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Uncovering traits in recovering grasslands: A functional assessment of oil and gas well pad reclamation

Randi C. Lupardus[a,b,*], Ermias T. Azeria[c], Kierann Santala[d], Isabelle Aubin[d], Anne C.S. McIntosh[a]

[a] University of Alberta, Augustana Faculty, Camrose, AB T4V 2R3, Canada
[b] Environmental Monitoring & Science Division, Alberta Environment and Parks, Edmonton, AB T5J 5C6, Canada
[c] Alberta Biodiversity Monitoring Institute, University of Alberta, Edmonton, AB T6G 2E9, Canada
[d] Great Lakes Forestry Centre, Canadian Forest Service, Natural Resources Canada, Sault Ste Marie, ON P6A 2E5, Canada

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ABSTRACT

Oil and gas exploration has disturbed extensive areas of grassland in North America. Reclamation of this human footprint is only a first step towards ecological recovery. A trait-based approach may provide a mechanistic understanding of biological and edaphic filters influencing longer-term plant community assembly on reclaimed sites. Using taxonomic indices, trait community weighted means (CWM), and functional diversity (FD_Q) combined with multivariate models, we compared biological and edaphic properties of 18 reclaimed well pads in Alberta (Canada), to proximate native grasslands. These well pads were certified reclaimed under two reclamation criteria (old, new). Consistent with practices in other regions, newer criteria emphasize using native plant species in place of historically-used introduced agronomic species. We found significant differences between reclaimed and undisturbed reference soil properties (e.g., pH, electrical conductivity), with greater differences on sites reclaimed using the older criteria (e.g., lower TOC, higher bulk density). Plant trait composition also differed between reclaimed and undisturbed sites, with a lower prevalence of short, native, xeric species, with semi-abundant seed production and large seed weight on reclaimed sites. We found a strong trait-environment relationship underlying trait composition difference. While not significantly different in overall trait composition from new sites, old sites included higher prevalence of introduced species, dispersed by animals, preferring mesic conditions, and high seed production. The increased cover of introduced species reduced trait FD_Q and led to an arrested succession. New sites included higher prevalence of tall, native species preferring hydric conditions, therophytes, geophytes, and species with low dispersal capacity. The use of native seed with higher FD_Q on new sites seemed to alleviate arrested succession; However, biological trait filters (e.g., tall, hydric preference) and altered edaphic properties, might continue to drive differences between reclaimed and reference sites. Our results suggest that even as practices and policies evolve, reclamation does not fully alleviate the legacy effects of this industrial disturbance. We have demonstrated how trait-based approaches can inform recovery assessment and future reclamation best practices. We must go beyond simply seeding with native species for recovery of plant communities – the traits of these native species matter too.

1. Introduction

Grassland ecosystems in North America are under anthropogenic pressure. Oil and gas exploration has transformed millions of hectares of the North American Great Plains into industrially-disturbed landscapes (Allred et al., 2015). Such extensive land conversion represents a major threat to biodiversity and ecosystem functioning (Jones et al., 2015). Reclamation of such degraded landscapes is increasingly recognized as a critical step in alleviating impacts of industrial human footprint (Menz et al., 2013). Despite reclamation, there is a concern that resource exploration can have long-lasting legacy effects on spatial (Pickell et al., 2013), soil, and biological (Viall et al., 2014) characteristics of ecosystems.

Assessment of reclamation actions are typically conducted over the short-term and have often evaluated the *greening* of disturbed sites. Such short-term studies are insufficient in evaluating the long-term ecological recovery of reclaimed sites (Suding et al., 2004). In addition, practitioners require quantifiable measures of reclamation success that go beyond the traditional species-focused approach that compares species richness, diversity, and composition among sites (Lavorel and

* Corresponding author at: University of Alberta, Augustana Faculty, Camrose, AB T4V 2R3, Canada.
E-mail address: lupardus@ualberta.ca (R.C. Lupardus).

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Gamier, 2002; Cadotte et al., 2009). These measures of recovery can be less generalizable across regions, because species composition is often regionally specific (Clark et al., 2012). In this regard, plant trait-based approaches are suggested as a complementary approach providing a more mechanistic understanding and more generalizable information about ecological recovery of plant communities that can be applied operationally (Mouillot et al., 2013; Czerwiński et al., 2018). The morphological, physiological, and phenological traits of species are thought to confer fitness within given environmental conditions (e.g., soil pH, bulk density, moisture) and thus determine which species from the species pool will make it through different environmental filters (Lavorel and Gamier, 2002). Abiotic site conditions can influence ecosystem processes indirectly by changing the physiological rates of plants, which are bound and determined by functional traits (Lavorel, 2013; Hajek et al., 2016). By examining the trait link, we can have a better understanding of why a species might be absent from or dominate a reclaimed well pad. For example, high salinity and compacted soil can create stressful conditions that would limit species with certain traits, such as extensive lateral growth and resource-demanding, as opposed to ruderal/opportunistic species with limited lateral growth and high seed production. In addition, certain species traits are linked to ecosystem function, including primary productivity, nutrient cycling, energy cycling, site stability, and invasion resistance (Lavorel and Gamier, 2002; Letts et al., 2015). The identification of missing traits on reclaimed well pads can provide a direct link to missing or shifting ecosystem functions and processes. Thus, trait-based analyses provide the power to differentiate shifts in ecological function across a large geographical area, regardless of regionally-specific species composition. Although studies have shown the trait-environment relationship (e.g., Moradi et al., 2017) and have examined recovery of mixedgrass communities following industrial reclamation (Nasen et al., 2011; Frouz et al., 2013; Rottler et al., 2018), we have not yet transitioned to a trait-based approach for monitoring and research.

In this study we examined the long-term recovery of taxonomic, trait, and functional composition of plant communities on reclaimed sites as compared to adjacent undisturbed reference sites, and their relationship to edaphic variables in the Grassland Natural Region of Alberta, Canada. During typical well pad construction, the original vegetation is completely removed. In addition, soil is highly degraded through removal of the topsoil organic layer, soil horizon mixing and soil compaction (Mason et al., 2011; Larney and Angers, 2012; Viall et al., 2014; Day et al., 2015; Butler et al., 2018). These modifications may also continue to occur during oil and gas production and closure. The post-production site reclamation activities can include respreading of stockpiled soil, tilling, and reseeding to help speed up ecological recovery of the mixedgrass prairie. Yet, previous studies examining oil and gas disturbance impacts on grassland landscapes have found a general delay in recovery of reclaimed sites that can endure for decades after reclamation (Hammermeister et al., 2003; Nasen et al., 2011). This delayed recovery has been partially attributed to enduring legacy effects of soil degradation. In addition, reclamation activities (e.g., reseeding) can sometimes unintentionally promote the succession of introduced herbaceous vegetation, creating yet another barrier to recovery (Powter et al., 2012; Lupardus et al., 2019). As in many other jurisdictions where land is degraded for industrial use, legislation in Alberta requires the conservation and reclamation of all land disturbed for industrial purposes to mitigate the physical, chemical and biological degradation caused by operators [Government of Alberta (GOA) (1995a)]. To facilitate ecological recovery, reclamation practices have changed over time, and in turn criteria to evaluate reclamation have adapted to improve best practices. For example, Colorado legislation for grasslands defines satisfactory reclamation as meeting plan requirements and having a diversity of desired vegetation at 80% potential cover (i.e., compared to adjacent, undisturbed areas; USDA 1997). In Alberta criteria have also been updated from *greening* practices that often included non-native agronomic seed mixes to requiring the use of native species on sites constructed/reclaimed post-1993 (GOA, 1995b; Environment and Sustainable Resource Development (ESRD), 2013). However, until the current study, no sites in the region had ever been monitored, post-reclamation certification, to assess longer-term recovery or effectiveness of either reclamation criteria. Our results have implications well beyond the province; Saskatchewan uses the Alberta reclamation criteria to compare control versus well pad vegetation conditions, although they have their own, less rigorous detailed site assessment criteria (Government of Saskatchewan, 2013). Colorado, Wyoming and Kansas grasslands all have similar industrial reclamation policy focusing on revegetation with native species and control of noxious weeds, without any focus on dominant plant traits (USDA, 1997; Kansas Department of Health and Environment, 2006; Wyoming Department of Environmental Quality, 2017). Given that reclamation practices are continually improving, and policies in turn are being updated to reflect these changes, there is a lack of ability to effectively substitute space for time to quantify successional recovery of reclaimed well pads across all ages of development, so comparing factors influencing community recovery among reclamation criteria is a useful alternative approach.

This study tests for convergence in trait composition of plant communities and edaphic properties of well pads reclaimed under evolving criteria, towards those of undisturbed grassland. The goal of this study was to gain a mechanistic understanding of biological and edaphic factors influencing community recovery on reclaimed oil and gas well pads. Specifically, we hypothesized that consistent trait-environment relationships across sites reclaimed under multiple criteria could be used to identify traits and environmental conditions that possibly hinder recovery. To address this hypothesis, we ask (1) are there differences in taxonomic, trait and functional diversity metrics between well pads reclaimed under multiple criteria (old criteria: pre-1993 and new criteria: post-1993) and adjacent reference sites? and (2) if significant differences exist, are there trait-environment relationships indicating biological and edaphic legacy effects among reclamation criteria groups? We then address how industrial disturbance and subsequent reclamation may impact long-term site recovery and affect the ecological integrity of sites in the future. Our study identifies some of the biological and edaphic barriers that may be limiting post-reclamation ecological recovery.

2. Materials and methods

2.1. Study area

This study took place in the Dry Mixedgrass Natural Subregion of southern Alberta (Appendix A Fig. S1). Mean annual temperature in this Subregion ranges from 2.4 to 4.2 (°C) with a mean temperature during the warmest month of 18.5 (°C), making it the warmest of Alberta's Natural Subregions (Natural Regions Committee, 2006). The mean annual precipitation is 333 mm, 72% of which falls between April and August. Major soils of this region are characterized as brown Chernozems with significant areas of Brown Solonetz, whereas wetlands are Gleysols (Soil Classification Working Group, 1998). Plant communities of the native mixed-grass prairie consist predominantly of species such as blue grama *Bouteloua gracilis*, needle-and-thread *Hesperostipa comata*, junegrass *Koeleria macrantha*, and western wheatgrass *Pascopyrum smithii*. In moister areas, shrubs such as prairie sage *Artemisia ludoviciana* and pasture sage *Artemisia frigida* are common.

2.2. Sampling design and data collection

We sampled 18 study sites that included both reclaimed well pads and adjacent reference plots following protocols developed for monitoring ecological recovery of well pads (Appendix A Fig. S1; McIntosh et al., 2019). Selected study sites ranged from 8 to 30 years post-certification on publicly-owned land with grazing leases and were all

Table 1
Soil variables and functional traits identified on reference and reclaimed oil and natural gas well pads in southern Alberta, Canada.

	Variable	Acronym	Class	Description
Traits*	Typical maximum height	HT	–	Shortest distance (m) between the upper boundary of the main photosynthetic tissues on a plant and the ground level (based on Cornelissen et al., 2003)
	Seed weight	SDWT	–	Seeds or spores mg^{-1}; Seeds and spores are defined as generative units of reproduction
	Raunkiaer lifeform	RA	ch	Chamaephyte (bud between 1 mm & 25 cm from ground)
			g	Geophyte (herbaceous, bud is located in the ground) + helophyte (bud often submerged)
			h	Hemicryptophyte (herbaceous, bud on the surface of the ground)
			mc	Micro & nano phanerophyte (bud between 25 cm & 8 m from ground)
			mg †	Mega & meso phanerophyte (bud ≥ 8 m from ground)
			t	Therophyte (annual)
	Lateral extension	LE	l	Limited
			cc	Compact
			ce	Extensive
	Seed production	SDPRO	f	Few (1 to 20 seeds per year)
			s	Semi-abundant (21 to 1000 per year)
			a	Abundant (> 1000 per year)
	Dispersal mechanism	DI	l	Gravity +low (ant or explosive discharge)
			a	Animal (internal and external transport) includes human and bird
			ws	Short wind dispersal includes herbs dispersing by wind but lacking seed structures that allow them to disperse far via wind (i.e. plumes or wings)
			wf	Far wind dispersal includes herbs that have structures that allow them to disperse far via wind (i.e. plumes or wings) and phanerophytes that are wind dispersed
	Water preference	WP	h	Humid and humid-mesic species
			m	Mesic and mesic-xeric species
			x	Xeric and xeric-mesic species
	Light tolerance	LI	i	Shade intolerant
			m	Mid tolerant
			t	Shade tolerant (note-the dataset did not contain shade tolerant species)
	Status	S	n	Native
		S	i	Introduced
Soil variables	pH	pH	–	Measured at depths 0–15 cm, 16–30 cm, 31–60 cm, 61–100 cm
	Bulk density	Db	–	g cm^{-3}, measured at depths 0–15 cm, 16–30 cm
	Electrical Conductivity	EC	–	μS cm^{-1}, measured at depths 0–15 cm, 16–30 cm, 31–60 cm, 61–100 cm
	Total Organic Carbon	TOC	–	%, measured at depths 0–15 cm, 16–30 cm, 31–60 cm, 61–100 cm
	Total Nitrogen	N	–	%, measured at depths 0–15 cm, 16–30 cm, 31–60 cm, 61–100 cm
	Carbon:Nitrogen Ratio	CN	–	Proportion, measured at depths 0–15 cm, 16–30 cm, 31–60 cm, 61–100 cm

* Traits assigned to species using the TOPIC database (Aubin et al., 2019).
† There were no species with the RA (mg) lifeform in the study.

considered as having good potential for reclamation: level surface, loamy ecosites, with similar soil textures. To counter the random effects of geographic location, each reclaimed well had a directly adjacent proximate reference (~35 m) in the same geographic location, and all sites were located within ~75 km of one another. In addition, we ensured young reclaimed sites were mixed with old reclaimed sites across the landscape. All sampled oil and natural gas wells were plugged and abandoned from 1980 to 1997 without ever entering the production phase.

Reclaimed well pads were categorized as either reclaimed under new reclamation criteria (constructed post-1993; 8–10 years post-reclamation; hereafter called new sites n = 6) or under old criteria (constructed pre-1993; 17–30 years post-reclamation; hereafter called old sites n = 12). Under the 1995 criteria (GOA, 1995b; ESRD, 2013) vegetation pass/fail conditions were categorized by construction date (old: pre-1993 construction; new: post-Jan 1, 1993 construction). The old pre-1993 sites frequently included introduced forage cover such as crested wheatgrass *Agropyron cristatum* and smooth brome *Bromus inermis*. Under the new reclamation criteria, post-1993 sites required ≥ 70% cover of native species compared to control for certification. One site (Well 9), constructed pre-1993 was certified reclaimed post-2001, requiring an extra stipulation, different from all other pre-1993 sites. This site was more similar to the new sites constructed post-1993 in that problem introduced forages had to be controlled or reduced for certification, and so this site was placed in the new group to more accurately estimate effects of reclamation criteria (Table S1). The criteria were updated again in 2013, but we did not include sites reclaimed under these criteria, as they were only a year into recovery at the time of site selection. Sites reclaimed under the updated 2013 criteria are the same as our new group, except for an additional rule requiring ≥ 15% native-infill species, including only allowable substitutions (Fig. S2; ESRD 2013). Soils did not follow the same implementation dates as vegetation, but instead had pre-1994, post-1994 topsoil replacement pass/fail conditions, reducing allowable variance from 40% to 20% compared to control.

We could not account for variance due to individual operators' drilling differences (e.g., equipment size, winter/summer drill) or reclamation efforts (e.g., reseeding methods, source of seeds, mechanical/chemical weed treatment, topsoil removal and replacement methods). These historical efforts were not recorded for most sites (Table S1) and could not be accounted for in statistical analyses, thus they were lumped into site-level reclamation effects. As reclamation practices varied widely in time and space (Table S1), potentially clouding the interpretation of time-since-reclamation effects (Walker et al., 2010), we could not use a chronosequence approach in our analysis, but instead compared sites reclaimed with new and old criteria to reference sites. Reference sites were defined as an area outside the perimeter of the well pad, minimally disturbed by the industrial activities, representing soil and vegetation characteristics present on the well pad prior to its development.

Floristic community composition and soil characteristics were determined during June and July 2013 following methods described in detail by McIntosh et al. (2019). In each reference site, four soil plots measuring 10 × 10 m, four shrub plots measuring 5 × 5 m (25 m^2), and four vascular plant plots measuring 0.5 × 0.5 m (0.25 m^2) were established along with four ~50 × 50 m (0.25 ha) census plots. Reclaimed well pads contained five plots for soil and vegetation sampling (exception of only four census plots), with the fifth plot in the center of the well pad (Appendix A Fig. S3). We used systematically-located sampling points to determine plot locations, except when reference plots were relocated to avoid areas impacted by anthropogenic disturbance (e.g., road, pipeline, fence edge). Soils were sampled for pH, total organic carbon (TOC), and electrical conductivity (EC) at four depth increments of 0 to 15 cm, 16 to 30 cm, 31 to 60 cm, and 61 to 100 cm. Bulk density (Db) was only sampled to 30 cm. Depth zones were used instead of horizons to ensure consistency of sampling and because horizon boundaries were difficult to identify in reclaimed soil profiles after soil layers A through C were mixed. We determined floristic composition using percent cover vegetation surveys (0.25 m^2 and 25 m^2 plots) along with timed censuses (80 min per site type – i.e., well pad or reference - within a study area). To account for species present on a site captured in the timed censuses (0.25 ha), but not in the 0.25 m^2 and 25 m^2 plots, we assigned a cover value of 0.5%.

2.3. Plant traits

We selected a set of traits considered sensitive to soil changes following oil and gas reclamation (Table 1) and related to species' colonisation potential (lateral extension, seed weight, seed production, seed dispersal distance, shade tolerance, water preference) as well as competitive ability (Raunkiaer lifeform, maximum height, status) of a species (Violle et al., 2007). We use the term "trait" in its broader sense, which includes morphological, physiological and/or phenological features of the plant related to individual fitness (Violle et al., 2007). We obtained trait information from the Traits of Plants in Canada (TOPIC) database (Aubin et al., 2019).

2.4. Statistical analyses

All analyses were performed using R 3.4.4 (R Core Team, 2018) and with a significance level of 0.05 for all models. Fig. 1 presents a diagram of the different datasets and analytical steps used to address our research objective. Sites-by-traits matrices for analysis of trait-environment relationships were created from the original species relative abundance-by-sites (L) matrix and the species–by-trait (Q) matrix. We then combined these matrices to create a community aggregated trait matrix also known as a community-weighted mean traits matrix (CWM; Violle et al., 2007; Funk et al., 2017). Before analyzing CWMs, we performed log transformations on the two continuous response variables (i.e. the trait weighted means for height and seed weight), but did not center or standardize to avoid negative values (Májeková et al., 2016).

CWM and trait FD_Q summary statistics (i.e., median, range, mean, 95% confidence intervals) were calculated for traits within reclamation criteria groups (reference, old and new). Taxonomic metrics included species richness (S; i.e. the number of species per site) and Simpson diversity index (D; Simpson, 1949), which were computed using matrix L and compared among reclamation criteria groups.

To determine if reclamation mitigates the legacy effects of well pads on biological characteristics, functional diversity was computed for each individual trait and was compared among reclamation criteria groups (reference, old, new). Functional diversity was computed based on the L and Q matrices using Rao's quadratic entropy index (FD_Q; Rao, 1982). We used the divc function in ade4 with a gowdis distance matrix to calculate Rao for each trait and for the global Rao (mean FD_Q for all traits). Differences in diversity indices among traits were assessed for each group using functions adonis, pairwise.perm.manova, and the Holm adjustment for multiple comparisons.

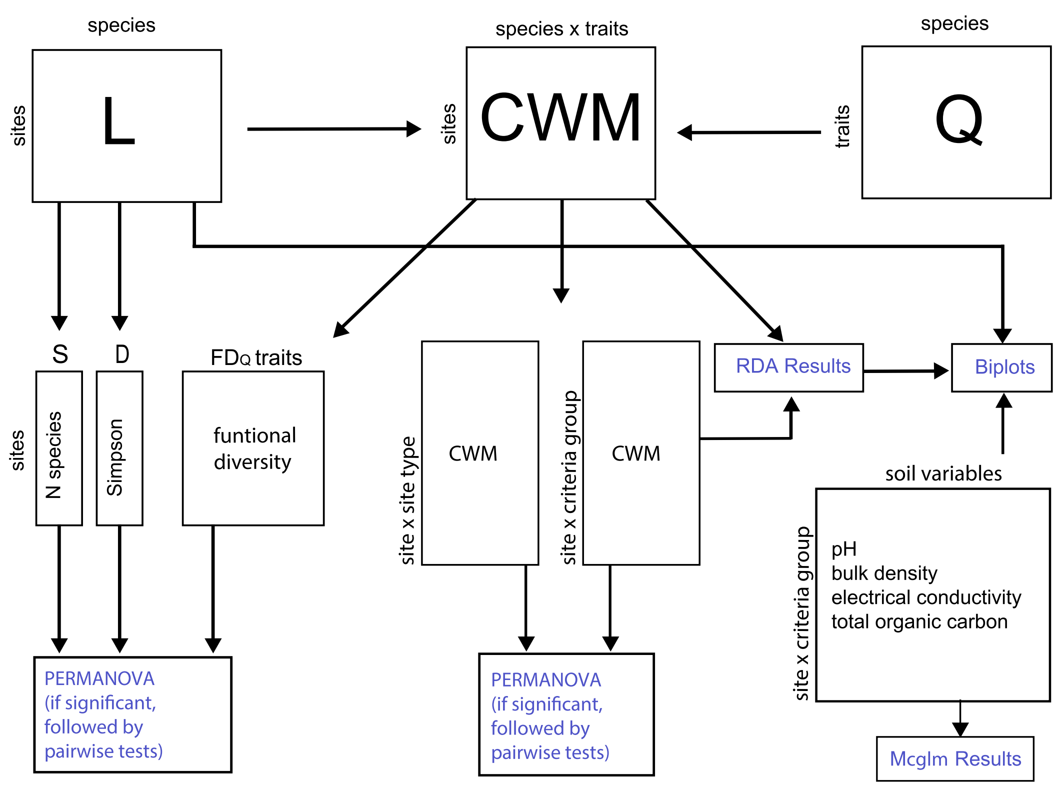

Fig. 1. The different datasets and their roles in the analytical steps used to address our research objectives. Grouping variables include site type (reclaimed well pad, reference) or reclamation criteria group (new, old, reference). The L matrix (species relative abundance-by-sites) and the Q matrix (species–by-trait) were combined to create a community aggregated trait matrix also known as a community-weighted mean trait matrix (CWM). Pathways for Rao's quadratic entropy index (FD_Q), Simpson Index (D), species richness (S), redundancy analysis (RDA), Permutational analysis of variance (Permanova), Pearson correlation biplots and mixed effects multivariate regression models (Mcglm), are shown.

To examine differences in trait composition between site type (reference, well pads) and reclamation criteria group (reference, new, old), we used permutational multivariate analysis of variance (permanova; Anderson, 2001) with 999 permutations and a Bray–Curtis dissimilarity matrix of CWMs (adonis function in vegan; Oksanen et al., 2018). Based on permanova results, we selected the best grouping variable (i.e., either site type or reclamation criteria) then ran pairwise contrasts using the pairwise.perm.manova function and the Holm adjustment for multiple comparisons. Permanova and pairwise contrast analyses were repeated for each trait group (e.g., RA containing 5 levels: h, g, t, ch, mc) to determine trait differences between new wells, old wells and references.

To examine differences in trait composition spatially, we used a CWM-RDA. The sites-by-traits CWM matrix was subjected to a PCA followed by a redundancy analysis constrained by the reclamation criteria groups (reference, old, new). The PCA was performed using the dudi.pca function of the ade4 package and the CWM redundancy analysis was perfomed using the pcaiv function of the ade4 package (Dray and Dufour, 2007). We constrained the CWM-RDA ordination by the factor reclamation criteria group to determine variance explained by the post-reclamation legacy effects among sites of varying reclamation criteria groups and tested CWM-RDA validity with the function randtest. We did not constrain the CWM-RDA by the "best" subset of edaphic variables, as there was multicollinearity among edaphic variables and reclamation criteria groups (reference, old, new). In addition, the constrained ordination became nearly equivalent to the unconstrained ordination. Instead, after running the CWM-RDA, we determined which edaphic variables (at all soil depths) and vascular species were significantly correlated with the ordination axes using Pearson correlation analyses and biplots (envfit function in vegan; Oksanen et al., 2018). To test for multivariate homogeneity of group dispersions (variances) we used vegan function betadisper with type = Euclidean to match the Euclidean RDA, and function TukeyHSD.betadisper to determine significant differences between mean distance-to-centroid of reclamation criteria groups.

To determine if reclamation mitigates the legacy effects of industrial disturbance on soil we used a mixed effects multivariate regression model mc_mixed in the mcglm package (mcglm; Bonat, 2018), with site as the random effect, to determine reclamation criteria group fixed effects on edaphic variables. Response variables included soil variables significantly correlated with CWM-RDA axes. We used the link function: identity, variance function: constant, covariance function: identity, and the Wald statistic in a stepwise procedure to determine significant fixed effects. Robust and bias-corrected standard errors and confidence intervals for regression parameters were calculated, and to estimate fit we conducted residual analyses and measured goodness-of-fit.

3. Results

3.1. Taxonomic assessment

One hundred and fifteen vascular species were identified in this study, 39 were unique to the reclaimed well pads while 33 were found solely on the reference sites (Appendix A Table S2 for species percent relative abundance per site). Species richness (S; $F_{2,34}$ = 1.16, P = 0.31) and Simpson diversity (D; $F_{2,34}$ = 2.44, P = 0.12), did not statistically differ between reference (S = 21 ± 1; D = 0.84 ± 0.01) and reclaimed sites, new (S = 21 ± 2; D = 0.78 ± 0.04) or old (S = 17 ± 1; D = 0.63 ± 0.06; Fig. 2) after accounting for site-level random effects. While not significantly different, the old reclamation criteria group was generally the lowest in both S and D, whilst the reference group was the highest. Over 67% of the reclaimed well pads contained introduced species. There were 36 introduced species identified among all sites, yet only *A. cristatum* reached relative abundance of ~80% on old sites and ~54% on new sites and was able to spread and become established on 5/18 reference sites. *B. gracilis* was the most frequent species, found on all reference sites and 7 well pads, albeit in low abundance on well pads. The species *P. smithii* was the most abundant native plant (max of 54% on any one site), found on both references and reclaimed well pads.

3.2. Functional diversity assessment

Permanova results indicated trait functional diversity (FD_Q) global (all traits combined) did not show differences between reclamation criteria groups (Appendix A Tables S3 and S4), yet individual trait FD_Qs showed two patterns (Fig. 3). For each individual trait, FD_Q was lowest on the old sites (except status), whereas, in traits including maximum height, lateral extension, Raunkiaer lifeform, plant status, and water preference, the new sites had the highest FD_Q. In contrast, dispersal ability, light tolerance, seed production and seed weight had the highest FD_Q in the reference sites. There were statistical differences between trait FD_Q means for reference sites versus old sites (seed weight, seed production and dispersal mechanism) and reference sites versus new sites (seed weight; Table S4). The lowest FD_Q scores among traits were for seed weight and plant height for all reclamation criteria groups (reference, old and new) and dispersal mechanism was the highest.

3.3. Trait assessment

Permanova and pairwise tests determined that trait CWMs on reference sites were statistically different from both the new sites (P = .003) and old sites (P = .003), although new versus old sites were not significantly different (P = .07). Site type was a significant grouping variable (P = .003) as was reclamation criteria group (P < .001). Hence, we used our reclamation criteria group for the remaining analyses.

Permanovas and pairwise tests on individual traits confirmed differences between reference sites and the well pads for plant height, seed weight, hemicryptophytes, abundant and semi-abundant seed production, short distance wind dispersal and animal dispersal mechanisms, hydric, mesic and xeric water preferences, as well as native and introduced status (Table S5; Fig. 4). The random factor site was significant for therophytes, micro- and nano- phanerophytes, abundant seed producers and mesic water preference, indicating a site effect (i.e., plants with these traits are spreading from well pad to reference sites or vice versa).

CWM-RDA results showed reclamation criteria group (reference, new, old) explained 28.2% of the total variance. The proportion of variance explained was 67.7% for axis one and 32.3% for axis two (Fig. 5). Traits were correlated with axes one and two in relation to predicted positions of reference sites, old sites and new sites [Fig. 5(a); Appendix A Table S6 for correlations]. The first axis differentiated between reference (negative loading) and reclaimed sites (positive loading), while the second axis distinguished between new (positive) and old (negative) reclaimed well pads. The test for multivariate homogeneity of group dispersions determined that the new sites had the highest dispersion (0.56), followed by the old sites (0.49) and then references (0.38). The 95% family-wise confidence levels determined old sites had higher dispersion than reference (P < .001), new sites had higher dispersion than reference (P < .001), but that new vs old sites were not different (P = .74). The projected positions by regression on constraining variables (reclamation criteria group) had the greatest spread among sites reclaimed under the new criteria (e.g., site 16), showing the variation in trait community among this group [Fig. 5(b)]. Sites reclaimed under the old criteria generally clustered strongly together, with the exception of four sites, two of which were near their paired reference in ordination space (i.e., 15 and 5), indicating similarity, and two which were much further apart (i.e., 18 and 17), indicating strong dissimilarity.

The CWM-RDA showed introduced species, abundant seed

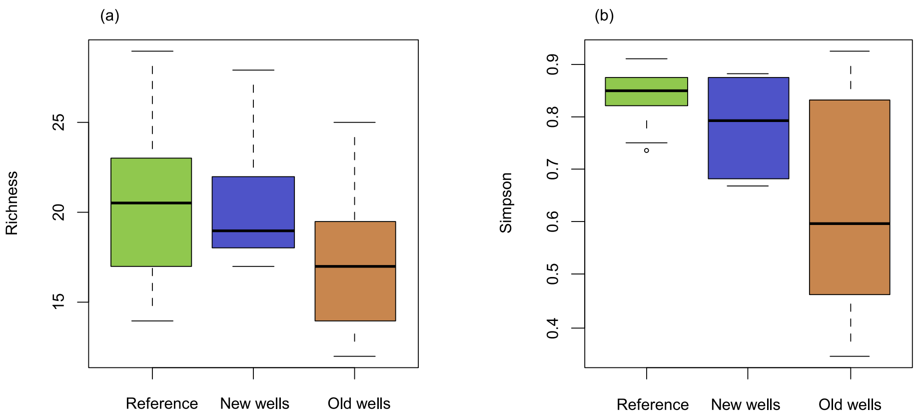

Fig. 2. Box plots showing the range of species richness (S), and Simpson diversity (D) for the new reclamation criteria (constructed post-1993; 8–10 years post-reclamation; n = 6) and old reclamation criteria (constructed pre-1993; 17–30 years post-reclamation; n = 12) reclaimed well pads and adjacent references sites in the grasslands of southern Alberta, Canada. There were no significant differences (α = 0.05) between group means after controlling for site-level random effects.

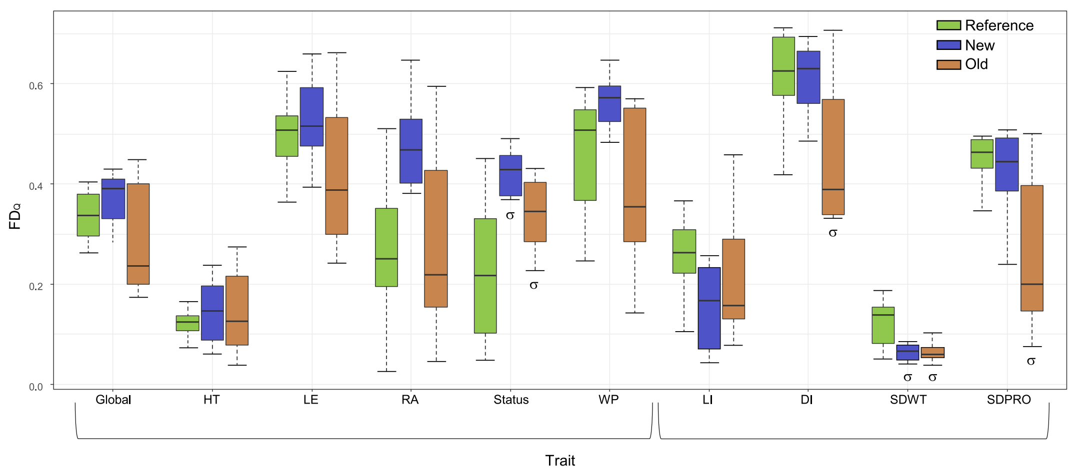

Fig. 3. Box plots of individual and global trait diversity (FD_Q; Rao, 1982) calculated for new reclamation criteria (constructed post-1993; 8–10 years post-reclamation; n = 6) and old reclamation criteria (constructed pre-1993; 17–30 years post-reclamation; n = 12) reclaimed well pads and adjacent references sites in the grasslands of southern Alberta, Canada. Two groups showing similar trends in FD_Q are indicated by brackets. Symbol σ indicates statistical difference (α = 0.05) from the reference. Refer to Table 1 for a full description of variables.

producers and species with a mesic water preference were most strongly and positively correlated with axis one [Fig. 5(a)]. There were strong negative correlations between axis one and native species, semi-abundant seed producers, species with a xeric water preference, and high seed weight. There were weak positive correlations with geophytes, therophytes, species with low dispersal mechanism, and hydric water preference [Fig. 5(a)]. Traits weakly, negatively correlated with axis two included hemicryptophytes and animal dispersal mechanism.

Several vascular plant species were significantly correlated with axes one and two of the CWM-RDA, indicating associations with the plant communities [Fig. 5(d); Appendix A Table S7 for correlations]. Species positively and significantly correlated with axis one and the old sites included *A. frigida*, alfalfa *Medicago sativa*, sweet clover *Melilotus officinalis*, *B. inermis*, and *A. cristatum*. Species negatively and significantly correlated with axis one and associated with reference sites included *K. macrantha*, scarlet globemallow *Sphaeralcea coccinea*, shortbristle needle-and-thread *Hesperostipa curtiseta*, *B. gracilis*, and clubmoss *Lycopodium annotinum*. Species positively and significantly correlated with axis two and the new sites included yellow salsify *Tragopogon dubius*, *P. smithii*, flaxweed tansymustard *Descurainia sophia*, slender wheatgrass *Elymus trachycaulus*, and annual hawksbeard *Crepis tectorum*.

3.4. Edaphic assessment

Generally, mean and median soil pH, Db and EC were lower on reference compared to reclaimed sites and TOC was higher (0–15 cm), whereas N and C:N had no clear trend (Table 2). Mean pH on new and old sites was > 8 for all soil layers. Soil variables significantly correlated with first two axes of the CWM-RDA (Fig. 5(c)) included pH, TOC, Db and EC (Appendix A Table S7 for correlations). Results indicated that high pH (0–15 cm), EC (0–15 cm and 31–60 cm), and Db (0–15 cm and 16–30 cm) in shallower soils were positively correlated with axis one, the old reclamation criteria group and traits including introduced status, mesic water preference, and abundant seed production. High Db (0–15 cm and 16–30 cm) and pH (0–15 cm) were directly opposite reference sites and xeric water preference, indicating an inverse relationship, whilst high EC (0–15 cm and 31–60 cm) was directly aligned with *A. cristatum* and *B. inermis*. High TOC (31–60 cm) and pH in deeper soils (61–100 cm) were positively correlated with axis two and negatively correlated with axis one, placing them in-between the reference group and the new reclamation criteria group. High TOC (31–60 cm) was directly opposite the chamaephyte life form, indicating an inverse relationship, and positively aligned with *T. dubius*, extensive lateral extension and far wind dispersal, although these two traits were not statistically correlated with the axes.

Mcglm results indicated reclamation, after controlling for the random effects of site, had an effect on the soil variables pH, EC, and Db at differing soil depths (Fig. 6; Appendix A Table S8). Goodness-of-fit tests for the univariate (pAIC = -19.62) versus multivariate (pAIC = -93.30) models determined the multivariate model was the best option for analyses. Compared to reference sites, old sites had 0.52 and 0.78 times higher EC (per μS cm^{-1}) within the 0–15 cm and 16–30 cm depths respectively. Db in old sites was 0.09 times higher (g cm^{-3}) at

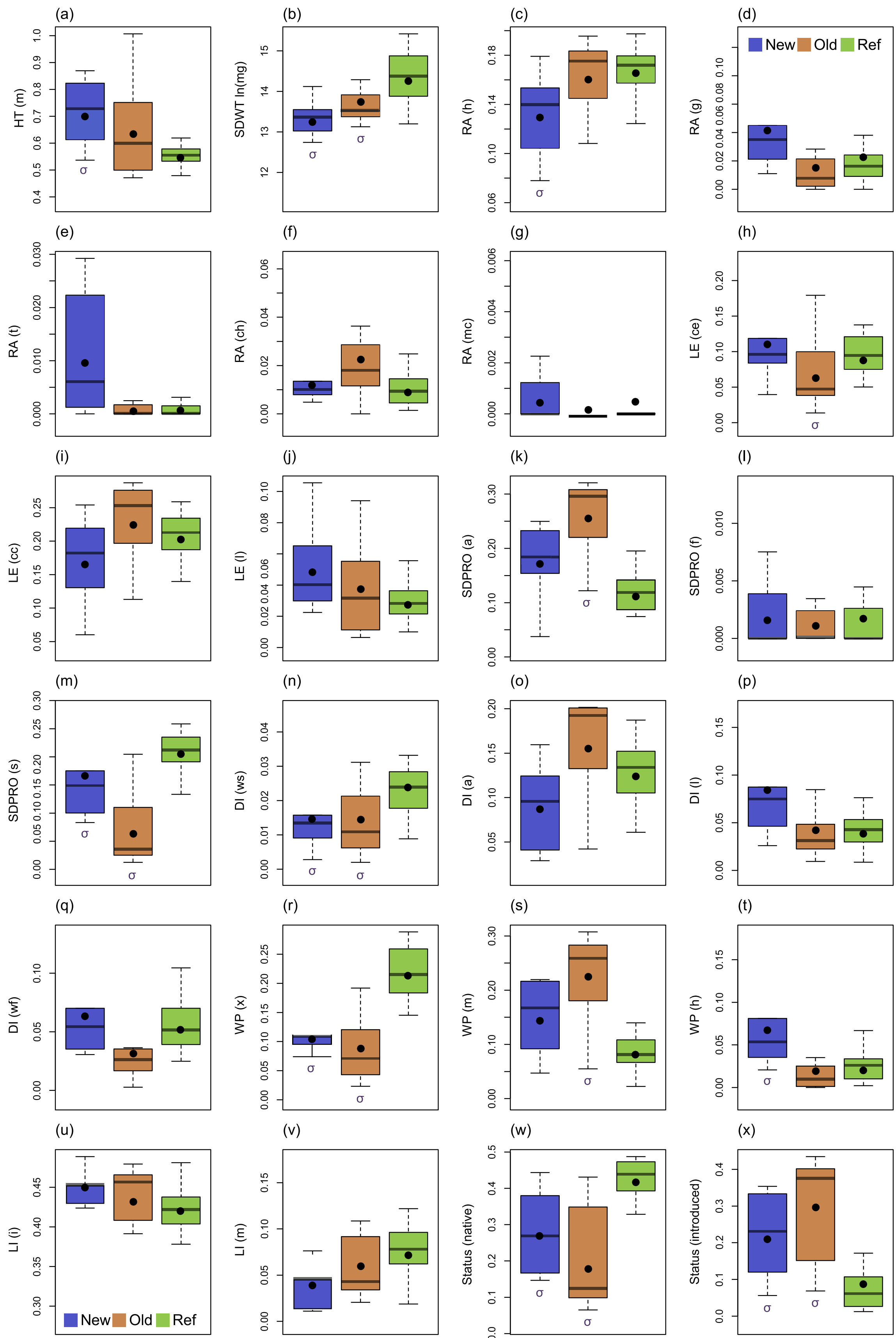

Fig. 4. Box plots of community weighted means (CWM) calculated for new reclamation criteria (constructed post-1993; 8–10 years post-reclamation; n = 6) and old reclamation criteria (constructed pre-1993; 17–30 years post-reclamation; n = 12) reclaimed well pads and adjacent references sites in the grasslands of southern Alberta, Canada. Symbol σ indicates statistical difference (α = 0.05) from the reference. Black dot indicates group mean CWM. Refer to Table 1 for a full description of variables.

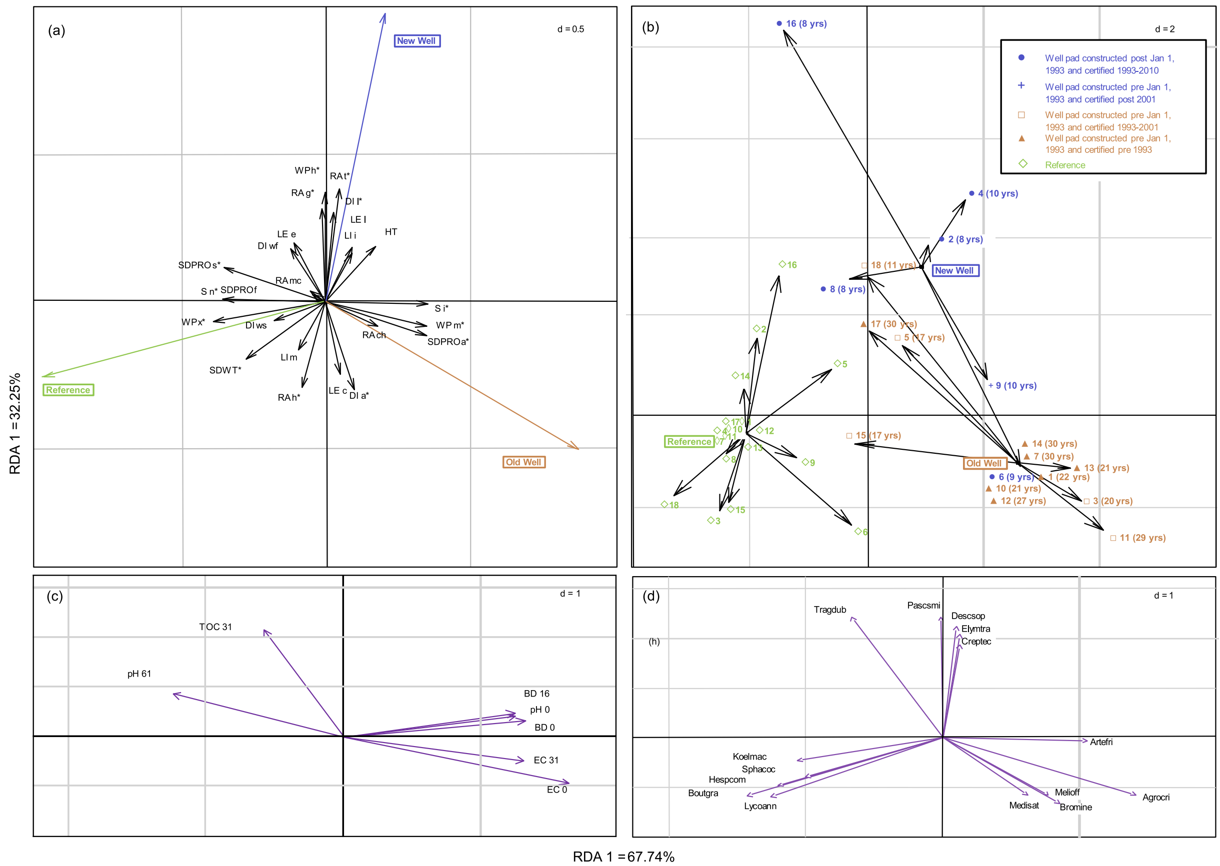

Fig. 5. First two axes of the RDA performed on the community weighted mean matrix and constrained by reclamation criteria groups. Plot (a) shows all traits and their correlations to axes one and two in relation to predicted positions of site reclamation criteria group: reference, new criteria, and old criteria. Significant Pearson correlations are indicated by asterisks. Plot (b) shows the prediction of site positions by regression on constraining variables: reference, new criteria, and old criteria. Plots (c) and (d) contain biplots of soil variables and vascular plant species significantly correlated (α = 05) with axes. Soil variable depth 1 = 0–15 cm, 2 = 16–30 cm, 3 = 31–60 cm, 4 = 61–100 cm. Please refer to Table 1 for a full description of variables.

both 0–15 cm and 16–30 cm depths, in comparison to reference sites. In old well pad soils near the surface, pH was more basic (0–15 cm, E = 0.2), yet more acidic in deeper soils (61–100 cm, E = -0.19). TOC was 14% lower on old sites when compared to reference sites, however this difference was not statistically significant ($P = 0.08$). The effects of reclamation on soils of new sites were not as strong as they were for old sites. New sites had higher EC (0–15 cm, E = 0.24; 16–30 cm, E = 0.51) and pH (0–15 cm, E = 0.18) and although the effects were large, they were not significant (Table S8).

4. Discussion

Using a set of complementary taxonomic, trait, and functional metrics, we assessed if reclamation under new and old criteria was sufficient for the plant community to recover from the legacy effects ofindustrial disturbance and to converge toward that of an undisturbed grassland. By identifying common patterns in community assembly in response to well pad reclamation, we were able to identify commonality in edaphic and biological factors controlling recovery of well pads in mixed-grass prairie landscapes. This information is necessary to identify barriers limiting successful recovery of reclaimed grasslands, and to facilitate convergence of reclaimed sites toward trait communities and soil conditions of undisturbed sites.

We found significant differences in edaphic properties between reclaimed and reference sites. This effect appears to be enduring given that differences remain after ~10 years (new criteria group) and up to ~30 years (old criteria group). We also observed significant differences in trait composition and functional diversity between reference and reclaimed well pads, likely due to a combination of industrial disturbance and reclamation practices. In contrast, we did not detect significant differences in species richness between reference and reclaimed well pads. Our results indicate that basic taxonomic measures of recovery (richness and Simpson diversity) alone do not adequately indicate reclamation success. We also found a strong link between trait composition and edaphic variables suggesting an environmental filtering effect (legacy effect of industrial disturbance) and potential influence of reclamation procedures (legacy effect of reseeding). Taken together our results highlight the value of trait-based approaches in assessing recovery of reclaimed oil and gas well pads and in understanding underlying factors that might slow or arrest their recovery. This mechanistic understanding can inform future reclamation practices to better guide disturbed sites toward edaphic properties and plant trait communities of undisturbed sites and to avoid further permanent legacy effects moving forward.

4.1. *Factors influencing trait syndromes and functional diversity on reclaimed well pads*

4.1.1. *Edaphic properties of reclaimed well pads*

We found a long-lasting effect of industrial disturbances on edaphic variables that were not fully alleviated by reclamation after ~30 years (old criteria group), in alignment with previous studies (Janz et al., 2019). All reclaimed well pads were more saline, alkaline and compacted than adjacent reference sites, although the impact was greatest on sites reclaimed under the older criteria. Explanations for elevated pH and salinity are somewhat speculative. Mixing of the soil horizon prior

Table 2
Summary statistics of soil variables for 18 reference grasslands and 18 reclaimed oil and gas well pads, new (post-1993 construction/ certification) and old (pre-1993 construction/certification), in southern Alberta.

Soil Variable	Criteria Group	Mean	SE	Median	Min	Max
pH 0-15 cm	Reference	7.97	0.23	7.94	7.64	8.40
	New	8.15	0.28	8.17	7.78	8.55
	Old	8.17	0.21	8.19	7.63	8.47
pH 16-30 cm	Reference	8.15	0.28	8.11	7.62	8.54
	New	8.31	0.14	8.23	8.19	8.50
	Old	8.21	0.20	8.22	7.73	8.44
pH 31-60 cm	Reference	8.29	0.24	8.36	7.78	8.64
	New	8.33	0.09	8.36	8.19	8.43
	Old	8.15	0.16	8.20	7.86	8.37
pH 61-100 cm	Reference	8.35	0.21	8.37	7.85	8.66
	New	8.30	0.10	8.27	8.21	8.48
	Old	8.16	0.18	8.15	7.87	8.41
§Db 0-15 cm	Reference	1.13	0.10	1.14	0.97	1.32
	New	1.20	0.11	1.25	1.07	1.31
	Old	1.22	0.08	1.22	1.08	1.37
Db 16-30 cm	Reference	1.21	0.10	1.18	1.10	1.47
	New	1.28	0.10	1.26	1.16	1.41
	Old	1.30	0.11	1.30	1.18	1.51
*EC 0-15 cm	Reference	319	148	256	172	715
	New	382	79	398	239	462
	Old	523	165	538	268	794
EC 16-30 cm	Reference	422	485	320	147	2318
	New	643	469	409	268	1386
	Old	736	456	588	319	1594
EC 31-60 cm	Reference	452	452	366	216	2228
	New	731	432	626	322	1301
	Old	1112	934	924	260	3484
EC 61-100 cm	Reference	1295	1321	700	234	4413
	New	1425	1111	1139	345	3294
	Old	1996	1701	1369	267	5892
€N 0-15 cm	Reference	0.16	0.04	0.16	0.08	0.24
	New	0.15	0.04	0.16	0.10	0.20
	Old	0.14	0.04	0.15	0.06	0.19
N 16-30 cm	Reference	0.10	0.02	0.11	0.05	0.13
	New	0.10	0.02	0.10	0.06	0.13
	Old	0.10	0.03	0.10	0.04	0.12
N 31-60 cm	Reference	0.09	0.02	0.09	0.04	0.13
	New	0.09	0.02	0.09	0.07	0.11
	Old	0.08	0.02	0.08	0.04	0.11
N 61-100 cm	Reference	0.06	0.02	0.06	0.03	0.11
	New	0.05	0.01	0.05	0.04	0.06
	Old	0.06	0.01	0.06	0.05	0.07
†TOC 0-15 cm	Reference	1.68	0.42	1.69	0.86	2.52
	New	1.56	0.41	1.58	0.88	1.98
	Old	1.52	0.38	1.61	0.58	2.13
TOC 16-30 cm	Reference	1.01	0.30	1.09	0.43	1.47
	New	1.04	0.36	1.03	0.52	1.56
	Old	1.00	0.32	1.05	0.40	1.41
TOC 31-60 cm	Reference	0.94	0.23	0.98	0.41	1.30
	New	1.09	0.35	1.09	0.60	1.64
	Old	0.80	0.18	0.83	0.46	1.11
TOC 61-100 cm	Reference	0.59	0.17	0.59	0.31	1.08
	New	0.60	0.15	0.62	0.37	0.81
	Old	0.66	0.17	0.61	0.49	1.12
C:N 0-15 cm	Reference	10	1	10	9	12
	New	10	1	10	9	11
	Old	11	1	11	9	11
C:N 16-30 cm	Reference	10	1	10	7	13
	New	10	2	10	8	14
	Old	10	1	10	10	14
C:N 31-60 cm	Reference	11	2	10	8	16
	New	11	2	11	8	15
	Old	10	1	10	8	13
C:N 61-100 cm	Reference	10	2	10	6	16
	New	11	2	11	7	12
	Old	11	2	11	8	16

§ soil bulk density.
* soil electrical conductivity.
€ soil total nitrogen.
† soil total organic carbon.

to storage introduces calcium and magnesium carbonates and soluble salts from the C horizon into the soil mixture (Pennock et al., 2015) causing increased soil pH in A and B horizons. Changes in pH can have important impacts in grassland plant communities. Generally, slightly alkaline soils increase plant growth due to improved nutrient availability and increased TOC from root and litter decomposition (Brady and Weil, 2016); however, highly alkaline soils (pH > 8) observed on old and new well pad top soils can inhibit plant growth (Jensen, 2010) and microbial growth (Zhalnina et al., 2015; Kaiser et al., 2016; Hermans et al., 2017) due to negative effects on TOC, total N, available N and total P. Alkaline soils can also negatively influence plant traits such as height, lateral spread, biomass, pollen production, or flower size and number (Jiang et al., 2017). Interestingly, we also found that extensive lateral spread was negatively correlated with high salinity. Elevated salt concentrations in reclaimed soils can increase effects of plant-water stress and reduce plant growth and microbial activity (Manchanda and Garg, 2008; Yan et al., 2015). In our study we found that sites reclaimed under the old reclamation criteria were correlated with elevated salts and the dominant species on sites included introduced forages *A. cristatum* and *B. inermis*. This relationship between the success of introduced forages and elevated EC has been shown in other studies (e.g., Rutherford et al., 2005; Flynn and Ulery, 2011; Grieve et al., 2012). The effects of increased soil EC are intensified by increased soil Db, as compacted soils have poor water infiltration rates and drainage, increasing plant stress (Eldridge et al., 2012). This can add an additional filter on the plant community, as some plants are better adapted to grow in compacted soils with periodic flooding (Kozlowski, 1999; Bassett et al., 2005).

Soil disturbance and the resulting changes in soil quality can drive plant community recovery (Schnoor et al., 2015). Reclaimed sites had a higher abundance of species preferring moist and humid soil-water conditions than reference sites. Within grassland systems, mesic communities generally have both greater richness and higher abundance of introduced plants than drier communities (Larson et al., 2001), because in xeric conditions, native shortgrass species tend to outcompete introduced agronomic species (Trlica and Biondini, 1990; Hansen and Wilson, 2006). This could explain why we found traits such as high seed production and mesic water preference correlated with the old sites, where Db was highest and more susceptible to seasonal flooding than reference sites with native species preferring xeric conditions. For decades, *A. cristatum*, an introduced species, was used during well pad reclamation due to its high tolerance to drought and medium tolerance to salty, alkaline, and flooding soils (Watson et al., 1989). On sites reclaimed under the older criteria we also found a prevalence of species, such as *M. officinalis*, *B. inermis*, and *M. sativa*, known to tolerate saline and poorly drained soils (Coulman, 1987; Watson et al., 1989; Lei et al., 2018). Only four well pads had greater than 10% combined xeric species abundance (max 19%). This suggests that either native xeric species were purposefully excluded from seed mixes, or they were simply uncompetitive in post-reclamation soils.

4.1.2. Biological properties of reclaimed well pads

In our study we found low measures of trait-specific FD_Q, high cover

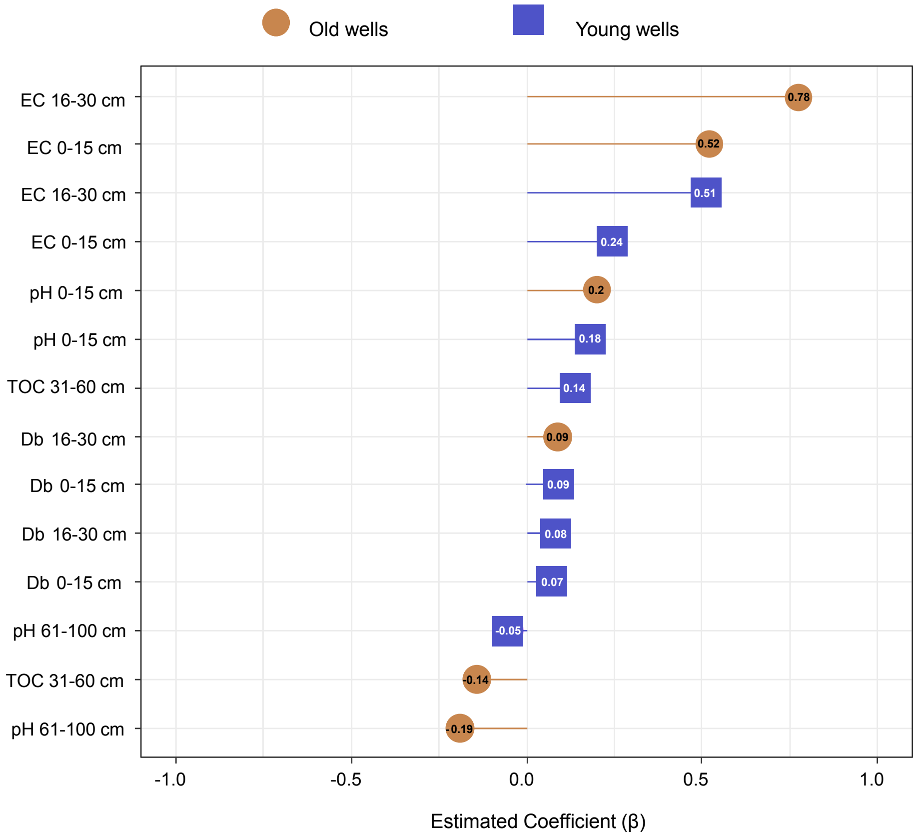

Fig. 6. Estimated response coefficients to both new (new criteria) and old (old criteria) for seven soil variables found significantly correlated with plant trait communities in the grasslands of southern Alberta, Canada. Filled circles and squares are estimated coefficients for an alpha of 0.1, where β of zero indicates reference levels. Db: soil bulk density, EC: soil electrical conductivity, and TOC: soil total organic carbon.

of introduced species and early colonizing species associated with sites reclaimed under the old criteria. Low FD_Q and variability in trait-specific FD_Q observed on old sites was likely due to introduced monocultures of *A. cristatum,* which tended to dominate these sites and were associated with traits of this species including abundant seed production and introduced status (Rogler and Lorenz, 1983). Sites reclaimed under the newer criteria had higher FD_Q in comparison to those reclaimed under the old criteria, but they also had a suite of traits different from reference sites, allowing for swift acquisition of resources including therophyte life form (Burnett et al., 2018), taller heights (Bazzaz et al., 2000; Grime, 2001; Westoby et al., 2002; Violle et al., 2009), and greater dispersal ability, including low seed weight (Donohue et al., 2010). The association of these traits within reclaimed well pads is the result of cultivated seed-mixes, some native and others introduced, that were sown onto stripped soils, given fertilizers, and thus provided an opportunity to establish with little competition from naturally occurring species.

Seed mixes containing introduced species can influence community assembly and functional diversity following reclamation (Hejda and de Bello, 2013; Dickie et al., 2017). Additionally, the disturbed nature of soils following site decommissioning and reclamation (Hammermeister et al., 2003; Eldridge et al., 2012) provided ideal conditions to facilitate colonization of species adapted to disturbance prone environments (Horáčková et al., 2016; Stanbury et al., 2018). The traits of dominant species likely have the most influence on ecosystem properties and processes (Mokany et al., 2008). Introduced species, and species with known adaptations to disturbed environmental conditions were present on sites, up to 30 years post-reclamation. Reclaimed sites composed of > 70% introduced species relative abundance are likely permanently modified (Alberta Environment and Sustainable Resource Development 2013). The relative abundance of the introduced species *A. cristatum* alone was ~50% on multiple sites reclaimed under the new criteria and ~80% on several sites reclaimed under the old criteria. This reflects the wide use of this species since the 1950s, as it was highly adaptive, inexpensive, and readily available (Richards et al., 1998). Similarly, the potential initial addition of fertilizer during reclamation could have given introduced species a competitive advantage (Hammermeister et al., 2003). Under higher N fertilization rates, studies have found that native species such as *B. gracilis*, *H. comata*, *K. macrantha* and clubmoss (*Selaginella* spp.) decrease in abundance while introduced species such as *P. smithi*, *A. cristatum*, thick spike wheatgrass *Elymus lunceolatus* and invading weeds tend to increase (Power, 1984; Samuel and Hart, 1998). After becoming established, introduced species such as *A. cristatum* flourished and spread from the reclaimed well pads into adjacent reference sites. It is not clear, however, when this spread to reference sites occurred, if it was during the reclamation process via vehicle and soil dispersal, or if it was over time via animal and wind dispersal mechanisms. Although old sites were associated with animal dispersed species, all study sites were located on public grazing leases and grazers (e.g., cattle) act as vectors for introduced propagules (Hobbs and Huenneke, 1992).

For new sites seeded with native species, such as green needle grass *Nassella viridula* and the native wheatgrasses (e.g., *P. smithii, E. trachycaulus*; Table S1), trait community and functional diversity revealed differences between reclaimed and reference prairie, uncaptured by species community analyses alone. We found that tall, rather than short, plant stature dominated the new sites. This information is relevant as reclaimed communities dominated by tall species may produce more aboveground biomass (Butterfield and Suding, 2013). This biomass can affect litter accumulation and breeding habitat for native birds. For example, both Sprague's Pipits *Anthus spragueii* and chestnut-collared Longspurs *Calcarius ornatus*, which are both protected species found in our study area, prefer native vegetation, less than 30 cm in height and sparse litter accumulation for breeding (COSEWIC, 2009, 2010, Cerney and Calon, 2015). Trait-based and functional diversity analyses can provide valuable tools for identifying habitat that supports threatened and sensitive species.

Sites reclaimed under the new reclamation criteria, although statistically different from reference prairie, had a higher FD_Q than old sites and shared some traits associated with reference conditions, including presence of microphanerophytes, production of fewer seeds, and a higher abundance of native species. Such traits are often associated with mature or undisturbed grasslands (Tilman and Wedin, 1991; Vujnovic et al., 2002; Spasojevic et al., 2010). Similarity of traits observed between new sites and reference sites likely reflect improvements to reclamation standards used on new sites that are potentially accelerating successional trajectories towards more desirable late-seral species composition, although long term monitoring is required to evaluate the long term succession. Higher functional diversity on new sites may also indicate these sites will be more resilient to future environmental stress, whereas the older sites may be at risk. When trait values become less frequent due to the filtering processes following reclamation, FD_Q decreases and may cause loss of resilience through decreased functional compensation, spatio-temporal complementarity among species, and ecosystem multifunctionality (Mori et al., 2013). The low FD_Q observed on sites reclaimed under the old criteria may limit these sites' ability to adapt to future environmental stressors such as climate change or pest outbreak (Badyaev, 2005; Scoville and Pfrender, 2010; Latta et al., 2011) and may decrease their resistance to colonization by invasive species (Díaz and Cabido, 2001).

4.2. Implications for management and future research

The overall lack of convergence of trait composition on well pads, particularly on sites reclaimed under the old criteria when compared to reference sites, suggests limited recovery of more desirable species assemblages and potential long-term impacts on ecosystem functions. This delay in recovery appears to be due to legacy effects of industrial activity and reclamation practices resulting in the dominance of introduced forage species and changes to soil characteristics, such as increased EC, pH, and Db and decreased TOC. Legacy effects of industrial activity and reclamation on edaphic characteristics emphasise the importance of using more recent best practices to minimize impacts.

From a management perspective, competitive species, particularly introduced species, will likely limit the long-term recovery of reclaimed sites, as they may develop a recalcitrant layer that can cause arrested succession (i.e., permanent site modification and inhibition of a timely successional recovery). Such arrested succession has been documented on older reclaimed mixedgrass prairie roads in North Dakota (e.g., Simmers and Galatowitsch, 2010) and well pads in Saskatchewan (Nasen et al., 2011). To redress the potential effect of introduced species, one of the management actions that has been implemented over the last few decades has been to shift away from reseeding with introduced species and towards reseeding with native species on well pads (Vilá et al., 2011; van Kleunen et al., 2010; ESRD, 2013). However, to prevent dissimilarities between newly reclaimed sites and reference sites, we must go beyond simply seeding with native species. Seeding an assortment of native species, with trait values similar to the community of undisturbed grasslands (i.e. high prevalence of species with heavy seeds, extensive lateral extension, and a xeric water preference) could prevent opportunities for invasive species to colonize these disturbed sites, and minimize differences between reclaimed well pads and native grasslands. Reclamation using locally collected seed stock is also crucial to maintaining what is left of the biological diversity of Canada's prairies (Morgan et al., 1995). Future work should focus on practical reclamation methods to increase the successful establishment of the native species associated with low fertility soils, including modifying the abiotic environment and using 'phased introduction' of species post-restoration, once both the plant community and the edaphic conditions have had time to stabilize (Pywell et al., 2003).

As the sites in the current study had minimal to no oil and gas production, they likely have a relatively low environmental disturbance baseline compared with sites that have produced. High production sites likely have a much greater impact on edaphic and biological variables due to increased traffic (e.g., soil compaction, transport of introduced species), chemical contamination of soil, water, and air (e.g., benzene, heavy metals; Lupardus, 2017), as well as increased site management (e.g., regular use of herbicides, fire suppressants). As the current study has shown, changes in environmental variables impact the abundance and variety of plant trait communities on reclaimed sites. Future studies focused on high production sites could provide insights into how recovery may differ if disturbance is even more severe and long-lasting.

Under an adaptive management framework, constant research is needed to monitor the effects of current criteria implementation on grasslands and to inform the revision of existing criteria, not only in Alberta, but across North America. Central to this research is access to site history information including soil ripping, species seeding ratios, and fertilization/pesticide usage for pre-site assessments, interim reclamation and final reclamation, to streamline international monitoring moving forward. With concise records and continued trait monitoring on new reclamation sites, we can more accurately identify areas in reclamation practice and policy that require improvement.

5. Conclusions

Our results have important, practical implications. Prior to the creation of native cover policy, reclamation practitioners across North America converted native grasslands into monocultures of introduced forages with the a1ttitude that *green is good*. Sites seeded with non-native, agronomic species are now stuck in an arrested successional state, with long-term impacts on edaphic and biological properties. After 30 years, edaphic conditions and plant trait communities of reclaimed grassland sites have not converged towards those of reference sites. What is particularly interesting about the current study, is that we are still finding long-term, edaphic and biological impacts on newly reclaimed well pads, reclaimed using *better* reclamation criteria.

There is an overlap between sites reclaimed with the old criteria and the new criteria, regardless of age (e.g., 9 and 10 year old sites group with the 30 year old sites), and all reclaimed sites have plant traits differing from those of the reference sites. Unless the ordination distance between new reclaimed and reference sites shrinks with time, they too are at risk of a similar fate, not because of introduced forages, but because of trait dissimilarities. Variance within sites reclaimed under the new criteria was high (i.e. had large spread) and this result was confirmed by the dispersion test. All new criteria sites, reclaimed under the same criteria and of the same age, were very different in terms of trait community structure. This indicates that differences are occurring at the site level. We believe the choices individual reclamation practitioners are making on each site are contributing towards this variance.

In the current study, plant trait community composition was influenced by biological and edaphic filters imposed by industrial disturbance and was not adequately alleviated by reclamation. Well pads reclaimed under the old criteria appear to have been substantially modified as many were composed of > 70% introduced species relative abundance and had lower trait FD_Q compared to sites reclaimed under the new criteria and reference sites. Edaphic properties were also affected by the oil and gas disturbance and were not fully recovered by reclamation. Our results suggest that the old reclaimed sites are in an arrested successional state that is unlikely to change without active restoration. The new reclaimed sites were more variable, with some sites sharing biological and edaphic properties of undisturbed sites, and others trending towards an arrested state, indicated by the abundance of persistent agronomic species. Long-term assessment will be necessary to assess time for recovery, to further identify sites with arrested succession, and to provide guidance for future revisions of constantly evolving reclamation practices and criteria.

CRediT authorship contribution statement

Randi C. Lupardus: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Ermias T. Azeria:** Conceptualization, Formal analysis, Validation, Writing - review & editing. **Kierann Santala:** Conceptualization, Validation, Writing - review & editing. **Isabelle Aubin:** Conceptualization,Validation,Writing - review & editing. **Anne C.S. McIntosh:** Conceptualization, Data curation, Investigation, Methodology, Project administration, Supervision, Validation, Writing - review & editing.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoena.2019.100016.

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