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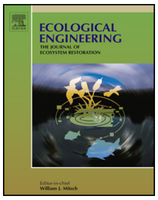

Mulch amendment facilitates early revegetation development on an abandoned field In northern mixed grass prairies of North America

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ABSTRACT

Extensive areas of the northern mixed grass prairies of North America require restoration and reclamation as they have been extensively disturbed by agricultural, mining and oil and gas related activities. Amending seedbeds with mulch may avoid soil erosion and help both plant recruitment and early vegetation development in these water limited landscapes. A field experiment was established to determine if straw and hay mulch facilitate early revegetation. The site is an abandoned irrigation area in southern Alberta, Canada. Soil was tilled and the seedbed prepared through manual harrowing, then plots were broadcast seeded with *Elymus trachycaulus*, *Bouteloua gracilis*, *Astragalus canadensis* and *Linum lewisii*. Hay and straw mulch were applied at two rates (300 and 600 g m^{-2}). Plant recruitment and cover were assessed through the first four years. Mulch had a positive impact on recruitment of all species planted except *Bouteloua gracilis.* While a thinner material like hay proved to be most effective at high rates (600 g m^{-2}), a thicker material like straw encouraged quick recruitment for these species only at low application rates (300 g m^{-2}). However, these early differences among mulch treatments did not show an impact in either recruitment or cover during subsequent years. *Bouteloua gracilis*, whose recruitment and growth were broadly impaired by mulch, showed an abundant and constantly increasing cover in the bare ground control and in plots with low application rates of hay. Both recruitment and cover per species indicate that plots are following two different trajectories that show some degree of resilience; the bare ground treatment is dominated by *Bouteloua gracilis* whereas the mulch treatments are characterized by vegetation dominated by *Elymus trachycaulus, Linum lewisii* and *Astragalus canadensis.*

1. Introduction

Northern mixed grass prairies of North America have been extensively disturbed through cropping and oil and gas extraction activities. Disturbances include the complete loss of vegetation and deep soil perturbations such as soil horizon admixing, soil compaction and soil contamination. Denuded dry mixed grass prairies are prone to erosion and encroachment of invasive species, so rapid plant cover is highly recommended (Kerr et al., 1993). Land use in the region is partitioned between crop production under irrigation or rainfed rangeland grazing, the latter more environmentally friendly than the former. Thus establishment of native vegetation resembling that of a natural prairie is a popular reclamation option as it satisfies requirements for attaining equivalent land capability linked to a positive impact on public opinion. However, a spontaneous return to native range conditions after disturbance is slow in the northern mixed grass prairies (Dormaar and Smoliak, 1985), making it critical to develop revegetation techniques to accelerate the process.

Successful revegetation in semi-arid grasslands is a challenge as water availability strongly limits plant establishment, growth and survival. The mixed grass prairies are characterized by their variability and deficiency in precipitation during the growing season (Coupland, 1992) so any measure to conserve soil water may have positive effects on revegetation. Practitioners have envisioned the use of surficial amendments with straw and hay as a way to control water and wind erosion and to improve the soil water balance during reclamation (Kerr et al., 1993; Fehmi and Kong, 2012). Surficial amendments can also improve germination rates of broadcast seeds (Mollard and Naeth, 2014), particularly on those grassland species whose seeds are photo-inhibited; thus germina-

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tion is encouraged on covered soils relative to bare soils (Baskin and Baskin, 1998, 2014; Mollard and Naeth, 2014). However, uncertainties about mulch effects on vegetation arise due to the lack of well documented scientific research for the region. Due to their similar nature, it is possible to draw a parallelism between straw or hay mulch and litter, with the purpose to overcome the scarce mulch research and use patterns found from litter research in the northern mixed grass prairies.

The importance of the effects of litter on structure and function of mixed grass prairies has been highlighted through litter manipulation experiments (Willms et al., 1986; Naeth et al., 1991; Deutsch et al., 2010). That knowledge can be used to anticipate possible outcomes of the effects of mulch types and rates on seedling emergence and establishment and on performance of adult plants. Litter has a significant effect on microclimate near the ground surface and plays a main role in the surface–atmosphere energy and water exchange (Facelli and Pickett, 1991). High litter amounts improve soil water content and stabilize plant production, providing an important drought management strategy in northern prairies (Willms et al., 1986, 1993; Deutsch et al., 2010). Those results justify the use of mulch as a revegetation technique; however, abundant litter may intercept rainfall and affect water available for infiltration (Naeth et al., 1991).

Despite the positive effects of litter on plant productivity and range value (Willms et al., 1986, 1993; Deutsch et al., 2010), its effects on plant performance and on development of a diverse prairie vegetation are not clear. Litter may have a positive effect on seedling survival and establishment by improving soil water balance or attenuating soil maximum temperatures; or negative effects due to its high mechanical impedance and the increase in the path a seedling needs to penetrate during emergence (Facelli and Pickett, 1991). Meta analyses of global data have shown that litter usually has neutral to inhibitory effects on seedling establishment and on plant diversity, especially at high quantities (Xiong and Nilsson, 1999; Loydi et al., 2013). In the aspen parkland prairies, litter has a negative influence on diversity by reducing plant richness (Lamb, 2008) and dense litter accumulation in temperate grasslands can affect plant growth and development, so plants grow more slowly and flower more sparsely due to lower soil temperatures (Weaver and Rowland, 1952). This background suggests that litter quantity is a main driver of plant and vegetation responses. Therefore, we hypothesized that both mulch application rate and texture would affect plant performance which prompted us to evaluate two mulch materials, cereal straw and hay, at two contrasting amendment rates for grassland restoration.

A manipulative experiment in the northern mixed grass prairies of southern Alberta showed that mulch improved seedbed environmental conditions and increased seedling emergence during the first year of prairie revegetation (Mollard et al., 2014). That experiment, on an abandoned irrigated crop field, showed that the effect of mulch on plant establishment varied from facilitative to inhibitory depending on mulch texture (hay vs. straw) and amendment rates as high straw rates hindered plant recruitment (Mollard et al., 2014). In this paper we continue the above mentioned research during the first four years of reclamation to determine if straw and hay mulch at different rates accelerated native plant species revegetation in northern mixed grass prairie.

2. Materials and methods

2.1. Experimental site

The experimental site is situated on the Rangelands Research Institute of the University of Alberta in the Dry Mixed Grass Prairie Ecozone of southern Alberta (50°53′30.7″ N, 111°56′52.1″ W), Canada. Natural vegetation is dominated by *Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths (blue grama grass), *Hesperostipa comata* Trin. & Rupr. (needle and thread grass)) and *Koeleria macrantha* (Ledeb.) Schultes (june grass) (Strong and Leggat, 1992). The climate is continental, sub-humid, characterized by long cold winters and short summers. Mean July and January daily temperatures of the region are 18.3 and −11.3 °C, respectively (Environment Canada, 2016). Mean annual precipitation in the region is 348 mm, two thirds occurring during the growing season (Environment Canada, 2016; Kjearsgaard et al., 1983). Potential evapotranspiration deficit during the growing season exceeds 100 mm (Strong and Leggat, 1992). Elevation is 720 m above sea level. The landscape is rolling with fluvial-eolian loamy sand surficial deposits (Kjearsgaard et al., 1983). Topsoil is well drained, sandy to loamy sand texture, with a sand content of 87%, an organic matter content of 1.2% and a pH of 6.45 (Naeth et al., submitted manuscript).

Research was conducted in an old abandoned irrigation field which was seeded with *Bromus inermis* Leyss. (smooth brome) after agricultural use. Established vegetation was dominated by *Bromus inermis*, *Calamovilfa longifolia* (Hook.) Scribn. (prairie sand reed) and *Artemisia frigida* Willd (pasture sage). The land is used as cattle range on a rotational grazing basis.

2.2. Soil preparation, seeding and mulch treatments

On May 15, 2012, a 0.36 ha (65 × 55 m) site was sprayed with glyphosate (Roundup Transorb, Monsanto, St. Louis, MO, USA) at a rate of 8 l/ha, rototilled to a depth of 15 cm 10 days later, and fenced to prevent cattle and wildlife grazing. Six replicate 2 × 2 m plots per treatment were hand raked to remove dead plant material and to prepare a smooth seedbed.

Certified seeds purchased from local suppliers were used in the experiment. Pure seed units were selected by diaphanoscopy. These pure seeds units consisted of intact natural dispersal units (caryopses, one seeded florets or seeds, hereafter referred as seeds). Seeded species were: *Hesperostipa comata* (Trin. & Rupr.) Barkworth (Syn = *Stipa comata* Trin. & Rupr. (needle and thread grass), *Elymus trachycaulus* (Link) Gould ex Shinners *ssp. trachycaulus* (Syn = *Agropyron trachycaulus* (Link) Malt. (slender wheat grass)), *Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths var. Bad River (blue grama grass), *Astragalus canadensis* L. var. ARC Aspen (Canada milkvetch) and *Linum lewisii* Pursh (wild blue flax). Plots were hand seeded on June 8 2012. Fifty seeds per species were carefully spread in a core area of 1 × 1 m centered in the 2 × 2 m treatment plots. The area outside the core worked as an area for soil monitoring, sampling and plant measurements. In this area seeds were weighted to get a target rate of 50 PLS per m^2 and species before seeding.

The experiment assessed two mulching materials commonly used for reclamation, wheat straw and rangeland hay. Different mulching properties were expected between these two materials due to coarser texture of straw (mostly wheat culms approximately 30 cm long and 0.5 cm in diameter) and finer texture of native hay (mostly thinner grass culms and leaves). The experiment followed a randomized single factor design with a bare ground control. Mulch treatments were: high hay rate, low hay rate, high straw rate, low straw rate and bare ground (control). Hay and straw were applied at rates of 300 (low) and 600 (high) g m^{-2}, considered appropriate for grassland revegetation (Kiehl et al., 2006; Kiehl and Wagner, 2006). On June 6, 2012, fresh native hay was mechanically mowed in a nearby field and harvested two days later (seeding day). Hay was composed of grass and forb plant material (green and dead leaves, vegetative stems with no previous year standing inflorescences). The surface layers of one year old wheat straw bales were used for straw mulch. Water content of the native hay and wheat straw was 8 and 7%, respectively, determined after oven drying at 90 °C to constant weight. Plots were covered with open mesh plas-

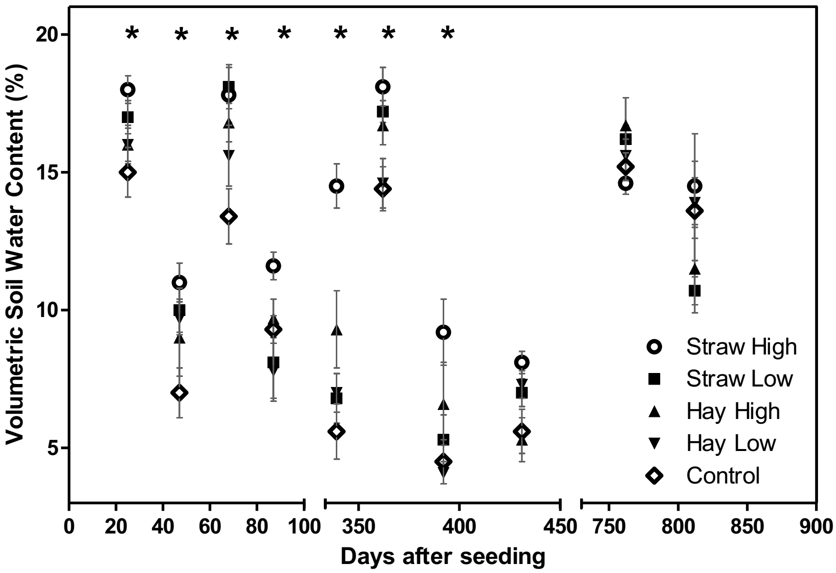

Fig. 1. Volumetric soil water content in the seedbed. Volumetric soil water content (mean ± SE, n = 6) of different treatments. Asterisks indicate significant differences among treatments for each date ($p < 0.05$).

tic (used to wrap bales) to prevent wind blowing the straw and hay material.

2.3. *Seedling recruitment monitoring*

Seedling recruitment was assessed annually from 2012 to 2015 during June. Individual seedlings were identified to species and marked with different coloured sticks. New recruiters in subsequent monitoring dates were marked and tracked as different cohorts. A seedling was considered emerged when it could be seen without disturbing the mulch. Since the seeded species were absent or had very low frequency and density at the site, all emerged seedlings were assumed to have originated from planted seed or seed of seeded plants.

2.4. *Plant canopy and* Bouteloua gracilis *reproduction assessment*

Canopy cover for each of the seeded species was ocularly assessed in 1 × 1 m quadrats in all plots in late August 2012 to 2014. Total canopy cover was visually assessed in August 2013 and August 2014, in parallel to canopy transmitted Photosynthetic Photon Flux Density of PAR light (used as an indirect measure of canopy structure). Transmitted daily photosynthetically active radiation (PAR) was measured just above mulches with a Li-Cor LI-191 Line Quantum sensor (Li-Cor Biosciences, Lincoln, Nebraska, USA). During each monitoring date, soil volumetric water content of the upper 5 cm of soil was measured in all replicates with an ML2x ThetaProbe (Delta-T devices, Cambridge, UK). *Bouteloua gracilis* reproductive plants and seed head density were evaluated in August 2013 in all plots with the exception of the high straw mulch treatment in which recruiters were never recorded. *Bouteloua gracilis* reproductive plants were counted as the fraction of plants that bore at least a seed head.

2.5. *Data analyses*

Cumulative seedling recruitment, cover per species, total plant cover and the fraction of intercepted PAR light were evaluated by repeated measures analysis of variance (rmANOVA), with mulch as the between subject main effect and time as the within subject factor (Von Ende, 1993). Significance of time and the interaction of mulch × time were determined through Wilks' Lambda multivariate tests. Contrasts were performed with *a posteriori* Tukey tests. Cumulative recruitment data were transformed using square root transformation to satisfy the assumption of homogeneity of variances. To satisfy the same assumptions, cover data and the fraction of intercepted PAR light were transformed using the arc sine formula $\sqrt{x}$. The significance of the comparison of *Bouteloua gracilis* reproductive capacity among treatments was assessed through Kruskal-Wallis non-parametric tests followed by post-hoc Dunn's comparisons. Soil volumetric water content from each monitoring date was analyzed with one-way ANOVAs followed by *a posteriori* Tukey tests ($p < 0.05$; Sokal and Rohlf, 1995). All statistical analyses were conducted using STATISTICA version 10 (StatSoft Inc. Tulsa, OK). All results are presented as untransformed means of six replicates ± standard error.

3. Results

3.1. *Mulch effects on seedbed and soil conditions*

Volumetric soil water content was significantly affected by mulch treatments (Fig. 1). Pairwise comparisons showed that straw mulch, especially at high rates, most effectively maintained high soil water contents relative to bare ground ($p < 0.05$, six out of ten sampling dates), while low straw rates were less effective in conserving soil water ($p < 0.05$, three out of ten sampling dates). Hay mulch effects were intermediate between high straw and control treatments and even high hay rates were rarely statistically different relative to bare ground ($p < 0.05$, two out of ten sampling dates). Interestingly, statistically significant differences in soil water among treatments disappeared after the peak of the second summer ($p > 0.05$) when gaps in mulching left soil exposed in most of the mulched treatments except the high straw treatment which was noticeably thicker in the first year.

3.2. *Mulch effects on cumulative seedling emergence*

Seedlings of all sown species emerged; however, results are focused on *Elymus trachycaulus*, *Bouteloua gracilis*, *Linum lewisii* and *Astragalus canadensis* due to lack of consistency and low emergence

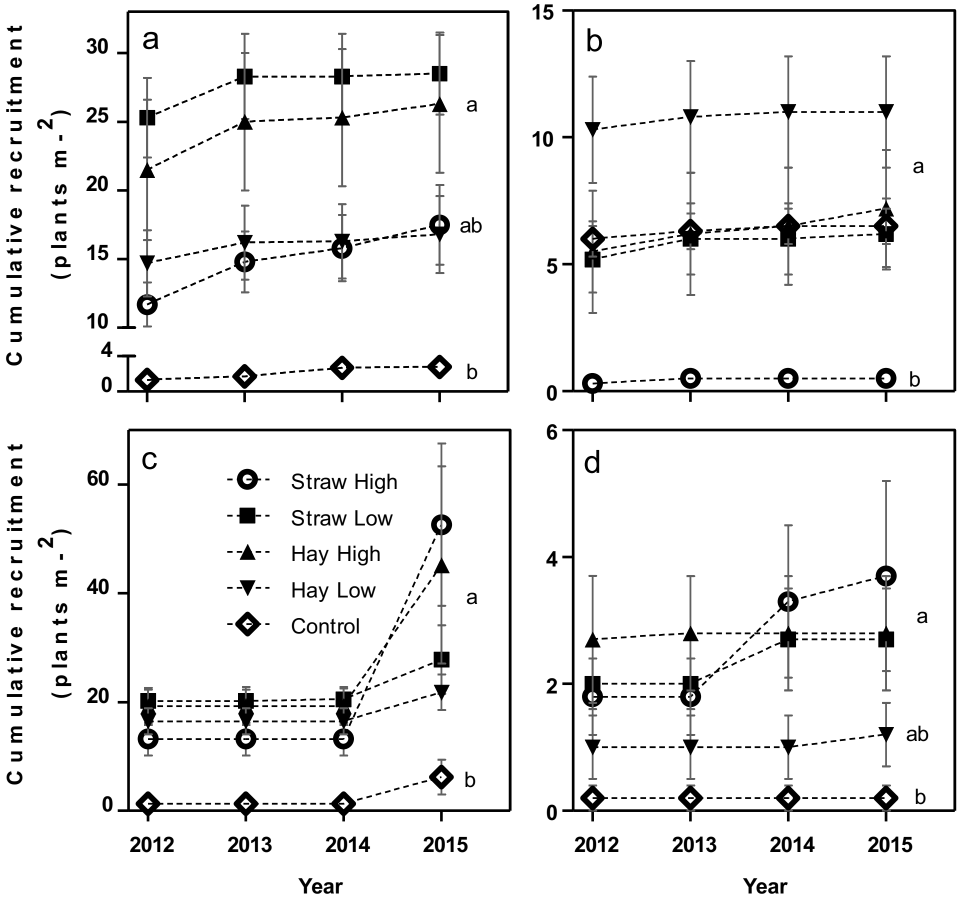

Fig. 2. Cumulative recruitment. Cumulative recruitment for *Elymus trachycaulus* (a) *Bouteloua gracilis* (b), *Linum lewisii* (c) and *Astragalus canadensis* (d). Data are presented as means ± SE (n = 6). Time courses not sharing the same letter are significantly different according to rmANOVA between subject main effects ($p < 0.05$, interaction mulch × time NS).

Table 1
Summary results of rmANOVA analyses for the effects of mulch and time on cumulative plant recruitment and canopy cover per species.

	Cumulative Recruitment			Canopy Cover		
	Main Effects		Interaction	Main Effects		Interaction
	Mulch	Time	Mulch × Time	Mulch	Time	Mulch × Time
E. trachycaulus	8.2^{***}	20.2^{***}	1.5^{ns}	8.3^{***}	72.8^{***}	1.5^{ns}
B. gracilis	10.1^{***}	10.1^{***}	0.9^{ns}	28.5^{***}	83.9^{***}	10.9^{***}
L. lewisii	7.8^{***}	15.4^{***}	0.2^{ns}	3.1^{*}	20.0^{***}	0.9^{ns}
A. canadensis	5.0^{***}	4.9^{***}	1.5^{ns}	3.0^{*}	32.0^{***}	2.4^{*}

F values of the rmANOVA are presented. Degrees of Freedom of each source of variation are: 4 (Mulch), 3 (Time in Cumulative Recruitment), 2 (Time in Canopy Cover per Species), 12 (Interaction in Cumulative Recruitment) and 8 (Interaction in Canopy Cover per Species). Significant differences: *, $p < 0.05$; **, $p < 0.01$; ***, $p < 0.001$; ns, $p > 0.05$.

of *Heterostipa comata* seedlings. The rmANOVA did not find significant mulch × time interactions for any of the analyses ($p > 0.05$) (Fig. 2, Table 1). In contrast, mulch and time effects were statistically significant for all species ($p < 0.001$, Table 1). Low straw and high hay rates improved *Elymus trachycaulus* seedling emergence relative to bare ground ($p < 0.05$). The rmANOVA analysis detected a significant increase in the number of *Elymus trachycaulus* recruiters over the years relative to 2012 ($p < 0.05$), differences that disappeared since 2013 ($p > 0.05$).

The time effect for *Bouteloua gracilis* showed a significant increase of emerged seedlings after 2012 ($p < 0.05$) (Fig. 2, Table 1). High straw application rates hindered its emergence ($p < 0.05$) (Fig. 2b), while other mulch treatments did not significantly improve its emergence relative to bare ground ($p > 0.05$, Fig. 2b).

All mulch treatments increased *Linum lewisii* emergence relative to the control ($p < 0.05$) (Fig. 2c). Interestingly, the analysis detected a sudden increase in number of recruiters during 2015 ($p < 0.05$). *Astragalus canadensis* seedling emergence was greater with high hay and both straw mulch rates relative to bare ground controls ($p < 0.05$) (Fig. 2d). The significant time effect indicates there was a low, yet significant, rise in number of emerged seedlings over the years ($p < 0.01$, Table 1).

3.3. Mulch effects on plant cover and light interception

The rmANOVA plant cover per species supported an anticipated experimental time effect with a steady increase in cover over the first three years for most combinations of species and

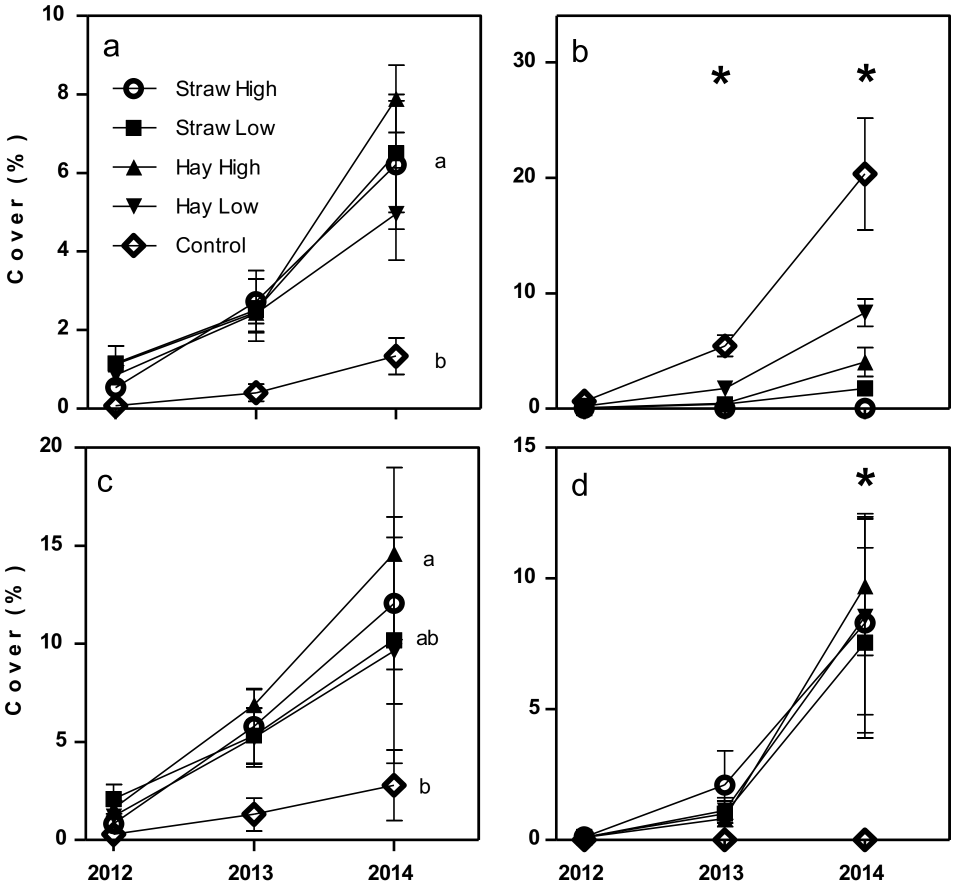

Fig. 3. Effects of mulch on canopy cover per species. *Elymus trachycaulus* (a) *Bouteloua gracilis* (b), *Linum lewisii* (c) and *Astragalus canadensis* (d). Data are presented as means (±SE, n = 6). Time courses not sharing the same letter are significantly different according to rmANOVA between subject main effects when interaction mulch × time was NS ($p < 0.05$; a, c). Asterisks indicate significant differences among treatments for each date ($p < 0.05$) when interaction mulch × time was S (b, d).

mulching treatments ($p < 0.001$) (Fig. 3, Table 1). The mulch × time interaction was significant just for *Bouteloua gracilis* and *Astragalus canadensis* ($p < 0.05$, Table 1). Mulching improved *Elymus trachycaulus* cover during the first three years of revegetation relative to bare ground ($p < 0.05$); nevertheless, there were no statistically significant differences among mulch treatments ($p > 0.05$) (Fig. 3a). Both hay mulch and the control accumulated *Bouteloua gracilis* cover with time ($p < 0.05$) (Fig. 3b); however, the control bare ground treatment showed a statistically higher cover relative to previously mentioned treatments ($p < 0.05$). Straw amended plots did not accumulate *Bouteloua gracilis* cover with time ($p > 0.05$). Low hay rate was the only amendment which improved *Linum lewisii* cover relative to bare ground ($p < 0.05$) (Fig. 3c). Notably, all mulching amendments showed significantly higher *Astragalus canadensis* cover than the control but only during the third year ($p < 0.05$) (Fig. 3d).

The rmANOVA detected marginally significant differences in total plant cover among treatments ($p = 0.092$, interaction time × treatment with $P > 0.10$). As expected, total plant cover significantly increased between the second and third years of revegetation ($p < 0.001$) (Fig. 4a). The fraction of intercepted PAR light, which is a result of light extinction by the canopy, detected differences among treatments in canopy evolution over time by showing a significant time × treatment effect ($p < 0.05$) (Fig. 4b). Canopies of both high straw and high hay mulch rates showed no significant changes in the fraction of intercepted light from 2013 to 2014 ($p > 0.05$). In contrast, straw and hay low rates and the control bare ground significantly increased the fraction of intercepted light between the second and third year of revegetation ($p < 0.05$).

3.4. *Mulch effects on reproduction of* Bouteloua gracilis *plants*

Despite the fact that mulch had a neutral effect on *Bouteloua gracilis* establishment at low rates, a detailed analysis showed that plants behaved as subordinate species in mulched treatments. Mulch negatively affected development of plants from vegetative to reproductive stages ($H = 14.6$, $p < 0.001$) (Fig. 5a) and strongly suppressed seed head production during 2013 ($H = 15.6$, $p < 0.001$) (Fig. 5b).

4. Discussion

One of the main functions of mulch is to avoid soil water losses through direct evaporation. This effect would be most critical in arid environments and sandy soils like those of our research site, where the surficial soil dries out quickly. Straw amendment at rates of 600 $g\,m^{-2}$ helped to conserve soil water relative to bare ground during the first two years of the experiment; however, differences among treatments disappeared after the second spring, suggesting that the canopy transpiration component of water loss outweighed soil direct evaporation during the second summer.

The extensive literature on litter effects on prairie structure and function suggests that mulch amendment impacts may be facilitative, inhibititive or neutral in prairie restoration (Xiong and Nilsson, 1999; Loydi et al., 2013). In our study they were positive for *Elymus*

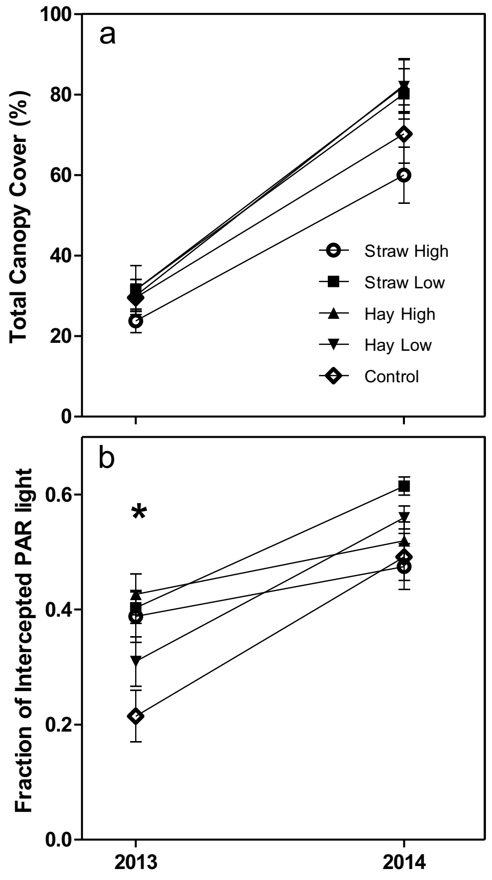

Fig. 4. Effects of mulch on total plant cover (a) and fraction of intercepted PAR light (b). Data are presented as means (± SE, $n = 6$). Asterisk indicates significant differences among treatments in (b) for 2013 ($p < 0.05$) when interaction mulch × time was S.

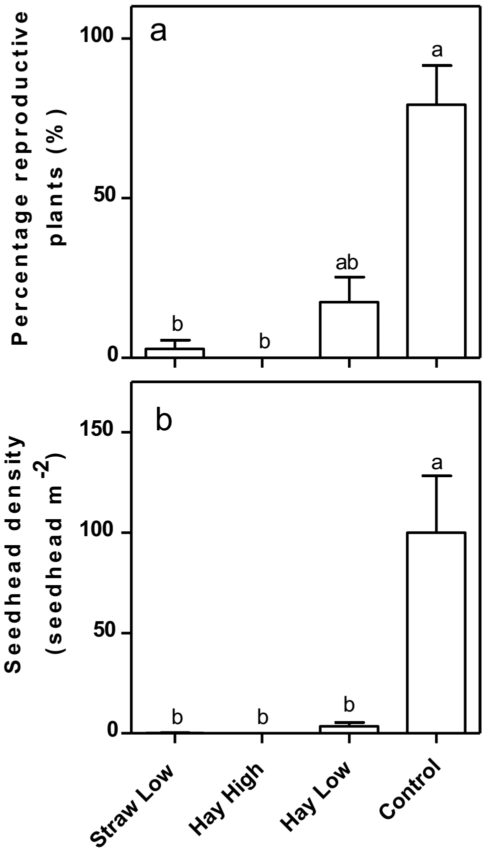

Fig. 5. Effects of mulch on percentage of *Bouteloua gracilis* reproductive plants (relative to established plants) (a) and seed head density per plot (b) during 2013. Data are presented as means (±SE, $n = 6$). Bars not sharing the same letter are significantly different ($p < 0.05$).

trachycaulus, *Linum lewisii* and *Astragalus canadensis* recruitment. While a thinner material like hay was most effective at high rates (600 g m^{-2}), a larger, thicker and more porous material like cereal straw encouraged quick recruitment only at low rates (300 g m^{-2}). In contrast with first year numbers (Mollard et al., 2014), higher straw rates facilitated plant recruitment in the following years for those three species. This effect likley occurred due to several concurrently operating factors. Microsite limitations for seed germination and seedling emergence in seedbeds with high straw rates were evident during the first season (Mollard et al., 2014). Then, decay of thick straw in the first years of reclamation may have released recruitment from microsite limitations. A viable soil seedbank of sown seeds may have formed for *Elymus trachycaulus* and *Astragalus canadensis*, species which did not flower during the first summer. Sown seed from those species remained viable in the seedbank and eventually germinated during the second season. The dramatic recruitment of *Linum lewisii* during 2015 is a consequence of natural reseeding as this species had outstanding blooming and seed production since 2013. On the contrary, despite *Bouteloua gracilis* showing a lavish seed head production since the first season on bare ground (Mollard et al., 2014), a foreseeable recruitment as a consequence of natural reseeding was not seen during the following years. Microsite limitations for *Bouteloua gracilis* seedling recruitment in heavy mulch plots were evident during the first year of the experiment (Mollard et al., 2014). However, even though microsite limitations might have disappeared with time due to material decay, *Bouteloua gracilis* failed to recruit with high straw rates in later years. *Bouteloua gracilis* shows episodic recruitment (Lauenroth et al., 1994) and its seeds readily germinate even under suboptimal environmental conditions (Mollard and Naeth, 2015), so it is unlikely there was a persistent seedbank of sown seeds after the first season.

In mature grasslands, vegetative reproduction is more important than seeds to enable plant colonization in vegetation gaps (Benson and Hartnett, 2006). *Bouteloua gracilis*, which is a low stature grass with great ability to establish an extensive plant carpet through tillering, showed an abundant vegetative reproduction in both the bare ground control and in plots with low hay rates (Mollard et al., 2014) regardless of its low capacity of recruiting by seeds. This behaviour was translated into its constantly increasing cover in those treatments over time. In contrast, in heavy mulch treatments where *Bouteloua gracilis* developed fewer tillers (Mollard et al., 2014), established plants were unable to generate significant cover. However, *Elymus trachycaulus*, *Linum lewisii* and *Astragalus canadensis* significantly increased cover over the years in mulch treatments. Remarkably, there were no statistically significant differences in cover among mulch treatments. This indicates that, regardless of the early differences among mulch amendments in seedbed environmental conditions and first year recruitment and plant performance (Mollard et al., 2014), these differences did not show an impact in either recruitment and cover during the first years of revegetation for *Elymus trachycaulus*, *Linum lewisii* and *Astragalus canadensis*.

Plant cover is the most used structural attribute to measure restoration success (Ruiz-Jaen and Mitchell Aide, 2005). Despite facilitating seedling recruitment and having a strong effect on species cover, mulch had marginally significant treatment effects on canopy cover as the bare ground control tended to develop lower total cover. The reason is evident when focusing on canopy cover per species as the studied species had contrasting performances with either mulched or bare ground treatments. *Elymus trachycaulus*, *Linum lewisii* and *Astragalus canadensis* had a relatively high canopy cover in all mulch treatments but a scarce cover on bare ground. In contrast, *Bouteloua gracilis* complemented this scarce abundance on bare ground by reaching a relatively high cover. A similar species-specific response to protective cover was found in dry, exposed surfaces at a mine site in the Canadian Rocky Mountains. On this site erosion control blankets favoured establishment and higher plant cover of *Elymus trachycaulus* while limited the establishment of non-native weedy species (Cohen-Fernandez and Naeth, 2013). In our study, other species also colonized and contributed to total cover, with a low constancy on different plots. These species were *Hesperostipa comata* (seeded), *Calamovilfa longifolia, Artemisia frigida*, *Artemisia ludoviciana*, *Bromus inermis, Sporobolus cryptandrus*, *Equisetum* spp. and *Carex* spp. The fraction of intercepted PAR light by the canopy was included as an additional measure of vegetation structure. That variable, which is especially sensitive to plant community leaf area index (Monsi and Saeki, 2005), showed significant structural differences during the second year of the experiment as amended plots (with the exception of hay low rates) intercepted more light than bare ground plots.

High vegetative expansion and early and abundant seed production are critical plant features which allow attainment of high plant cover in the shortest time. However, accumulation of litter and standing dead plant material can impair plant development so grasses produce fewer tillers and flower more sparsely (Weaver and Rowland, 1952; Hulbert, 1969; Deutsch et al., 2010). We found that the ability of *Bouteloua gracilis* plants to develop to a reproductive stage was repressed by even moderate low straw and hay mulch rates as the ones used in this research that dramatically affected seed head production in mulch treatments. The same low rates not only arrested *Bouteloua gracilis* plants in a pre-reproductive stage but intensely decreased its tiller production (Mollard et al., 2014), affecting its capacity for ground covering. These effects were seen (not recorded) during the third year of the experiment suggesting a long term effect of mulch on *Bouteloua gracilis* reproductive potential.

Mollard et al. (2014) previously found that while low straw rates and both hay rates had facilitative (*Elymus trachycaulus*, *Linum lewisii*) or neutral (*Bouteloua gracilis*) effects on semiarid prairie seedling establishment, high straw rates had neutral effects on *Elymus trachycaulus* and *Linum lewisii* and prevented *Bouteloua gracilis* seedling establishment. The current research indicates that mulch had a facilitative effect on recruitment and plant cover for *Elymus trachycaulus, Linum lewisii* and *Astragalus canadensis* and the neutral effects of high straw rates during the first year turned into a positive impact in ongoing early years of vegetation development. However, the inhibitory impact of mulch appeared to be long lasting for a flagship species for revegetation such as *Bouteloua gracilis.* Although species composition converged over time in a semi-natural grassland restoration field trial (Auestad et al., 2015), in our study both recruitment and canopy per species results indicate that plots are following two different trajectories that show some degree of resilience as they continued through 2015; the bare ground treatment is dominated by *Bouteloua gracilis*. The mulch plots are characterized by vegetation dominated by tall plants such as *Elymus trachycaulus, Linum lewisii* and *Astragalus canadensis* wherein *Bouteloua gracilis* growth is impaired.

5. Management implications

In northern mixed grass prairies of North America, dry years tend to be grouped so periods of severe drought occur. If revegetation is conducted during such dry spells, straw mulch at rates as high as 600 g m^{-2} may be used as an effective drought management strategy by providing a way to conserve soil water during early plant recruitment. For a thinner material such as hay, amendment rates of 600 g m^{-2} would be less effective than straw in conserving soil water and higher amendment rates should be tested.

Our results justify the use of mulch amendment for northern mixed grass prairie reclamation as mulch represents a reliable method to improve recruitment and cover of the majority of species assessed in this experiment. However, mulch rates greater than 300 g m^2 should be applied with caution as *Bouteloua gracilis* sexual and vegetative reproduction was sensitive to even small mulch rates. The reliability of a seeding practice for enhanced plant cover can be improved by adding a species able to colonize denuded soil such as *Bouteloua gracilis* to the seed mix.

The contrasting plant composition of mulch vs. bare ground treatments indicates that early steps of succession proceeded along alternative trajectories. These differences might be used as a way to enhance patchiness in the reclaimed landscape by means of strategic use of different mulching rates.

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