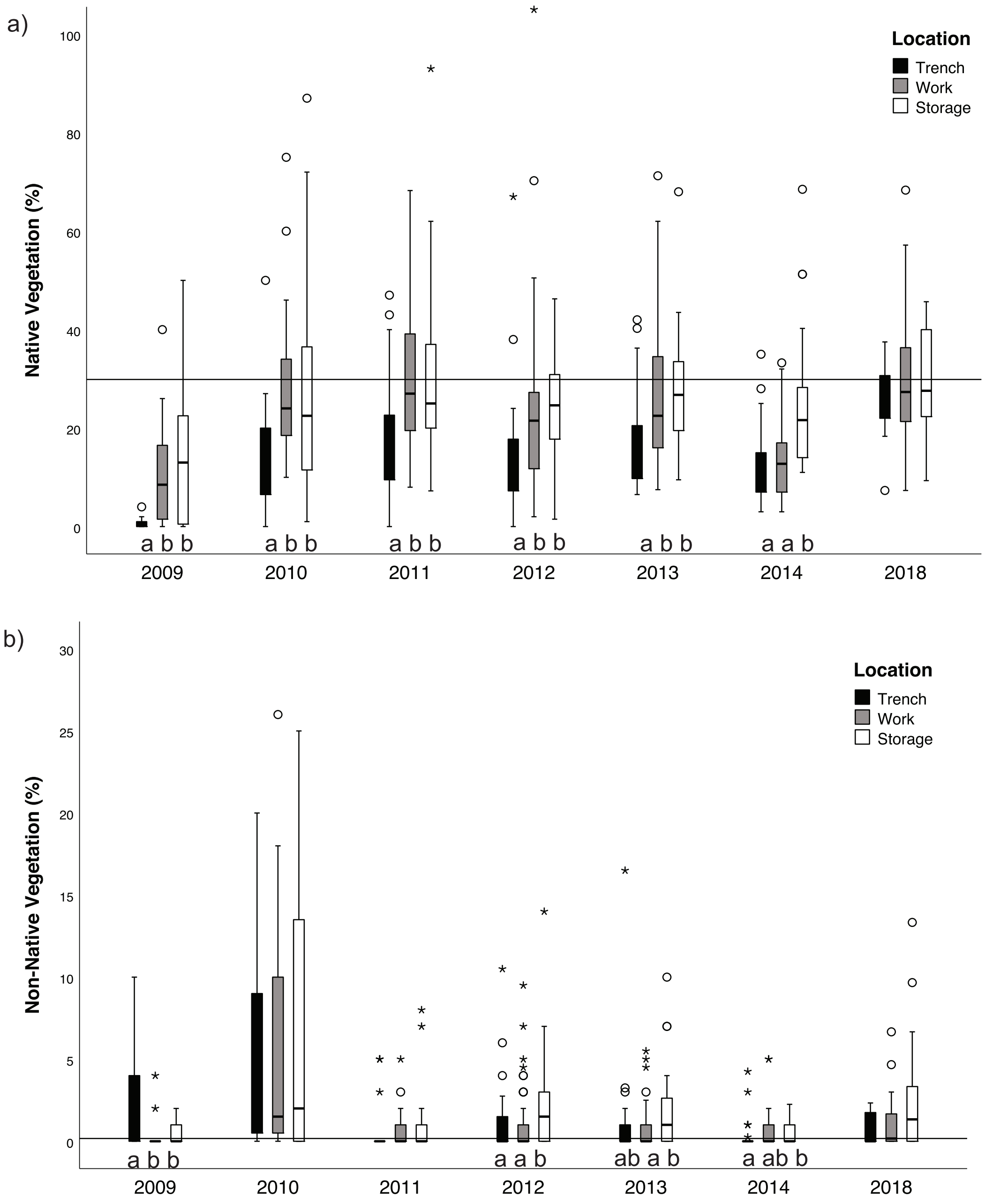

Fig. 1. Mean percent **a,** native and **b,** non-native vegetation canopy cover on pipeline trench, storage, and work areas 2009–2018. Lines represent undisturbed prairie reference cover mean. Letters indicate significant differences within yr.

tem vascular plant element list (2015) and then categorized as graminoid (grasses, sedges); forb; shrub; or cactus. Species richness and Simpson diversity index were calculated for each quadrat.

Data were tested for normality and homogeneity of variance before analyses. Differences in soil and plant response variables were tested using 1-way analysis of variance (ANOVA) with yr; ROW area (trench, work, storage); and distance from ROW edge as factors. Data that did not meet parametric assumptions were log transformed, and ANOVA was conducted if assumptions were then met. Tukey post hoc tests were employed following significant ANOVA tests. Nonparametric Kruskall-Wallis and Wilcoxon rank post hoc tests were employed for data that did not meet parametric assumptions when log transformed. Correlation analyses were conducted to assess the relationship between vegetation response variables and distance from ROW edge in 2009, 2010, 2012, and 2013. Select distances were used for analysis of variance. All analyses were conducted using an alpha value of 0.050, and all references to significant results are at $P \leq 0.050$.

A reference distance of 100 m was used to compare with ROW areas; this distance was assessed in most yr and is approximately halfway between the edge and 300 m. There were few differences among 100, 150, 200, 250, and 300 m, and between-yr variability was consistent for each of these distances (data not shown).

Results

Soil properties

Soil texture was generally sandy loam with no significant differences among ROW areas and distances from ROW edge (data not shown). Trench surface soil pH decreased significantly between yr, and calcium, magnesium, and electrical conductivity increased

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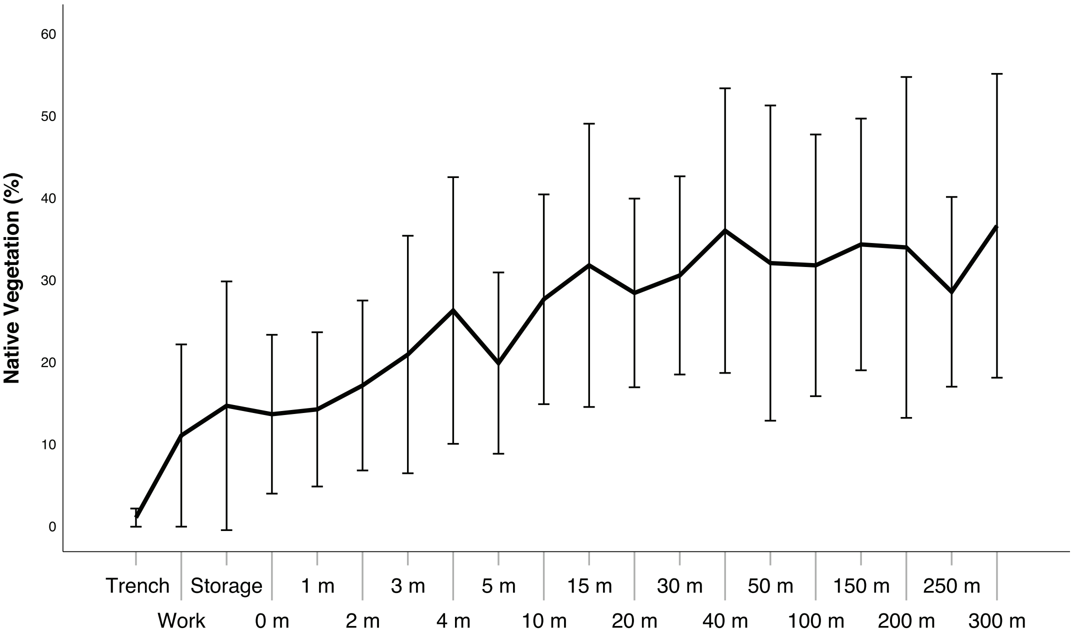

Fig. 2. Mean native vegetation canopy cover at distance from the right-of-way edge in 2009. Bars represent standard deviation.

(Table 1). Electrical conductivity and sodium adsorption ratio were < 1 in all ROW areas and not of concern for plant growth. Trench total nitrogen was greater at surface and depth in 2013 and 2018 than in 2010. Soil chemical properties did not differ significantly among yr for storage and work areas or between distances from ROW edge within or between yr.

Within yr, trench surface soil had significantly lower organic carbon and total nitrogen than the storage area in 2010 and significantly higher pH than storage and work areas (see Table 1). In 2013 trench pH was greater than work areas; in 2018 it was significantly higher than work or storage areas, and magnesium was significantly higher on the trench than work area. In 2010 trench soil at depth (data not shown) had the highest pH, sodium adsorption ratio, and sodium content. Soil pH remained significantly higher on trench at depth in 2013 and 2018 than the work area. Magnesium was higher on the trench at depth in 2018.

Soil chemical properties on ROW were compared with 10 m from the ROW edge; a distance assessed in all yr as a reference. In 2010, trench surface soil had significantly less organic carbon and total nitrogen and greater pH, sodium adsorption ratio, percent saturation, and sodium content than 10 m from the ROW (see Table 1). In 2013, differences in organic carbon and pH remained, and in 2018 pH differences remained. At depth, pH and magnesium were greater on trench than 10 m from the ROW in 2013 and 2018 and calcium in 2013.

Penetration resistance was not significantly different among ROW areas at any depth. Across ROW, surface penetration resistance was 0.4–5.7 MPa and at depth 0.9–6.4 MPa. Values increased to 10-cm depth on all ROW areas and continued to increase with depth on the trench. Penetration resistance was significantly lower at 10 m from the edge than all ROW areas at 5 cm, and trench and work at 10 cm and 15 cm, respectively. Mean values at 5 cm were consistently < 2 MPa off ROW (0.5–3.9 MPa) and > 2.9 MPa on ROW. At the ROW edge, 2010 values were significantly higher than other distances at 5- and 10-cm depths; there were no differences with distance in 2013. Penetration resistance was significantly higher in 2013 than 2010 at all depths from 5 m to 50 m from ROW edge, likely due to drought.

Vegetation canopy cover

Postconstruction ROW vegetation cover was primarily native species and dominated by native graminoids, many seeded, although common in the undisturbed community. The dominant graminoid on and off ROW was *Bouteloua gracilis;* other common species included *Agropyron smithii, Agropyron dasystachyum, Stipa comata, Agropyron trachycaulum,* and *Carex*. Dominant forbs on ROW were *Lepidium densiflorum* Schrad. (pepper weed), *Silene drummondii* Hook (drummond's campion), and *Ratibida columnifera* (Nutt.) Wooton & Standl. (prairie coneflower). Dominant forbs off ROW were *Selaginella densa* Rydb. (prairie selaginella), *Phlox hoodii* Richardson (moss phlox), and *Sphaeralcea coccinea* (Nutt.) Rydb. (scarlett mallow).

Native cover on trench, work, and storage areas differed significantly among yr (Fig. 1a), significantly lowest in 2009. By 2018 it increased significantly on ROW, 2 × on storage and work areas and 50 × on the trench. It was significantly lower on trench than work or storage areas from 2009 to 2013 (see Fig. 1a). By 2014 trench cover was similar to work and less than storage; by 2018 there were no differences among ROW areas. Native cover was dominated by graminoids, over 80% in most yr.

Native forb cover varied among yr and ROW areas, from 0.0% ± 0.0% (storage 2009) to 4.6% ± 7.4% (storage 2010). In 2018 it was greater than in 2009 (3.8% ± 5.3% and 0.1% ± 0.6%, respectively). Native shrub cover increased significantly with time on trench, work, and storage areas. In 2009 it was only on the storage area ($< 1\%$); by 2010 it was on all ROW areas and increased by 2018 (6.2% ± 7.7% storage, 6.5% ± 12.7% work, 4.8% ± 4.9% trench). There were no biologically meaningful differences in shrub cover between ROW areas or yr.

Non-native canopy cover was generally $< 2\%$ in any yr or ROW area (see Fig. 1b). The exception was 2010, when it was significantly greatest across ROW areas. This increase was mainly composed of annuals including *Taraxacum officinale* L. (common dandelion), *Chenopodium album* L. (lamb's quarters), *Amaranthus blitum* L. (purple amaranth), *Polygonum aviculare* (prostrate knotweed), and *Descurainia sophia* (L.) Webb ex Prantl (flixweed).

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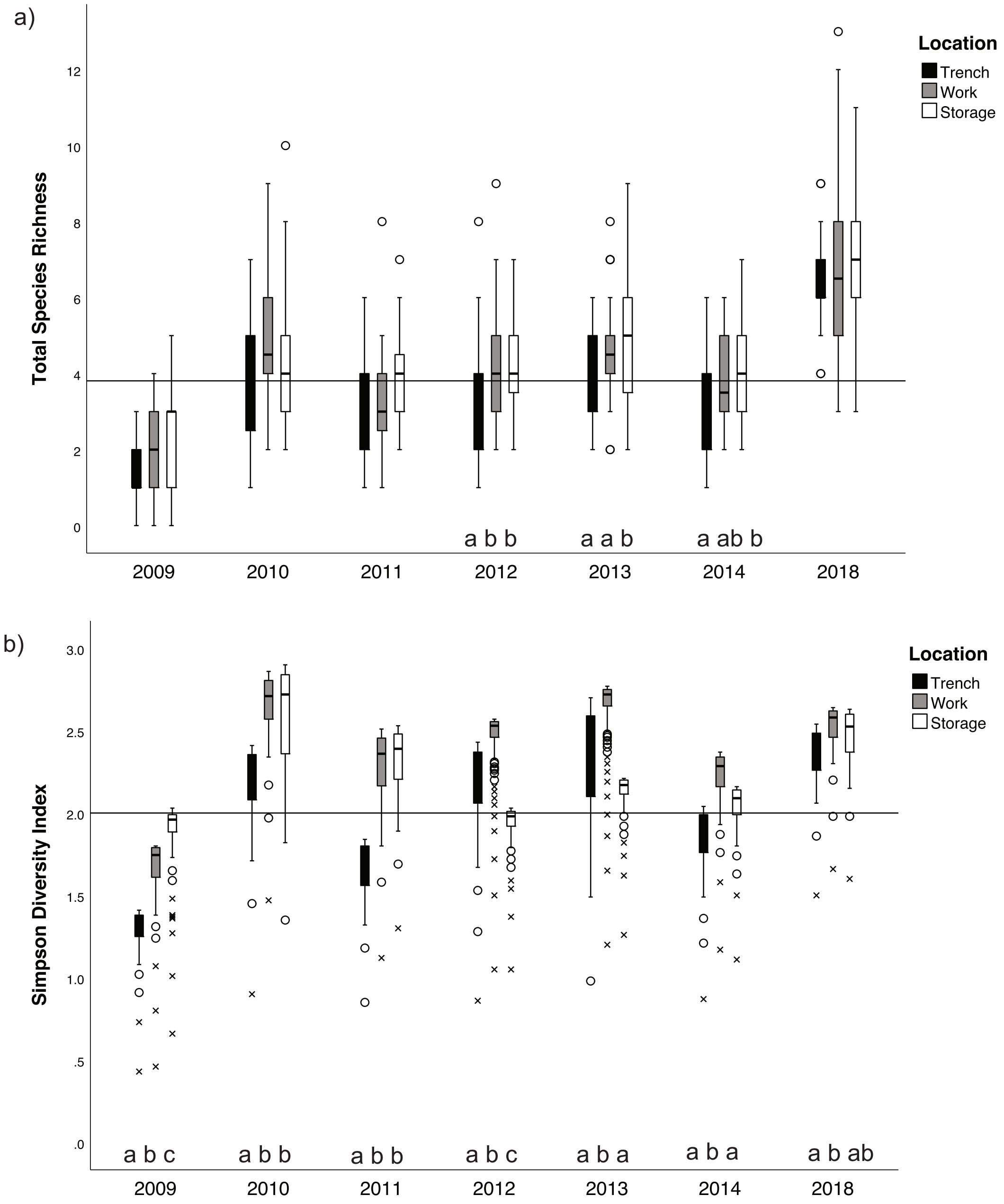

Fig. 3. Mean **a,** total species richness and **b,** Simpson diversity index on trench, storage, and work areas from 2009 to 2018. Lines represent undisturbed prairie reference mean. Letters indicate significant differences within yr.

Most were not present or in very low occurrence on ROW by 2011.

Non-native plant cover was significantly higher on the trench than work or storage areas in 2009, with few biologically meaningful differences in other yr (see Fig. 1b). *Triticum* species (seeded cover crop) dominated non-native cover in 2009, disappearing on the work area in 2009 and on any ROW area after 2010. Non-native forb cover was significantly greater on the storage than work area in 2012, 2013, and 2014. The dominant species was *Taraxacum officinale*.

With distance from ROW edge, native cover significantly increased in 2009; non-native cover decreased in most yr significantly in 2009, 2010, and 2014. In 2009 native cover was significantly less a few m from the ROW edge than beyond 10 m, with few biologically meaningful differences by 5 m (Fig. 2). Non-native graminoid cover was significantly greater at 10 m than 20 m from ROW edge in 2014 and 2018. Increases were due to *Agropyron cristatum* L. Gaertn. (crested wheatgrass) at 10 m at some sites, although it was not in higher abundance on ROW in these yr. Variability between yr at a given distance from the ROW edge was low.

Relative to a reference distance of 100 m from ROW edge, total native, graminoid, and shrub vegetation cover on ROW were generally similar after 2009. Native forb cover was less than the reference distance in all yr. Non-native canopy cover was generally $< 2\%$ in any yr or ROW area but greater than the reference non-native cover in all yr.

Plant species richness and diversity

Total species richness on ROW areas was significantly lowest in 2009 and greatest in 2018 (Fig. 3a). There were no differences among ROW areas in 2009 or 2018; in other yr, richness was

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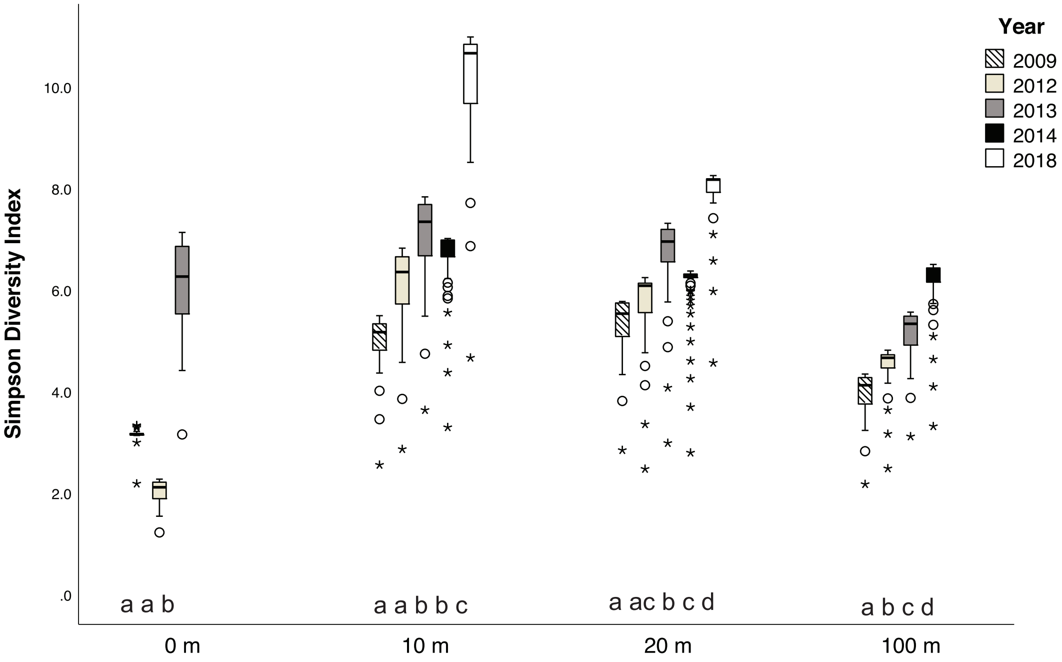

Fig. 4. Simpson diversity index at distance from the right-of-way edge from 2009 to 2018. Letters indicate significant differences within distances.

higher on the trench than work and storage areas, significantly in 2012, and lower than storage in 2013 and 2014. Native species richness was significantly lower on the trench than work and storage areas in 2009 and 2012 and the storage area in 2014.

There was a significantly positive trend in native species richness and a negative trend in non-native species with distance from ROW edge in 2009. Non-native species richness was negatively associated with distance in other yr, significantly in 2010 and 2014. Native species richness was significantly lower in the first couple of m from the ROW edge than farther distances in 2009. Species richness on ROW was similar or greater than reference prairie at 100 m and the same species were present.

Species diversity trends were highly variable on ROW areas between yr. Diversity was greatest across ROW areas in 2010, with abundant annual weeds, and increased with time on trench and work areas (see Fig. 3b). Diversity was lowest on the trench in 2009, 2010, and 2011 and then became more similar to the storage area. It was significantly lower on ROW than 10 m or 20 m from the ROW edge in 2009 to 2011. In 2018 it was less on ROW than at 10 m but similar at 20 m and at the 100-m reference point. Diversity at distance from the ROW edge was significantly less in 2009 than 2013 to 2018 at 0, 10, 20, 50, and 100 m (Fig. 4). Differences among distances within yr were not biologically significant, reflecting natural variability in species abundance and composition.

Ground cover

In the first 5 yr vegetation ground cover was significantly lowest on the trench (Fig. 5a) and similar on storage and work areas. In 2018 there were no differences among ROW areas. Bare ground declined, and litter increased with time, with annual fluctuations on the trench. In 2009 bare ground was similar among ROW areas, after which it was highest on the trench, significantly greater than on work or storage areas in 2010, 2012, 2014, and 2018 (see Fig. 5b). There were few biologically meaningful differences in litter cover among ROW areas (see Fig. 5c).

There was a significant positive association in the first 2 yr between distance from the ROW edge and vegetation ground cover and litter and a negative association with bare ground. There were no significant correlations in later yr. Near the ROW edge, litter almost doubled and bare ground was reduced by half (data not shown) within a yr. By 2014, bare ground and litter were similar to reference cover (100 m) in storage and work areas. By 2018, differences were significant only on the trench and vegetation ground cover on ROW was similar to that at distance (see Fig. 5).

Discussion

This study contributes significantly to the body of scientific knowledge on pipeline construction effects on grassland soil and plant communities, of particular relevance with the increased scrutiny of pipelines in the past decade and the 10-yr study period. Understanding the resilience of grasslands is important for conservation planning incorporating multiple types of disturbance. A large-diameter pipeline ROW constructed in dry mixed-grass prairie using minimal disturbance techniques and rare plant mitigation measures had negligible effects on surrounding soil and plant communities 10 yr after construction. Any changes to vegetation that persisted on ROW were mainly confined to the trench, followed by work and storage areas, and relative to construction disturbances on these areas.

Of specific significance were the negligible changes in soil properties after pipeline construction. Although there were small reductions in organic carbon and total nitrogen, as well as increases in pH and penetration resistance, most variability was within expected ranges for undisturbed soil in mixed-grass prairie. This lack of significant impact from pipeline construction was likely due to minimal disturbance construction techniques, such as construction under frozen soil conditions (Desserud et al. 2010; Desserud and Naeth 2013). Results support other grasslands studies that show changes in organic carbon and salinity the first yr following pipeline construction (Gasch et al. 2014, 2016), with recovery of most soil properties in work and storage areas (Shi et al. 2014). Other studies have shown that factors affecting recovery

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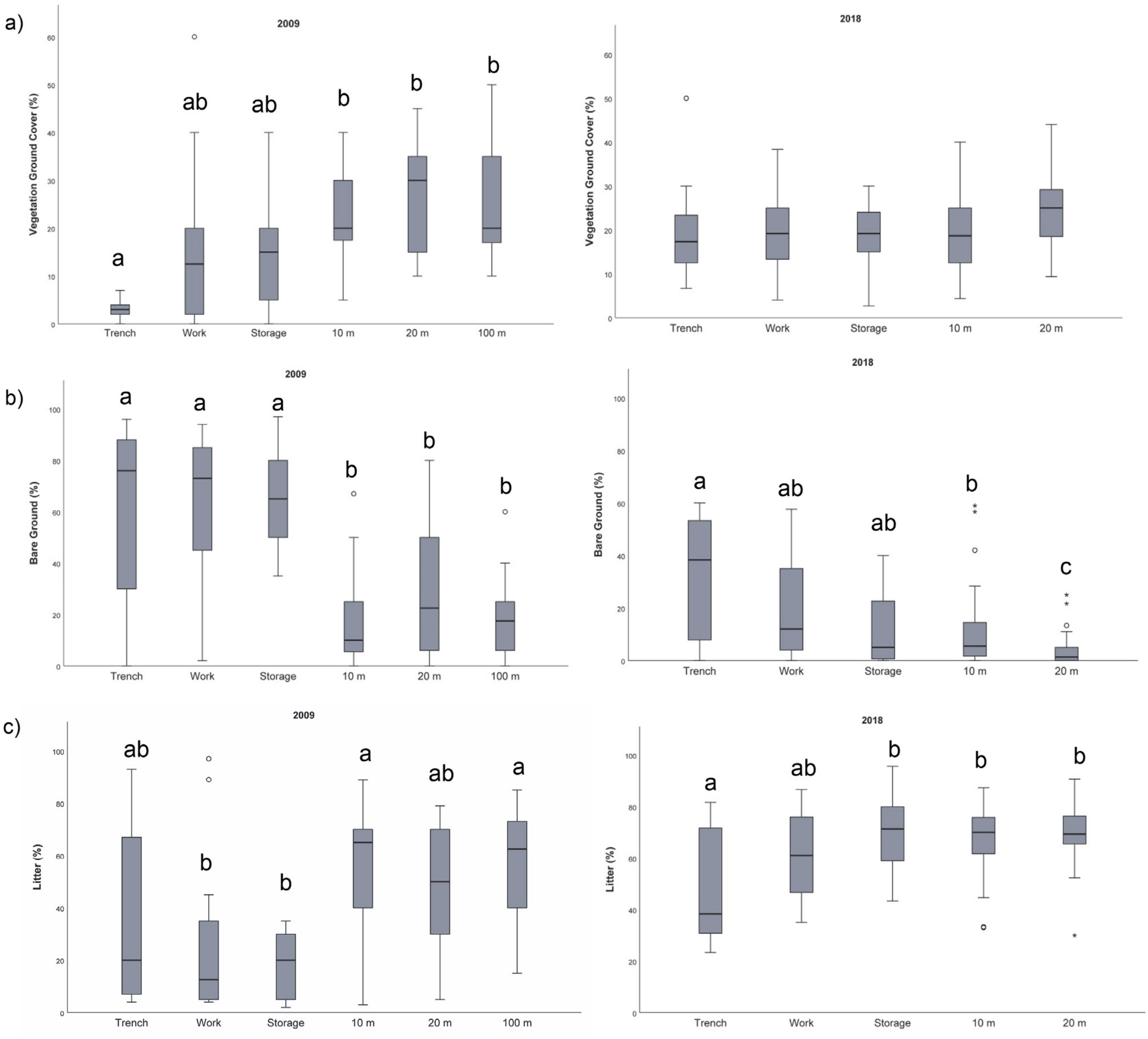

Fig. 5. a–c, Ground cover (%) on right of way (ROW) and at distance from the ROW edge in 2009 (left), the yr of construction and reclamation, and in 2018 (right), 10 yr later. Letters indicate significant differences.

from pipeline disturbances include precipitation and air temperature (Bayramov et al. 2012; Xiao et al. 2016), topography (Shi et al. 2014), and management practices (Desserud et al. 2010; Xiao et al. 2016). Higher-than-average precipitation 2 yr after pipeline construction would have been beneficial to recovery, and considerably lower spring precipitation and temperatures in 2014 could explain the decline in overall vegetation and noticeable change in the recovery trend that yr.

In dry mixed-grass habitat, pipeline construction and reclamation had no persistent impacts on soil and vegetation off ROW. Impacts that extend considerable distances from ROW edges are more prevalent with disturbances that increase access, traffic, and soil erosion and/or create airborne dust (Farmer 1993; Forman and Alexander 1998; Rai 2016). There is much literature on impacts from transportation corridors (e.g., Angold 1997; Forman et al. 1998; Spellerberg 1998; Mullerova et al. 2011). However, pipelines do not result in heavy traffic following construction. As in this study, if constructed during winter with frozen ground, careful topsoil salvage and replacement, and summer seeding of native species soon after, soil disturbance, erosion, and dust are minimized. Dust and erosion following pipeline construction only last as long as it takes for vegetation to establish. Within a few yr, vegetation cover and composition on ROW were similar to off ROW reference sites in our study. Bare ground persisted on the trench, although the trend with time was positive, suggesting it will eventually be mitigated. Less disturbed ROW areas recovered more quickly than the trench, even though the disturbance area was greater. Expected differences in recovery between storage and work areas were not consistently found and may reflect mitigative measures to reduce impacts of vehicular traffic in work areas.

Changes in plant species composition were not always measured in studies of edge effects and were expected to result in detrimental long-term changes in ecosystem function (Avon et al. 2010). Impacts resulting from pipelines include absence or reduction in keystone species, such as *Festuca hallii* (Vasey) Piper (rough fescue) in fescue grassland 6–30 yr following pipeline construction (Elsinger 2009) and *Selaginella densa* in fescue and mixed-grass prairie for up to 32 yr (Naeth 1985; Ostermann 2001; Elsinger 2009). In our study, after 10 yr all species reestablished on ROW, although abundances of a few were lower including *Se-*

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laginella densa. Shrubs, which provide important microsites for plants in arid environments including rare species (ASRD 2005), reestablished on ROW with time and had the same abundance as off ROW. Reintroduction of some plant groups on ROW, specifically forbs, rather than the historic focus on native grasses could accelerate plant community restoration. Two forbs, both legumes, were seeded but uncommon in adjacent native prairie and did not readily establish. Inclusion of dominant forb species in revegetation seed mixes could enhance recovery, including reducing bare ground.

It is sometimes difficult to separate effects of a given current disturbance (pipeline) from longer-term management impacts (poor grazing management) or climate aberrations. In our study the same plant species pool was present near and far from the ROW, with varying abundances. Non-native plant species occurred in native prairie near and far from the ROW. Abundance of these species was highly variable, between distances and yr, with no increasing or decreasing trend with time. Weedy annuals established on the ROW initially, but their abundance declined rapidly, as is common in early successional stages on disturbed sites. Persistence of bare ground resulted in the somewhat greater abundance of non-native, although mostly naturalized species, on ROW than native prairie. Grasslands are commonly managed, as many sites in this study were, with high diversity and low abundance of non-native plant species maintained by appropriate grazing regimes (Hickman et al. 2004).

Implications

A large-diameter pipeline ROW constructed with minimal disturbance techniques and rare plant mitigation measures had small but persistent effects on ROW and negligible effects on surrounding dry mixed-grass prairie after 10 yr. First-yr impacts on soil and vegetation on ROW, and at distances up to 5 m from it, were pronounced; however, within 2 growing seasons, they were dramatically reduced with trends toward reference prairie conditions. Surrounding mixed-grass prairie was not impacted. The study area is critical habitat for a number of rare plant species, and resilience of soil and plant communities in this study following a linear disturbance created by a pipeline provides important knowledge for grassland conservation and management. Use of minimal disturbance construction techniques reduced size and intensity of the disturbance footprint, allowing for even sensitive arid habitat to recover within a short period of time. Similar construction techniques for other disturbances in grasslands would reduce impacts to soil and vegetation communities and increase ecosystem resiliency.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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