Ecological Recovery Monitoring of Dry Mixedgrass Wellsites

Results of vegetation and soil indicator analyses

Version 2014-09-30

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Executive Summary

There is uncertainty related to the long-term consequences of reconstructing landscapes on Alberta's specified lands. Alberta has over 100,000 wellsites that have been certified under evolving reclamation criteria over the past 50+ years. These wellsites are not currently revisited post-certification to evaluate their long-term ecological recovery. Ecological recovery is achieved when the biological, physical and chemical properties (e.g., vegetation community composition, soil properties) of a reclaimed site are similar to the properties of an undisturbed reference or pre-disturbance site. With the lack of long-term monitoring of wellsites post-certification in Alberta, there is currently no way of knowing if or when ecological recovery will be achieved on these reclaimed sites. The absence of this information is a potential liability that detracts from government's stewardship commitments, and from industry's social license to operate on public lands.

The Ecological Recovery Monitoring (ERM) Project Team was established in November 2012. The overarching goals of the ERM are to: i) undertake a set of field studies to assess historical wellsites to address key knowledge gaps that currently constrain the assessment of ecological recovery after reclamation, and ii) create a scientifically-robust, transparent, and financially-sustainable long-term monitoring program to assess the ecological recovery trajectories of reclaimed wellsites. The initial focus on wellsites will provide a foundation for future work on other energy sector footprints.

In the first stage of the project (November 2012 – March 2013), three main project activities were completed. Using a series of workshops, the strengths and weaknesses of three programs that could potentially be used to develop integrated long-term monitoring protocols were evaluated. Workshop participants, who included members from research institutions, industry and government, selected a set of soil and vegetation indicators that could be used to monitor ecological recovery of certified sites. Integrated monitoring protocols that incorporated the selected indicators were developed for use in evaluating the long-term success of reclamation on certified reclaimed wellsites (ABMI 2013a). A governance and funding model to implement and sustain this project in the long-term was also recommended (ABMI 2013b). An extensive review of the literature and existing sources of pertinent data illustrated a lack of long-term monitoring data for certified sites in Alberta (ABMI 2013c).

In the most recent stage of the project (April 2013-March 2014), our project focused on two research areas: i) using the newly developed integrated monitoring protocols to assess soil and vegetation conditions at historical wellsites on a single common ecosite type in native grasslands by comparing them with reference locations (this report), and ii) developing a framework to support implementing a long-term monitoring program to track ecological recovery of certified sites in Alberta (see ABMI 2014).

The objective of this report is to show results from the field study comparing vegetation and soil properties (i.e., indicators of recovery) at certified reclaimed wellsites with adjacent reference locations (i.e., sites without industrial disturbance) across a range of age classes post certification (~10, 20, and 30 yrs) in native grasslands in the Dry Mixedgrass Natural Subregion.

We measured vegetation (percent cover by species and strata, species richness, Shannon diversity, and Sørensen's similarity index) and soil (bulk density, electrical conductivity, LFH depth, pH, total nitrogen (TN), total organic carbon (TOC), TOC:TN) indicators for up to four soil depths (0-15 cm, 15-30 cm, 30-60 cm, and 60-100 cm), comparing them among 18 wellsites and adjacent reference locations. For each indicator we conducted two-way ANOVAs to test for differences among location (wellsite vs reference) and age class (10, 20, 30 yrs post certification). We also used non-metric multidimensional scaling (NMS) ordination and a multi-response permutation procedure to explore plant community composition patterns among sites.

Vegetation analyses highlighted differences among the wellsite and reference locations, including lower species richness, Shannon diversity, and total vegetation cover on the wellsites compared with the reference sites, regardless of age class. In contrast, wellsites had significantly higher cover of non-native

vegetation compared with the reference sites across age classes. Several vegetation indicators only showed significant differences for the wellsite and reference locations in some age classes (i.e., forb (including non-native), graminoid (including non-native), clubmoss, and lichen cover, and Sørensen's similarity index). There were no significant differences among wellsite and reference sites for shrub cover. The plant community composition ordination illustrated separation of the wellsite and reference locations among age classes, with the 10-yr wellsite community composition more similar to the composition of the reference sites compared with the 20- and 30-yr age classes. These differences among site locations and age classes were primarily correlated with the cover of plant species (e.g., higher cover of crested wheatgrass in 20- and 30-yr wellsites).

For all soil indicators there were significant differences among the wellsite and reference locations for at least one soil depth. Bulk density (only measured for the two shallowest depths) and electrical conductivity (all four depths measured) values were higher in the wellsites for all sampled depths. Compared with reference sites, wellsite pH was significantly higher at 15-30 cm depth and significantly lower at 60-100 cm depth. LFH depth was significantly deeper in the reference sites compared with the wellsites for the 20 and 30 yr age classes. Total nitrogen levels were significantly higher in the reference sites for the two shallowest depths and total organic carbon levels were significantly higher for the reference sites in the most shallow depth (0-15 cm). The ratio of total organic carbon: total nitrogen was significantly higher on wellsites in the deepest depth (60-100 cm).

Overall, data show that for many vegetation and soil indicators, wellsite development impacts are long lasting and may remain for 30 years or more after reclamation. This lack of recovery was evident across the different age classes, although there was some evidence for plant communities in the youngest age class being more similar to reference locations compared with the older age classes post-certification. This suggests that newer conservation and reclamation practices may have less impact on native prairie plant communities than older practices did. We do not yet know how long it will take for these reclaimed wellsites to recover, and thus longer-term monitoring is needed to evaluate recovery trajectories. These study findings provide baseline information on differences between wellsite and reference locations that will aid in the development of an integrated, scientifically robust and financially sustainable monitoring program to enable the assessment of ecological recovery of physical, chemical, and biological indicators at certified reclaimed wellsites across Alberta. In the next stage of our project we will assess ecological impacts at historical wellsites in forested lands and continue to develop the framework for establishing the long-term monitoring program for certified industrial sites in Alberta.

Background

The Ecological Recovery Monitoring (ERM) Project Team was established in November 2012. The overarching goals of the ERM are to: i) undertake a set of field studies to assess historical wellsites to address key knowledge gaps that currently constrain the assessment of ecological recovery after reclamation among three land types (grasslands, forested lands, cultivated lands), and ii) create a scientifically-robust, transparent, and financially-sustainable long-term monitoring program to assess the ecological recovery of Alberta's reclaimed wellsites. The initial focus on wellsites during the first three stages of the project will provide a foundation for future work on other industrial sector footprints.

In the first stage of the project (November 2012 – March 2013), three main project activities were completed. Using a series of workshops, the strengths and weaknesses of three programs that could potentially be used to develop integrated long-term monitoring protocols were evaluated. The workshop participants, who included members from research institutions, industry and government, selected a set of soil and vegetation indicators that could be used to monitor ecological recovery of certified sites. Integrated monitoring protocols that incorporated the selected indicators were developed for use in evaluating the long-term success of reclamation on certified reclaimed wellsites (ABMI 2013a). A governance and funding model to implement and sustain this project in the long-term was also recommended (ABMI 2013b). An extensive review of the literature and existing sources of pertinent data illustrated a lack of long-term monitoring data for certified sites in Alberta (ABMI 2013c).

In the most recent stage of the project (April 2013-March 2014), our project focused on two research areas: i) using the newly developed integrated monitoring protocols to assess ecological recovery of historical wellsites on a single common ecosite type in native grasslands by comparing them with reference locations (focus of this report), and ii) developing a framework to support implementing a long-term monitoring program to track ecological recovery of certified sites in Alberta (see ABMI 2014).

In the next stage of the project (April 2014-March 2015), our project will again be focused on two research areas: i) using the integrated monitoring protocols to assess ecological recovery of historical wellsites in forested lands, and ii) continuing to develop a framework to support implementing a long-term monitoring program to track ecological recovery of certified sites in Alberta.

Introduction

Under current regulations, after upstream oil and gas facilities or other industrial developments have been decommissioned on Alberta's specified lands[1], reclamation is directed through the Environmental Protection and Enhancement Act (EPEA). After specified lands have been deemed to have met the legislated requirements, a reclamation certificate is issued. However, the conservation and reclamation guidelines for certificate issuance have changed since the first Alberta reclamation guideline, the *Surface Reclamation Act*, was enacted in 1963. In 1993 the first formal criteria for wellsite certification that linked reclamation and remediation were established. Since 1993, there have been several updates to these conservation and reclamation criteria; criteria have shifted from focusing on removal of surface debris to an increasing push towards reducing impacts and returning ecological function (Powter et al. 2012).

Reclamation of specified lands is a complex process because it may be decades or longer before plant communities, soil properties (e.g., Avirmed et al. 2014), and other ecological functions recover on reclaimed sites. Ecological recovery is achieved when the biological, physical and chemical properties (i.e., ecological functions) of reclaimed sites are similar to the properties of undisturbed reference or pre-disturbance sites. Published studies suggest that vegetation communities at reclaimed sites often differ

[1] land used for specified industrial disturbances – in this case oil and gas industrial disturbance

from undisturbed areas (e.g. Desserud et al. 2010; Raab and Bayley 2012). In Alberta, there are over 100,000 upstream oil and gas wellsites that have been certified reclaimed, with hundreds of thousands more currently in production or abandoned that will eventually be decommissioned and apply to receive a reclamation certificate. However, the ecological recovery of these wellsites after they have been certified, and how their recovery success may differ based on the conservation and reclamation policies and practices in place when certificates were issued are not currently measured and are thus unknown.

The absence of information on the ecological condition of Alberta's certified industrial footprints that may not have fully recovered is a potential liability that detracts from government's stewardship commitments, and from industry's social license to operate. Thus, measurements of soil and vegetation ecological recovery indicators at reclaimed sites are needed to quantify recovery after certification. However, without long-term monitoring there is currently no way of knowing if or when ecological recovery is achieved.

The objective of this study was to compare ecological recovery of selected vegetation and soil indicators including percent cover by species and strata, species richness, Shannon diversity, and Sørensen's similarity index, soil bulk density, electrical conductivity, LFH depth, pH, total nitrogen (TN) and total organic carbon (TOC), and TOC:TN at certified reclaimed wellsites and adjacent reference locations (without industrial disturbance). A range of site age classes (~10, 20, and 30 years) post certification were selected, focusing on native grasslands in the Dry Mixedgrass Natural Subregion. Monitoring of soil and vegetation indicators at reclaimed sites in native grasslands across a range of age classes will provide novel insights into how recovery varies depending on the conservation and reclamation practices applied at a site and length of recovery (time). In addition, this study, as a pilot of our newly developed field protocols for monitoring ecological recovery on specified lands, also contributes to understanding the sensitivity and variability of indicators across reference vs wellsite locations in both individual sites and among age classes post-certification. This study provides baseline information on differences between wellsite and reference locations that can be used as a foundation to support development of an integrated, scientifically robust and financially sustainable monitoring program to enable the assessment of ecological recovery of physical, chemical, and biological indicators at certified reclaimed industrial sites across Alberta.

Methodology

Study Area

The Ecological Recovery Monitoring of Certified Wellsites (ERM) Advisory Group participated in a series of workshops in Spring 2013 to discuss study sampling protocols and site selection strategies. Given the relatively small number of wellsites we could sample, the advisory group decided upon screening sites for inclusion in the study rather than randomly selecting wellsites. We felt it was important to select a group of sites with similar shared attributes to increase our ability to detect potential differences in recovery, rather than these recovery signals getting lost in the high degree of variability among sites had we not screened our samples. Recommendations from the group to narrow the scope of sampling to reduce variability and increase the power of our sampling included screening for:

- a particular natural subregion, the Dry Mixedgrass Natural Subregion,
- a single common ecosite type representative of the subregion (i.e., sampling medium texture chernozemic soils
- relatively level topography to avoid cut and fill soil disturbance
- selecting reference locations adjacent to wellsites and using sites as blocking variables, and
- selecting only certain age classes of reclaimed wellsites. To evaluate how recovery differed across different ages post-certification, but recognizing that different age sites were confounded because they had different

types of conservation and reclamation policies that were applied to them, the group decided to evaluate recovery patterns for 3 age classes: approximately 10, 20, and 30 years post certification.

The study was conducted from May-August 2013 in the Dry Mixedgrass Natural Subregion of Alberta (Natural Regions Committee 2006). A total of 18 sample units were selected for inclusion in this study; they were located on loamy ecosites on public grazing leased lands (Fig. 1; see Appendix I for detailed information on the sites). In addition we used 15 reference sites with < 2% human footprint and >50% loamy soil sampled by ABMI's monitoring program (ABMI 2012) to compare our vascular plant species composition (presence/absence) with (Fig. 1).

Data Collection

Vegetation and soil indicator data and samples were collected as described in the report "Ecological Recovery Monitoring of Certified Reclaimed Wellsites in Alberta: Field Data Collection Protocols for Native Grasslands (ABMI 2013d)" for both wellsite and reference locations within each of the 18 study sites. The same vascular plant census data collection protocols were used for the 15 ABMI 1 ha reference sites. (information on database and data fields can be found in Appendix III). Note that LFH depth measured the depth similar to the methods used in forested lands, rather than through an estimate of litter that is used in some other methods in grasslands, so that should be taken into consideration when interpreting the LFH data.

Statistical Analysis

We calculated plant species richness and alpha diversity (i.e., Shannon Index, Magurran 1988) per 0.25 m^2 quadrat as well as species richness at the site level (wellsite vs reference location) using species census data. We also used species presence/absence data from the species census to measure Sørensen's similarity index (Sørensen 1948) to make pair-wise comparisons among the percent of species shared among vascular plant communities for both the wellsite and reference sites and the core ABMI sites. Sørensen's index provides a measure of the similarity among two sites which ranges from 0 to 100 where 0 = totally dissimilar (i.e., two sites have no species in common), and 100 = 100% similar (i.e., two sites have all species in common, thus there are no unique species that are only present in one of the two sites). Sørensen's similarity index was calculated for i) wellsite vs reference location within individual age classes, and ii) to compare individual wellsite and reference locations with the 15 ABMI reference sites. Note that there were potentially slight differences in the areas sampled for vascular plant richness in the wellsites compared with the reference and ABMI wellsites, because wellsites were not always exactly 1 ha in size whereas ABMI plots are always exactly 1 ha. Given that the duration of sampling was the same (80 minutes of searching for plants) we expect that species richness was likely not dramatically influenced by the potentially small differences in area sampled, but in the future we should further explore and evaluate approaches to increase the direct one-one comparability of the two protocols.

This study used a split-plot design with age class as the plot-level 'treatment' and the location (wellsite vs reference) as the subplot 'treatment'. For univariate analyses, we first determined whether each variable met the assumptions for analysis of variance (ANOVA) and transformed response variables when necessary. Two-way ANOVAs were used to test for significant (α=0.05) differences in the response of individual variables (e.g., Shannon diversity, species richness, bulk density, electrical conductivity, pH, total organic carbon) to the age class (10, 20, and 30 years) and location (reference vs wellsite), as well as for significant (α=0.10) interactions between age class and location, including site (n=18) as a random factor in the mixed model (Proc Mixed, SAS Institute, Version 9.2 (32-bit), Cary, NC, USA; SAS Institute 2008). When age class was significant but location was not significant we used post-hoc linear contrasts to compare among age classes, combining data for all locations within each age class. When there was a significant age-class by location interaction we compared among locations for each age class separately and among age classes for each location separately. For all of these post-hoc comparisons we used Bonferroni-adjusted α values (family-wise α = 0.05).

Multivariate plant community composition patterns among locations (wellsite vs reference) and age classes (10, 20, 30) were examined using nonmetric multidimensional scaling (NMS) ordination (McCune and Grace 2002). Ordinations used PC-ORD (Version 5; MjM Software Design, Gleneden Beach, OR), with Sørenson as the distance measure, 100 runs with real data and 100 Monte Carlo

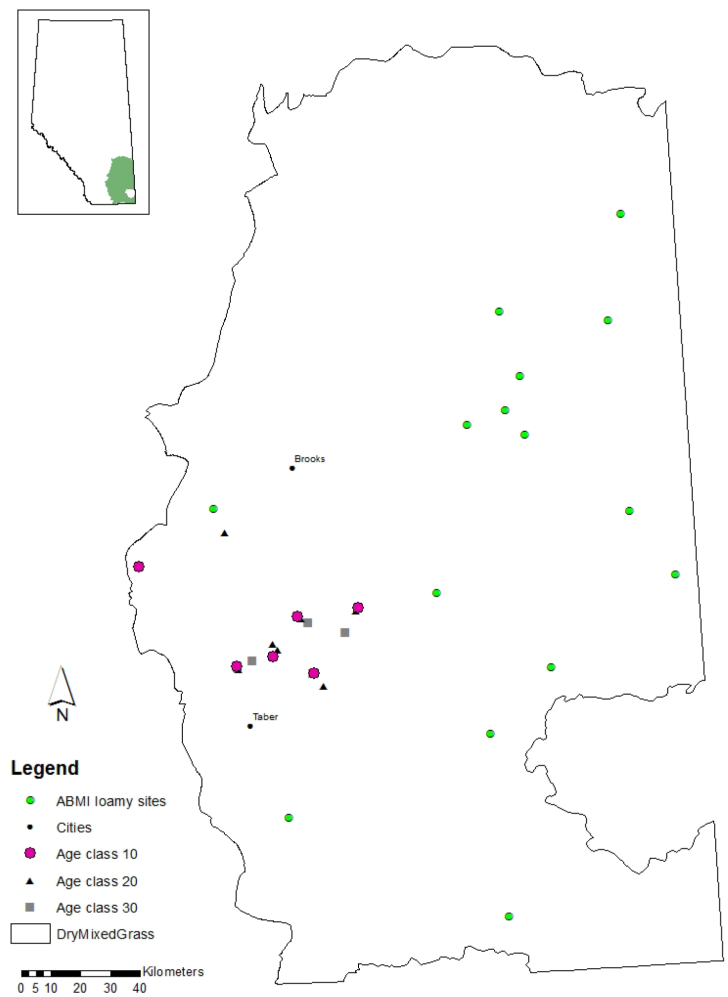

Fig. 1. Locations of the 18 study sites in the Dry Mixedgrass Natural Subregion delineated by post-certification age class, along with the location of the 15 ABMI monitoring sites that were compared with our 18 study sites.

randomized runs, starting with a six-dimensional solution and stepping down to a one-dimensional solution. We omitted species that only occurred in two of the 324 quadrats. We determined the number of dimensions of our final solution by evaluating the scree plot and the reduction in stress with step-down in dimensionality of the preliminary runs (McCune and Grace 2002). Stability of the solution (stability criterion = 0.00005) was assessed by plotting stress versus iteration. After the preliminary runs we ran a final NMS with the optimal number of dimensions, using the starting configuration that worked best in our preliminary runs, and omitting the Monte Carlo test. We then calculated the Pearson correlation coefficients of the vegetation and soil indicators (e.g., bulk density and pH at each of the soil sampling depths, cover by growth form, Shannon index) with the NMS ordination axes and overlaid variables with correlation ($R^2 > 0.25$) on the ordination plots. We used the multiresponse permutation procedure (MRPP) to test for statistically significant differences in plant community profiles among the locations and age classes. MRPP is a nonparametric multivariate procedure for testing the null hypothesis of no difference between two or more groups of entities (Zimmerman et al. 1985). The initial MRPP was followed up by pairwise comparisons among locations and age classes; P-values were Bonferroni-adjusted so the family-wise Type I error rate remained 0.05.

Boxplots of indicators for individual sites are included in Chapter 2 to assess within and between site variability of vegetation and soil indicators comparing among the wellsite and adjacent reference location for each site. Boxplots provide graphical displays that clearly represent the center, spread, and skewness of the distribution of the data by presenting a box that shows the middle 50% of datapoints from a dataset, with the tails of the boxplot representing the remainder of the data (Ramsay and Schafer 1997 – see Chapter 2 Fig. 2-2 for graphical display of a sample boxplot and the information it provides).

Results

Note that all graphs display results with locations (reference vs wellsite) separated out by individual age classes to display results at that fine scale. However, there was not always a significant interaction between location and age class (see Table 1 for which interactions were significant).

Vegetation

Species richness

Mean species richness for the number of species counted within both each (a) 0.25 m^2 quadrat and (b) within each site was consistently higher in the reference locations compared with the wellsite locations for each of the three age classes (Table 1; Fig. 2). There was no significant difference among non-native species in the wellsite vs reference locations (data not shown).

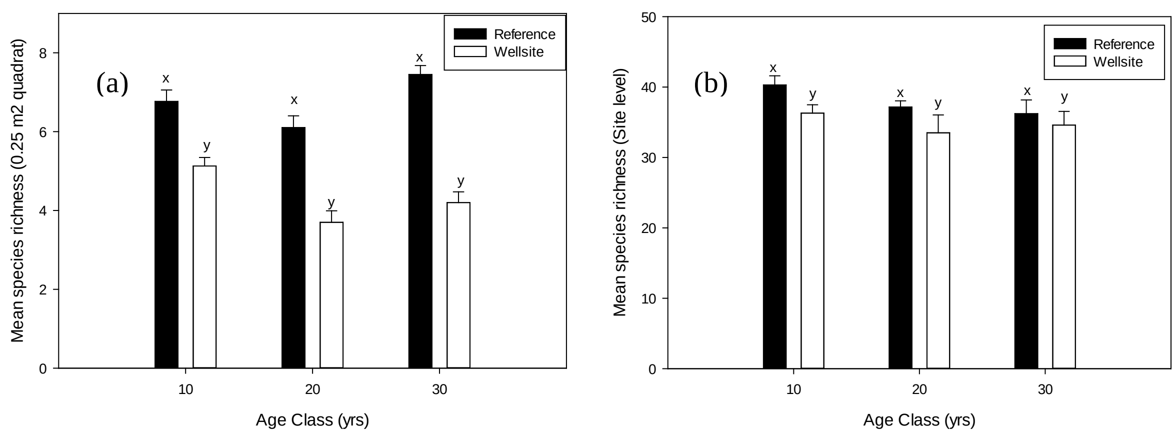

Fig. 2. Mean species richness (+ SE) by age class post-certification and location (reference vs wellsite). Locations with different letters (x, y) within individual age classes were significantly different.

Shannon diversity index

Mean Shannon diversity for each 0.25 m^2 quadrat was consistently higher in the reference locations compared with wellsite locations for each of the three age classes (Table 1; Fig. 3).

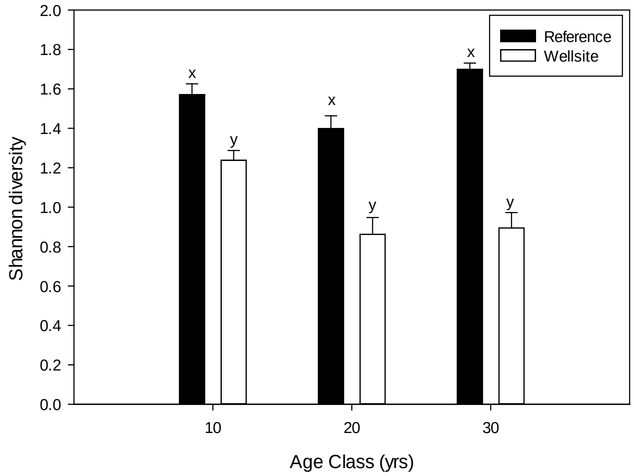

Fig. 3. Mean Shannon diversity (+ SE) by age class post-certification and location (reference vs wellsite). Locations with different letters (x, y) within individual age classes were significantly different.

Vegetation cover by growth form – all species combined

Mean percent cover of total vegetation and clubmoss cover were consistently higher in reference compared with wellsite locations for each of the three age classes (Table 1; Fig. 4a,e). Shrub cover did not differ between wellsite and reference locations across age classes (Table 1; Fig. 4b). Forb cover was only higher in the 10 yr age class on the wellsite compared with reference locations (Table 1; Fig. 4c). Graminoid cover was significantly higher in 30 year age class reference locations compared with wellsite locations (Table 1; Fig. 4d). Lichen cover was only higher in the 10 year age class on reference compared with wellsite locations (Table 1; Fig. 4f).

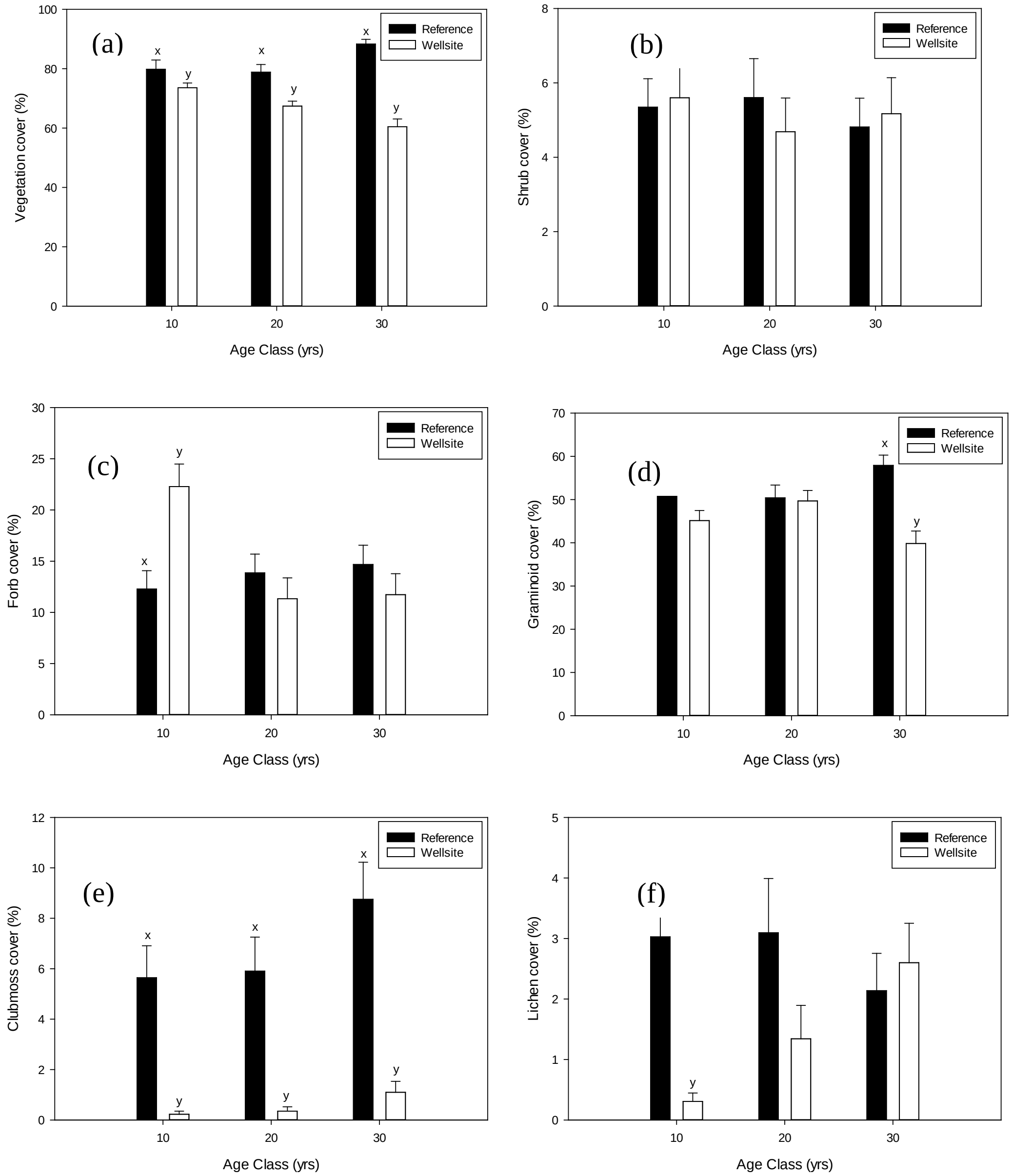

Fig. 4. Mean percent cover (+ SE) of (a) total vegetation, (b) shrubs (c) forbs (d) graminoids (e) clubmoss and (f) lichens by age class post-certification and location (reference vs wellsite). Locations with different letters (x, y) within individual age classes were significantly different. Note different cover axis ranges of values are used for the different cover types.

Vegetation cover by growth form – non-native species

Mean percent cover of total non-native vegetation was significantly higher on wellsites compared with reference locations regardless of age class (Table 1, Fig. 5a). For non-native forb cover wellsites had significantly higher cover than reference locations in the 10 year age class (Table 1, Fig. 5b). For graminoid cover, 20- and 30-year age classes of wellsites were significantly higher than reference locations (Table 1, Fig. 5c).

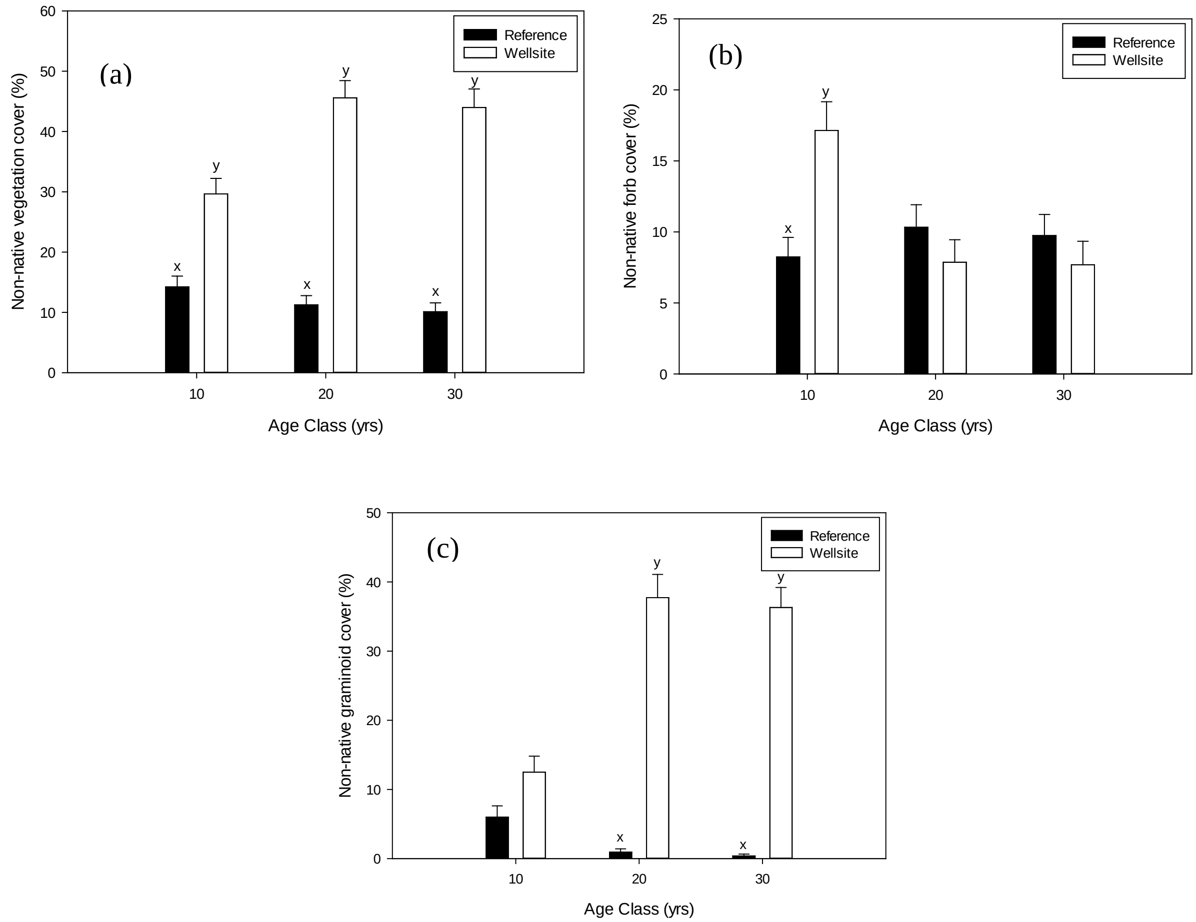

Fig. 5. Mean percent cover (+ SE) of non-native (a) total vegetation, (b) forbs and (c) graminoids. Locations with different letters (x, y) within individual age classes were significantly different. Note different cover axis ranges of values are used for the different cover types.

Sørensen's similarity index

Mean Sørensen's similarity index varied among age classes, with the 10 and 30 year age class wellsite vs reference locations being more similar than for the 20 year age class (Table 1, Fig. 6).

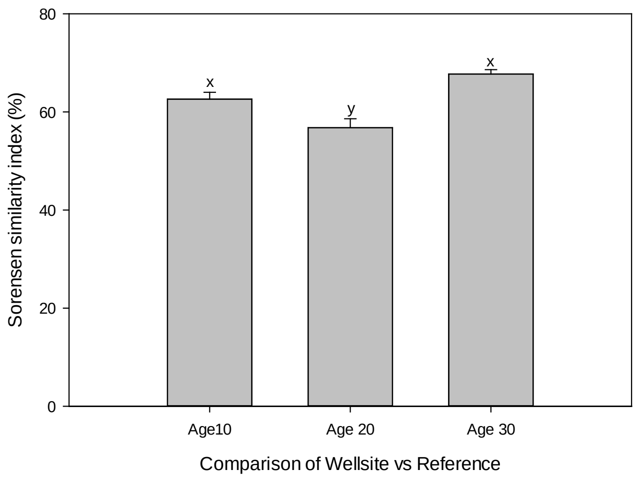

Fig. 6. Sørensen's similarity comparing among the presence/absence of vegetation data for wellsite and reference condition locations for 10 yr age class (Age10mix), 20 yr age class (Age20mix), 30 yr age class (Age30mix), combining all age classes (Mix), and all reference locations compared with each other (Ref) and all wellsite locations compared with each other (Well).

Comparing the mean Sørensen's similarity index of ABMI, wellsite, and reference sites, while reference and ABMI sites had similar percent similarity to each other, wellsites were significantly less similar to ABMI sites (Table 1, Fig. 7).

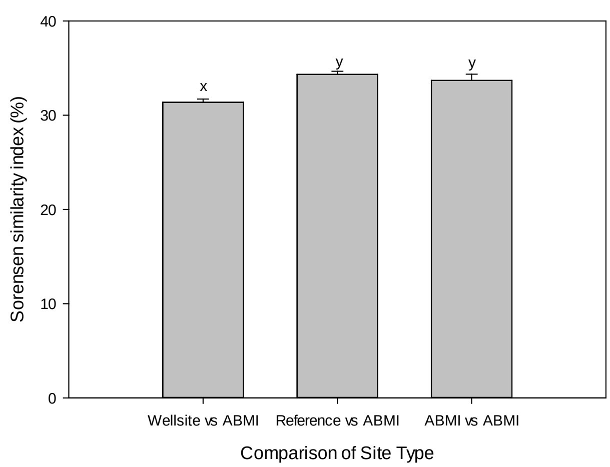

Fig. 7. Sørensen's similarity using presence/absence of vascular plant species data comparing among ABMI sites and ABMI (ABMI), reference (Ref vs ABMI), and wellsite (Well vs ABMI) site types.

Plant community composition ordination

The NMS three-dimensional solution (final stress = 10.4 after 34 iterations) explained 90.7% of the variation in the plant community; overlaying vegetation and soil descriptive variables on the NMS ordination of the plant community showed correlations of several plant and soil variables with the three ordination axes (Fig. 8; Table 2). The 20 and 30 year wellsite classes grouped together and based on their locations in the ordination plot showed positive correlations with cover of *Agropyron cristatum* (crested wheatgrass), and cover of litter. The 10 yr wellsites grouped together and based on their locations showed positive correlations with cover of *Taraxacum officinale* (dandelion), *Pascopyrum smithii* (western wheat grass), and forb cover. The reference locations overlapped for the three age classes and were positively correlated with Shannon diversity, total vegetation cover, cover of *Bouteloua gracilis* (blue grama grass), *Hesperostipa comata* (needle and thread grass), *Lycopodium annotinum* (stiff club-moss), and *Tragopogon dubius* (goat's-beard), and TOC and N in the 15-30 cm depth, and negatively correlated with bulk density in the two shallowest depths, as well as cover of *Heterotheca villosa* (golden aster) and *Thermopsis rhombifolia* (golden bean). MRPP analysis of plant communities showed significant differences between the locations among the age classes post-certification (A=0.18, P=0.000008); post-hoc pairwise comparisons also highlighted the differences between the wellsite and reference locations across age classes.

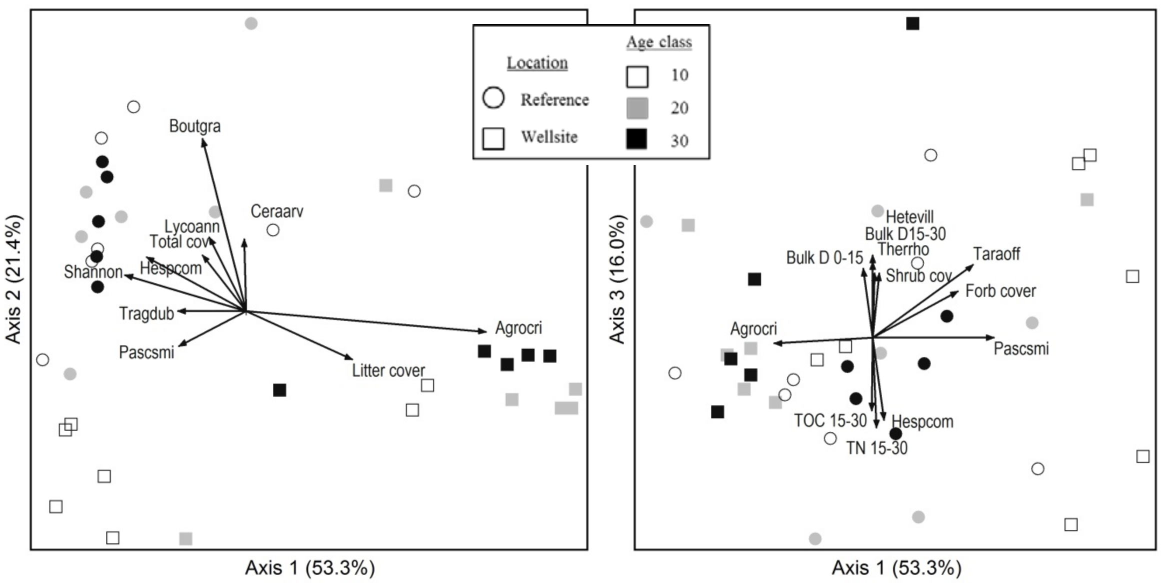

Fig. 8. Results of nonmetric multidimensional scaling (NMS) ordination of plant community composition. The final ordinations were 3-D solutions, so two plots are presented. Each symbol in the plots is a location and each color is an age class within an individual site. The amount of variation explained by each axis is included in parentheses. The angles and lengths of the vectors for the individual variables overlain on the ordination indicate direction and strength of associations of them with the ordination axes. Seven letter codes are species codes (See Appendix II). The cutoffs for display was $R^2 >$ 0.25.

Soils

Bulk density

Soil bulk density values were higher on wellsites compared with reference locations for each of the three age classes for both 0-15 cm and 15-30 cm depths (Table 1; Fig. 9).

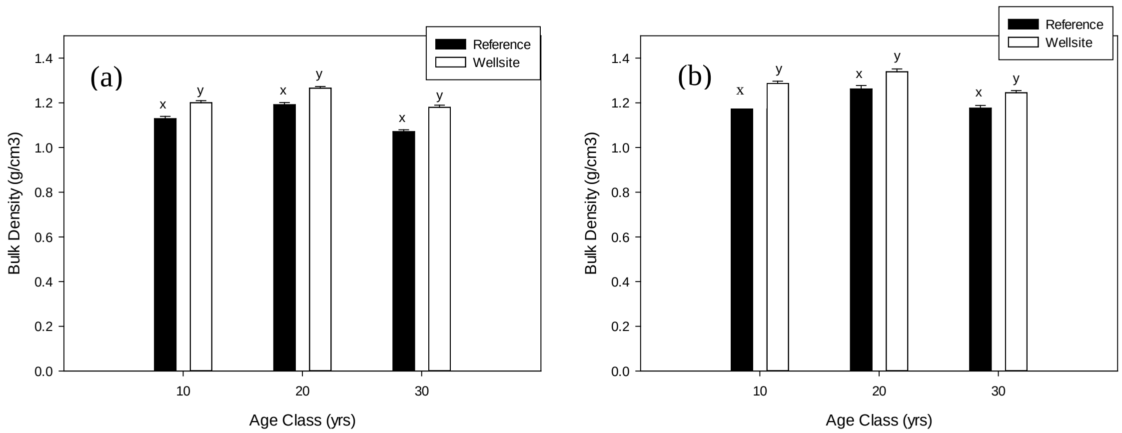

Fig. 9. Mean bulk density (+ SE) for (a) 0-15 cm depth and (b) 15-30 cm soil by age class post-certification and location (reference vs wellsite). Locations with different letters (x, y) within individual age classes were significantly different.

Electrical conductivity

Electrical conductivity (saturated paste) levels in the shallowest soil depth (0-15 cm) were higher on wellsites compared with reference sites across age classes (Fig. 10a; Table 1). For the three deeper soil depths (15-30 cm, 30-60 cm, and 60-100 cm), electrical conductivity was also higher on the wellsite compared with adjacent reference condition site, independent of age class (Fig. 10b-d; Table 1).

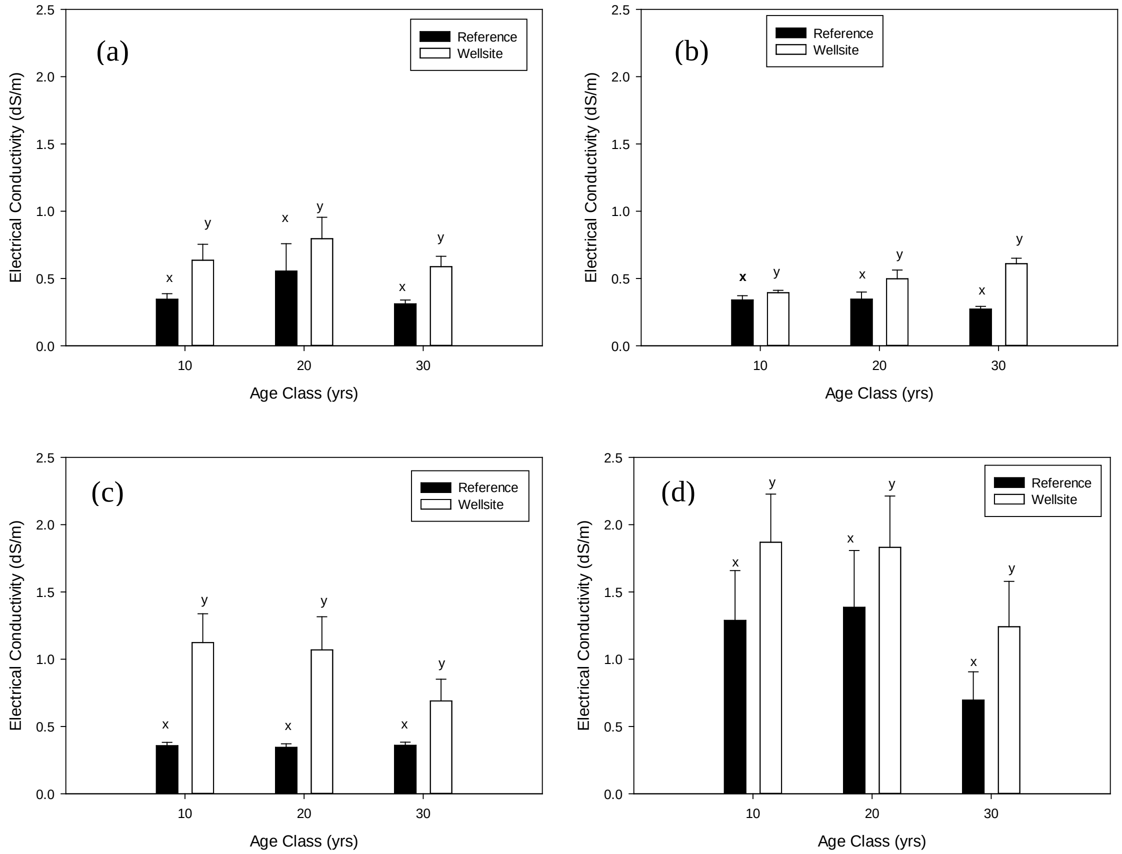

Fig. 10. Mean electrical conductivity (+ SE) for (a) 0-15 cm, (b) 15-30 cm, (c) 30-60 cm, and (d) 60-100 cm soil depth by post-certification age class and location (reference vs wellsite). Locations with different letters (x, y) within individual age classes were significantly different. Electrical conductivity was log transformed for analysis.

LFH depth

For the 20 and 30 yr age classes, LFH depth was significantly greater in reference locations compared with wellsite locations (Fig. 11; Table 1).

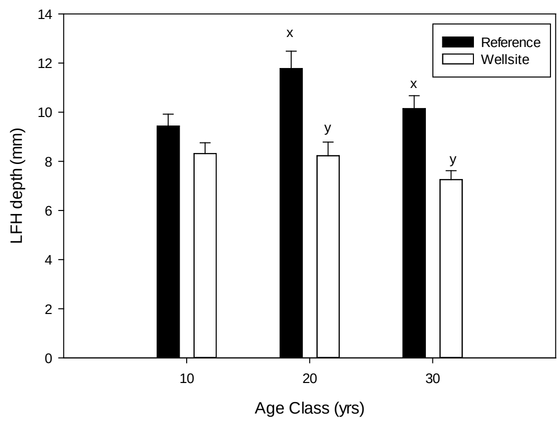

Fig. 11. Mean LFH depth (+ SE) by post-certification age class and location (reference vs wellsite). Locations with different letters (x, y) within individual age classes were significantly different.

pH

For the shallowest soil depth (0-15 cm), pH was significantly higher on wellsites compared with reference sites for the 20 and 30 yr age classes, but not the 10 yr age class (Fig. 12a; Table 1). For the 15-30 cm soil depth, pH was significantly higher on wellsites compared with adjacent reference sites, independent of age class (Fig. 12b, Table 1). For the 30-60 cm depth there was no significant difference in pH (Fig. 12c, Table 1). For the 60-100 cm depth, the pH was significantly lower on wellsites compared with the reference locations, independent of age class (Fig. 12d; Table 1).

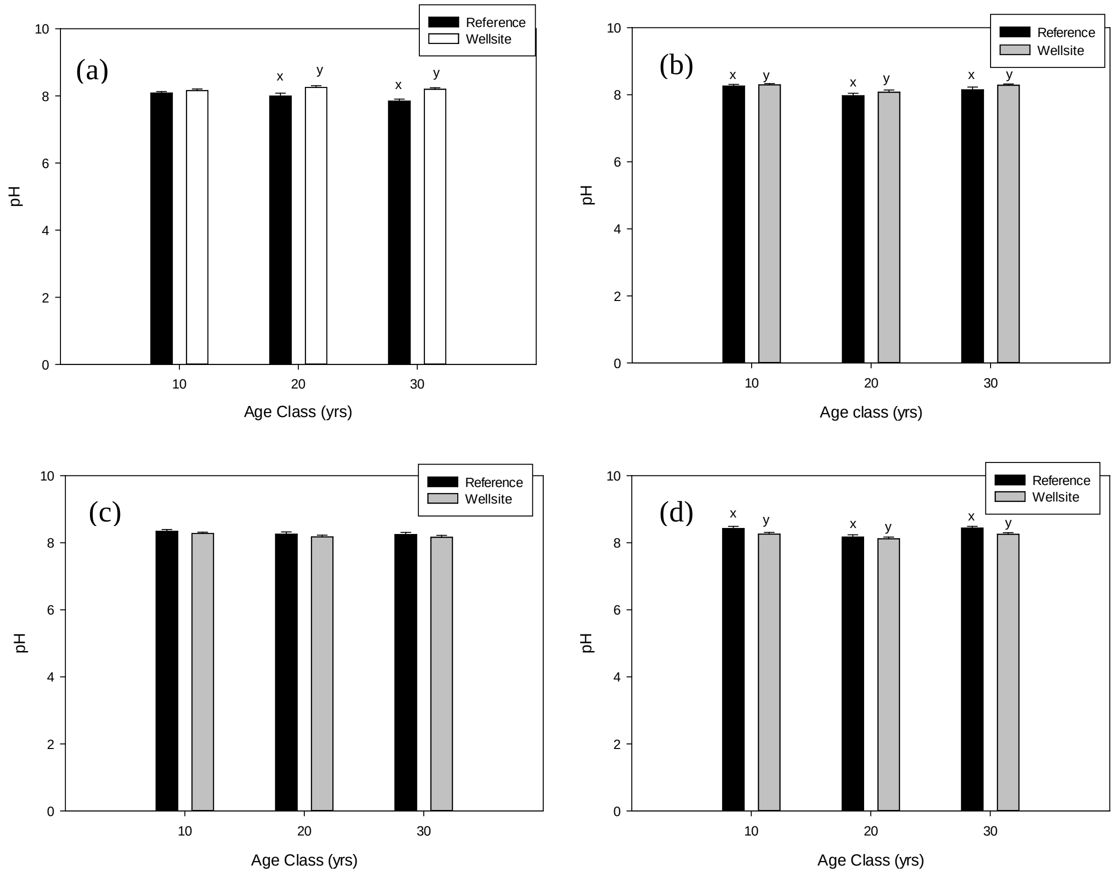

Fig. 12. Mean pH (+ SE) for (a) 0-15 cm, (b) 15-30 cm, (c) 30-60 cm, and (d) 60-100 cm depth soil by post-certification age class and location (reference vs wellsite). Locations in (a) with different letters (x, y) within individual age classes were significantly different. Locations in (b), (c), and (d) with different letters (x, y) among locations were significantly different.

Total nitrogen (TN)

Across all age classes, total nitrogen was lower on wellsites compared with reference locations for the upper three depths (0-15 cm, 15-30 cm, 30-60 cm), whereas there was no difference in the deepest soil sample (60-100 cm)(Fig. 13; Table 1).

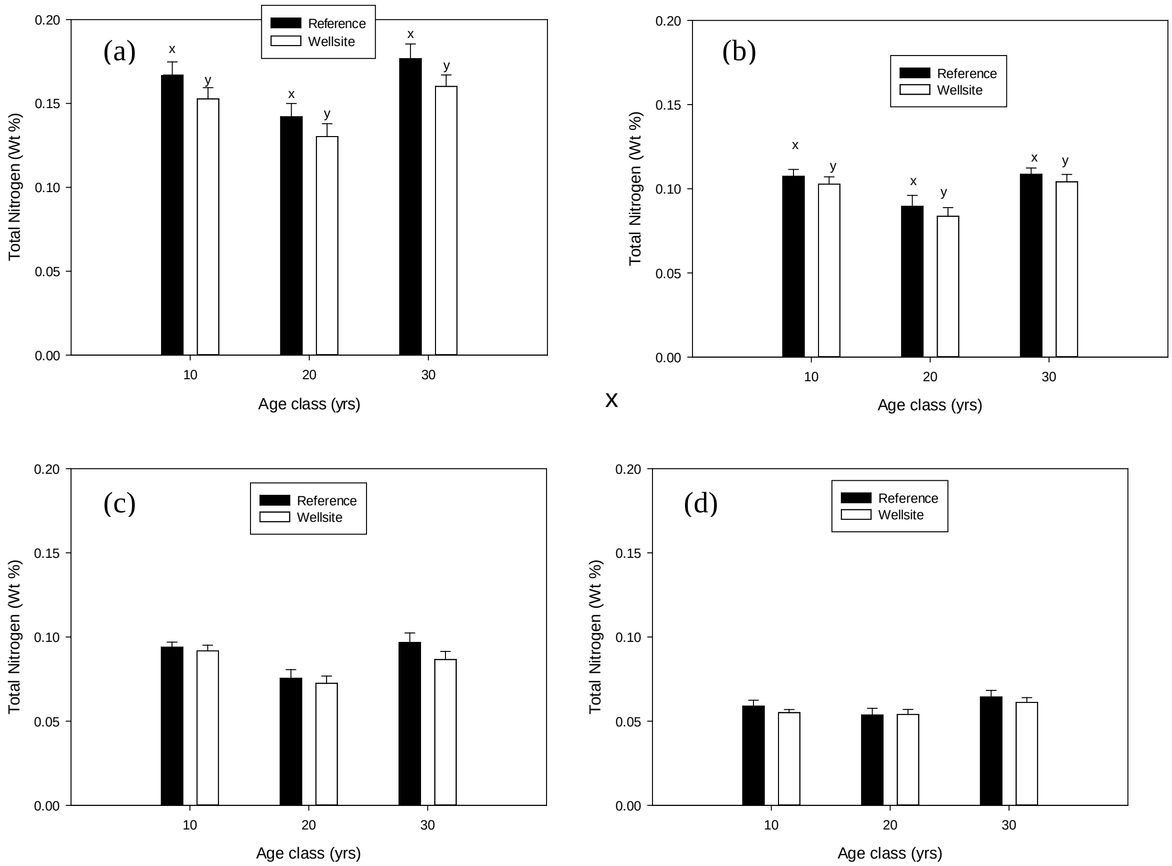

Fig. 13. Mean total nitrogen (+ SE) for (a) 0-15 cm, (b) 15-30 cm, (c) 30-60 cm, and (d) 60-100 cm depth soil by post-certification age class and location (reference vs wellsite). Locations with different letters (x, y) within individual age classes were significantly different. Total nitrogen for 60 cm depth was log transformed for analysis.

Total organic carbon (TOC)

Across age classes for the shallowest soil depth (0-15 cm), total organic carbon (TOC) was lower on wellsites compared with reference locations (Fig. 14a; Table 1). However, there were no differences in TOC among reference and wellsite locations for the three deepest depths (15-30 cm, 30-60 cm, 60-100 cm) (Fig. 14b-d, Table 1).

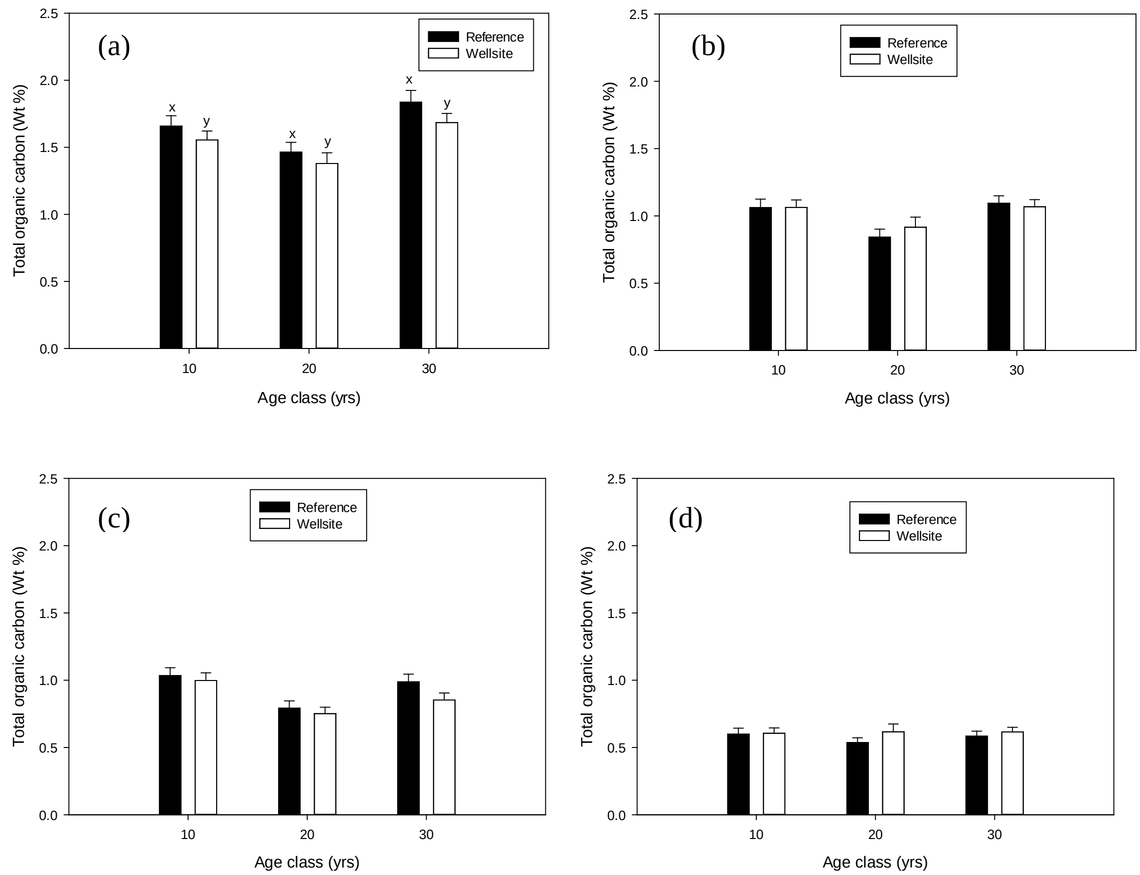

Fig. 14. Mean total organic carbon (+ SE) for (a) 0-15 cm, (b) 15-30 cm, (c) 30-60 cm, and (d) 60-100 cm depth soil by post-certification age class and location (reference vs wellsite). Locations with different letters (x, y) within individual age classes were significantly different.

Total organic carbon : total nitrogen (TOC:N)

Across age classes, there was no difference in TOC:N for 0-15 cm and 30-60 cm depths (Fig. 15a,c, Table 1). For the 15-30 cm soil depth 20 yr old wellsites had higher TOC:N ratios than reference sites (Fig. 15b, Table 1). For the 60-100 cm depth, wellsites also had higher TOC:N ratios than reference sites (Fig 15d, Table 1).

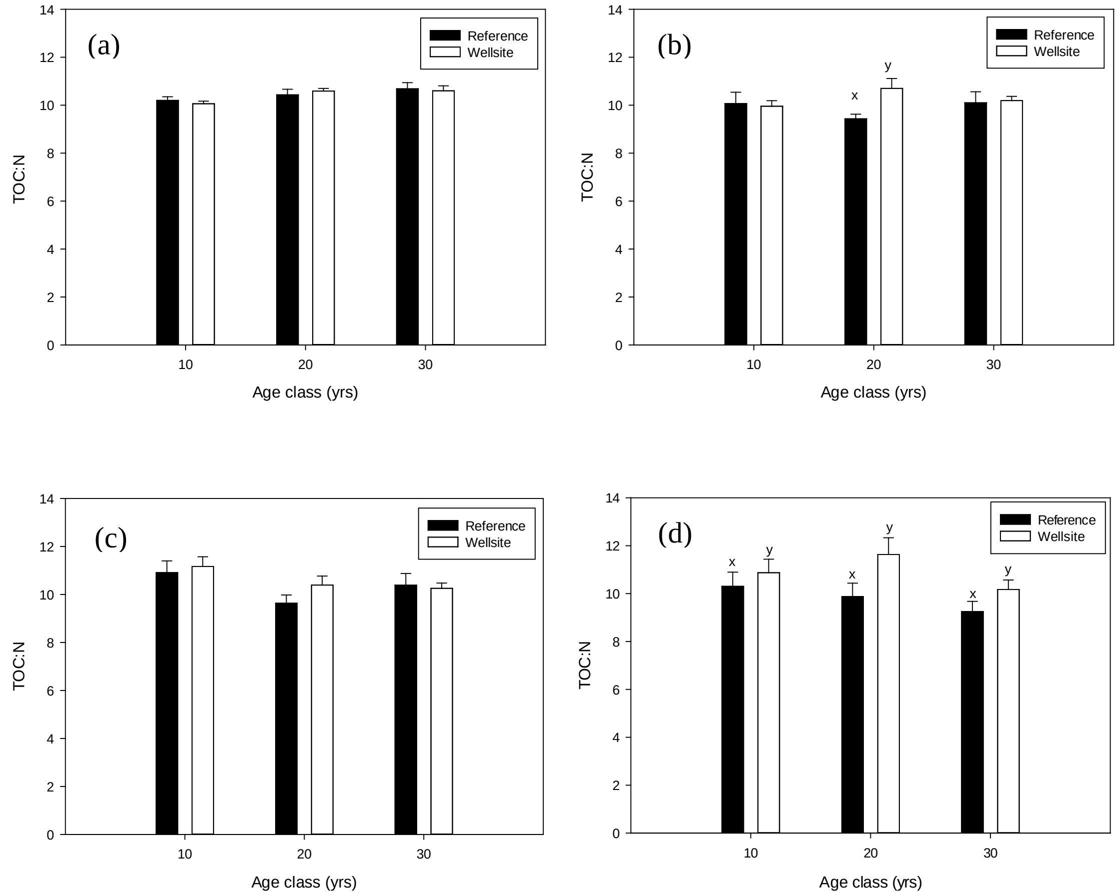

Fig. 15. Mean ratio of total organic carbon (TOC) to total nitrogen (+ SE) for (a) 0-15 cm, (b) 15-30 cm, (c) 30-60 cm, and (d) 60-100 cm depth soil by post-certification age class and location (reference vs wellsite). Locations with different letters (x, y) within individual age classes were significantly different. Note the difference in scale across graphs.

Table 1. Results (P values) for two-way ANOVAs testing for the effects of age class, location (reference vs wellsite), and the interaction between age class and location for vegetation and soil indicators in 18 loamy ecosite Dry Mixedgrass study units. Significant P-values highlighted in bold.

Variable	Age class	Location	Age class X Location
VEGETATION			
Species Richness			
Quadrat level	0.18	**<0.0001**	**0.03**
Site level	0.22	**0.02**	0.67
Shannon diversity	0.16	**<0.0001**	**0.007**
Total vegetation cover	0.60	**<0.0001**	**0.0003**
Shrub cover	0.97	0.91	0.78
Forb cover	0.59	0.41	**0.003**
Graminoid cover	0.91	**0.0003**	**0.03**
Clubmoss cover	0.38	**<0.0001**	0.36
Lichen cover	0.86	**0.01**	**0.06**
Total non-native cover[3]	0.69	**<0.0001**	**0.0009**
Non-native forb cover[3]	0.77	0.95	**0.0001**
Non-native graminoid cover[3]	0.41	**<0.0001**	**<0.0001**
Sørenson similarity index			
Age classes – well vs ref	n/a	**<0.0001**	n/a
Well vs ref vs ABMI	n/a	**<0.0001**	n/a
SOILS			
Bulk density			
0-15 cm depth	0.12	**<0.0001**	**0.02**
15-30 cm depth	0.26	**<0.0001**	**0.06**
Electrical conductivity			
0-15 cm depth	0.39	**<0.0001**	**<0.0001**
15-30 cm depth	0.97	**<0.0001**	0.55
30-60 cm depth	0.84	**<0.0001**	0.31
60-100 cm depth	0.59	**0.03**	0.96
LFH depth	0.86	**<0.0001**	**0.0044**
pH			
0-15 cm depth	0.61	**<0.0001**	**0.02**
15-30 cm depth	0.17	**0.02**	0.55
30-60 cm depth	0.44	0.06	0.97
60-100 cm depth	**0.03**[1]	**0.002**	0.38
Total nitrogen			
0-15 cm depth	0.26	**0.04**	0.74
15-30 cm depth	0.22	**0.04**	0.96
30-60 cm depth	0.054	0.06	0.54
60-100 cm depth	0.23	0.31	0.72
Total organic carbon (TOC)			
0-15 cm depth	0.29	**0.0004**	0.69
15-30 cm depth	0.43	0.68	0.30
30-60 cm depth	0.09	0.06	0.41
60-100 cm depth	0.92	0.26	0.60
TOC:N			
0-15 cm depth	0.27	0.83	0.53
15-30 cm depth	0.97	**0.009**	**0.03**
30-60 cm depth	0.43	0.19	0.43
60-100 cm depth	0.60	**0.01**	0.46

[1]Pairwise comparisons among age classes were not statistically significant.
[2]Log transformed prior to analysis.
[3]Square root transformed prior to analysis.

Table 2. NMS ordination Pearson, R-square, and tau correlations of variables with each of the 3 axes ordered from highest to lowest R-square for axis 1. Seven letter species codes refer to species described in Appendix II.

	Axis								
	1			2			3		
Variable	r	R^2	tau	r	R^2	tau	r	R^2	tau
Agrocri	0.95	0.91	0.77	-0.13	0.02	-0.05	-0.15	0.02	-0.08
Shannon diversity	-0.69	0.48	-0.32	0.27	0.07	0.18	0.19	0.04	0.12
Litter cover	0.65	0.42	0.38	-0.33	0.11	-0.25	-0.01	0.00	0.08
Hespcom	-0.63	0.40	-0.56	0.36	0.13	0.34	-0.57	0.32	-0.37
Tragdub	-0.50	0.25	-0.43	-0.11	0.01	-0.03	0.33	0.11	0.11
Pascsmi	-0.47	0.22	-0.46	-0.45	0.20	-0.23	-0.04	0.00	0.13
Boutgra	-0.45	0.21	-0.25	0.76	0.57	0.59	0.15	0.02	0.12
pH 0-15 cm	0.44	0.20	0.25	-0.29	0.08	-0.21	-0.16	0.03	-0.12
Forb cover	-0.44	0.20	-0.22	-0.33	0.11	-0.17	0.42	0.18	0.28
Electrical conductivity 0-15 cm	0.44	0.19	0.21	-0.27	0.08	-0.23	-0.12	0.02	-0.12
Total vegetation cover	-0.43	0.19	-0.37	0.40	0.16	0.31	-0.05	0.00	-0.01
Club-moss cover	-0.40	0.16	-0.22	0.48	0.23	0.41	-0.20	0.04	-0.18
Lycoann	-0.40	0.16	-0.22	0.48	0.23	0.41	-0.20	0.04	-0.18
Medisat	0.38	0.15	0.27	-0.13	0.02	-0.15	-0.15	0.02	-0.29
C:N ratio 15-30 cm	0.38	0.14	0.17	-0.03	0.00	-0.05	-0.18	0.03	-0.18
C:N ratio 60-100 cm	0.36	0.13	0.10	-0.15	0.02	-0.14	-0.17	0.03	-0.16
Taraoff	-0.34	0.12	-0.13	-0.50	0.25	-0.40	0.53	0.28	0.33
Bulk density 0-15 cm	0.34	0.11	0.29	-0.08	0.01	-0.11	0.52	0.27	0.38
TOC 60-100 cm	0.32	0.10	0.06	-0.10	0.01	-0.11	-0.17	0.03	-0.06
pH 60-100 cm	-0.31	0.09	-0.18	0.07	0.00	0.12	-0.12	0.01	-0.09
Electrical conductivity 15-30 cm	0.30	0.09	0.18	-0.23	0.05	-0.25	-0.18	0.03	-0.08
Elyminn	0.30	0.09	0.22	-0.09	0.01	-0.09	-0.08	0.01	-0.09
LFH depth	-0.30	0.09	-0.18	-0.06	0.00	-0.08	-0.01	0.00	0.00
Bromine	0.30	0.09	0.29	0.03	0.00	-0.11	0.40	0.16	0.26
Anteapr	0.28	0.08	0.28	-0.08	0.01	-0.15	0.34	0.12	0.18
Age of certification	0.28	0.08	0.19	0.20	0.04	0.16	-0.01	0.00	-0.02
Koelmac	-0.27	0.07	-0.25	0.36	0.13	0.31	-0.32	0.10	-0.14
Trifhyb	0.24	0.06	0.16	-0.04	0.00	-0.03	-0.06	0.00	-0.06
Achimill	-0.23	0.05	-0.15	-0.03	0.00	-0.15	-0.07	0.00	0.13
Descpin	-0.23	0.05	-0.16	-0.16	0.02	-0.13	-0.13	0.02	-0.08
Poasan	-0.23	0.05	-0.13	0.01	0.00	0.12	-0.17	0.03	0.00
Agrosca	-0.23	0.05	-0.30	-0.31	0.10	-0.24	-0.26	0.07	-0.26
Shrubs (less than 0.5 m tall)	-0.23	0.05	-0.07	0.01	0.00	0.15	0.50	0.25	0.30
Carespp	-0.22	0.05	-0.06	0.38	0.15	0.21	-0.19	0.04	-0.07
Descsop	-0.22	0.05	-0.17	-0.27	0.07	-0.17	0.33	0.11	0.16
Sphacoc	-0.21	0.04	-0.12	0.45	0.20	0.33	-0.24	0.06	-0.07
Festsax	-0.20	0.04	-0.13	0.06	0.00	-0.06	0.31	0.10	0.32

	Axis								
		1			2			3	
Variable	r	R^2	tau	r	R^2	tau	r	R^2	tau
Poapra	-0.20	0.04	-0.17	0.12	0.02	0.19	0.32	0.10	0.13
Elymtra	-0.19	0.04	-0.15	-0.25	0.06	-0.19	0.35	0.12	0.32
Mammviv	0.20	0.04	0.24	0.08	0.01	0.06	0.23	0.05	0.01
Non-native richness	-0.19	0.04	-0.18	-0.41	0.17	-0.25	0.01	0.00	0.05
TOC 15-30 cm	0.19	0.04	0.05	-0.10	0.01	-0.02	-0.53	0.28	-0.35
Carepen	-0.17	0.03	-0.10	0.12	0.02	0.10	0.30	0.09	0.26
Gaurcoc	-0.17	0.03	-0.15	0.11	0.01	0.09	-0.07	0.01	0.03
Melioff	0.17	0.03	0.15	-0.19	0.04	-0.29	-0.14	0.02	0.03
Electrical conductivity 30-60 cm	0.17	0.03	0.09	-0.28	0.08	-0.24	-0.29	0.08	-0.09
Lappsqu	-0.16	0.03	-0.22	0.18	0.03	0.02	-0.04	0.00	0.02
Soncasp	0.16	0.03	0.11	-0.11	0.01	-0.16	-0.01	0.00	0.06
Festcam	-0.15	0.02	-0.22	0.08	0.01	0.07	-0.27	0.07	-0.21
Lichspp	0.15	0.02	0.12	0.31	0.10	0.34	-0.42	0.17	-0.32
TN 30-60 cm	-0.15	0.02	-0.11	-0.23	0.05	-0.09	-0.20	0.04	-0.11
Convarv	-0.15	0.02	-0.20	-0.30	0.09	-0.21	-0.18	0.03	-0.18
Viciame	-0.15	0.02	-0.12	-0.18	0.03	-0.04	-0.04	0.00	0.03
Water cover	-0.15	0.02	-0.16	-0.18	0.03	-0.17	-0.28	0.08	-0.22
Careste	-0.14	0.02	-0.11	0.05	0.00	0.09	0.28	0.08	0.27
Medilup	-0.14	0.02	-0.10	0.10	0.01	0.09	-0.14	0.02	-0.16
Seladen	-0.14	0.02	-0.11	0.05	0.00	0.03	0.27	0.08	0.21
Chenalb	-0.14	0.02	0.01	0.19	0.04	0.14	-0.02	0.00	0.19
Hordjub	-0.14	0.02	-0.07	0.07	0.00	0.06	0.11	0.01	0.13
Allitex	-0.13	0.02	-0.07	0.12	0.01	0.12	0.20	0.04	0.22
Bulkd density 15-30 cm	0.13	0.02	0.15	-0.16	0.03	-0.26	0.54	0.30	0.39
Phlohoo	-0.13	0.02	-0.14	0.25	0.06	0.20	-0.02	0.00	0.03
Planpat	-0.13	0.02	0.08	-0.22	0.05	0.19	0.10	0.01	0.09
Creptec	-0.12	0.02	-0.18	-0.37	0.14	-0.17	0.07	0.00	-0.06
Therrho	-0.12	0.02	-0.05	0.00	0.00	0.00	0.50	0.25	0.36
Arabhol	-0.12	0.01	-0.03	0.11	0.01	0.10	0.19	0.04	0.17
Astrcra	-0.12	0.01	-0.03	0.11	0.01	0.10	0.19	0.04	0.17
Carefil	-0.12	0.01	-0.03	0.11	0.01	0.10	0.19	0.04	0.17
Linavul	-0.12	0.01	-0.03	0.11	0.01	0.10	0.19	0.04	0.17
Stelspp	-0.12	0.01	-0.03	0.11	0.01	0.10	0.19	0.04	0.17
Thlaarv	-0.12	0.01	-0.02	0.27	0.07	0.22	-0.09	0.01	-0.10
pH 15-30 cm	0.12	0.01	0.05	-0.30	0.09	-0.13	-0.03	0.00	0.02
Bromtec	-0.11	0.01	-0.05	-0.25	0.06	-0.10	0.28	0.08	0.25
Ceraarv	-0.11	0.01	0.01	0.52	0.27	0.36	0.27	0.07	0.22
Grinsqu	-0.11	0.01	-0.10	-0.35	0.12	-0.29	0.07	0.00	-0.07
Lactsca	-0.11	0.01	-0.01	-0.25	0.06	-0.20	0.28	0.08	0.22
Wood cover	0.11	0.01	0.10	0.22	0.05	0.30	0.18	0.03	0.21

	Axis								
		1			2			3	
Variable	r	R^2	tau	r	R^2	tau	r	R^2	tau
pH 30-60 cm	-0.11	0.01	-0.11	-0.10	0.01	0.00	-0.10	0.01	0.03
Liatpun	0.10	0.01	0.10	0.44	0.19	0.25	0.16	0.03	0.02
Raticol	-0.10	0.01	0.01	-0.34	0.11	-0.24	0.09	0.01	0.11
Soncarv	-0.10	0.01	0.02	-0.41	0.17	-0.30	0.34	0.12	0.28
Nassvir	0.10	0.01	-0.10	0.48	0.23	0.39	0.11	0.01	-0.04
TOC 30-60 cm	-0.09	0.01	-0.17	-0.22	0.05	-0.09	-0.26	0.07	-0.15
Fungi cover	0.09	0.01	-0.03	-0.01	0.00	0.00	-0.15	0.02	-0.09
TN 0-15 cm	-0.09	0.01	-0.07	-0.16	0.03	-0.09	-0.36	0.13	-0.19
TN 60-100 cm	-0.08	0.01	0.05	0.07	0.00	0.05	-0.11	0.01	-0.07
TOC 0-15 cm	-0.07	0.00	-0.08	-0.14	0.02	-0.03	-0.32	0.11	-0.20
C:N ratio 0-15 cm	0.07	0.00	0.08	0.01	0.00	-0.02	0.05	0.00	0.05
Hetevill	0.07	0.00	0.13	-0.11	0.01	0.07	0.57	0.32	0.31
Elymlan	-0.05	0.00	-0.02	-0.34	0.12	-0.26	0.21	0.04	0.16
Animal waste cover	-0.06	0.00	0.05	0.04	0.00	0.12	-0.17	0.03	-0.12
Artecan	-0.04	0.00	-0.07	0.47	0.22	0.24	0.30	0.09	0.22
Artefri	-0.04	0.00	0.15	-0.42	0.17	-0.17	0.08	0.01	0.19
Electrical conductivity 60-100 cm	0.04	0.00	0.02	-0.13	0.02	-0.16	-0.33	0.11	-0.16
Elymrep	-0.04	0.00	0.02	0.13	0.02	0.13	-0.30	0.09	-0.24
Andrsep	-0.03	0.00	0.03	-0.33	0.11	-0.22	0.21	0.04	0.18
Astrdas	-0.03	0.00	0.07	0.03	0.00	-0.02	0.15	0.02	0.01
Cirsflo	0.04	0.00	0.07	-0.11	0.01	-0.13	0.47	0.22	0.24
Psorlan	0.04	0.00	-0.04	-0.02	0.00	-0.13	0.24	0.06	0.27
Rosaaci	-0.02	0.00	0.05	0.40	0.16	0.24	0.18	0.03	0.16
Grass cover	-0.04	0.00	-0.22	0.21	0.04	0.12	-0.42	0.18	-0.26
Lichen cover	-0.03	0.00	-0.02	0.35	0.13	0.33	-0.48	0.23	-0.42
Mineral soil cover	0.03	0.00	0.15	0.10	0.01	0.06	0.16	0.03	0.03
Rock cover	-0.04	0.00	0.23	-0.12	0.01	0.06	-0.31	0.10	-0.21
TN 15-30 cm	-0.01	0.00	-0.14	-0.16	0.03	-0.05	-0.59	0.35	-0.40
C:N ratio 30-60 cm	0.00	0.00	-0.05	-0.06	0.00	-0.06	-0.27	0.07	-0.15
Shrub cover 0.5-2 m	0.01	0.00	-0.07	0.44	0.20	0.16	0.30	0.09	0.38
Moss cover	0.01	0.00	-0.07	-0.26	0.07	-0.32	-0.18	0.03	-0.09

Discussion

Patterns in vegetation differences among wellsite and reference locations observed in this study were generally consistent with what was expected based on the conservation and reclamation guidelines in place when the sites were certified (see Table 2 - Alberta Environment 2010). For example, observed differences in 20 and 30 year age classes were consistent with reclamation practices in place at the time; compatible species including both native and non-native varieties suitable for grazing purposes were used for sites reclaimed prior to 1993. While non-native vegetation cover was consistently greater at wellsites across all age classes, non-native forbs (e.g., dandelion, yellow sweet clover) rather than graminoids (e.g., crested wheatgrass) contributed to greater non-native cover in the 10 year age class compared with the 20 and 30 year classes post certification. This is also consistent with the shift in reclamation practices; for sites abandoned and/or reclaimed from 1993-2001 vegetation cover was required to be dominated by native species, but with the caveat that sites could be certified with whatever introduced forages came up from the seedbank (Alberta Environment 2010). The proximity of 10 year wellsite plant communities to reference plant communities in the NMS ordination suggests that the plant community composition of younger wellsites reclaimed under more recent reclamation criteria are more similar than are compositions of older age class wellsites. Interestingly, despite the lack of support for vegetation recovery of wellsites for most indicators, the Sørensen similarity index of both 10 and 30 year age class wellsites was more similar to reference sites than were 20 year age class sites post certification. The similarity of the 10 year age class to reference sites is likely a consequence of updated conservation and reclamation practices that now require more native species. Although the relative proportions of cover of the species present are still very different than reference locations, 30 year old wellsites did have similar species present on the wellsites compared with the reference sites. But we still do not know how long it will take for the plant composition of these sites to recover and have similar distribution of percent cover among species to those found in the reference sites. Given the still very high abundance of crested wheatgrass, which is now recognized as a problem introduced forage, on these sites 30 years after certification, it is unclear when (if ever) sites reclaimed under the pre-1993 historic reclamation criteria will recover to reference conditions.

Patterns in soil properties comparing wellsite and reference locations across age classes indicates a lack of recovery for most indicators for at least one soil depth. However, LFH depth and soil pH (0-15 cm depth) did not significantly differ among wellsite and reference locations for the 10 year age class, suggesting that recent reclamation practices may have less negative impact on these attributes than older reclamation practices did. This could be a function of improved topsoil conservation and reclamation guidelines and practices at sites constructed after 1994 (Alberta Environment 2010). The findings of differences between wellsite and reference locations for most soil indicators across age classes suggests that ecological recovery of these soil indicators will take longer periods of time than were evaluated in this study, and will depend on reclamation practices.

The study findings provide novel insights into long term impacts on soils and vegetation at reclaimed native grassland wellsites in Southern Alberta between wellsites and reference sites. We do not yet have repeated measures of reclaimed wellsites over time, so cannot estimate recovery direction or rate at these reclaimed wellsites. Further study is needed. A long-term monitoring program will enable evaluation of ecological recovery at industrial sites, and will also address key knowledge gaps on the effects of impacts on soil and vegetation that currently constrain the assessment of ecological recovery after reclamation.

Conclusions

This study focused on assessing ecological recovery of historical wellsites on a single common ecosite type in native grasslands by comparing vegetation and soil indicators on wellsites with adjacent reference locations. In general, results showed vegetation and soil indicators on the wellsites were significantly different from adjacent reference conditions, indicating that industrial impacts can be long lasting and may constrain ecological recovery for 30 years or more. This lack of recovery was evident across the different age classes, although there was some evidence for plant communities and surface pH in the youngest age class being more similar to reference locations compared with the older age classes post-certification. This suggests that newer conservation and reclamation practices may have less negative impacts on native prairie soils and plant communities than older practices did. We do not yet know how long it will take for these reclaimed wellsites to recover, and thus longer-term monitoring is needed to evaluate recovery trajectories over time. A long-term monitoring program with repeated measurements of conditions that can be monitored at regular intervals will enable development and refinement of predictive models that describe trajectories and rates of recovery at reclaimed industrial sites in Alberta. Overall, this project will greatly enhance the ability of industry and government stakeholders to evaluate the efficacy of reclamation practices on ecological recovery and provide assurances to the public that Alberta's public lands are being responsibly managed for both today and into the future. In the future this program can be expanded beyond wellsites to explore ecological recovery of other industrial sites.

In the next stage of the project (2014/2015), the focus will be on assessing ecological conditions at example ecosite types in forested lands in the Boreal Region. In addition to ground based soil and vegetation assessments, unmanned aerial vehicles (UAVs) and automated recording units (ARUs) will be used to monitor ecological conditions at reclaimed wellsites. We will use this information to continue to build the framework for development of an integrated, scientifically robust and financially sustainable monitoring program to enable the assessment of ecological recovery of physical, chemical, and biological indicators at certified reclaimed wellsites across Alberta. However, a key consideration to advancing this program will be to ensure that the long-term monitoring framework will fit within the governance structure that the Alberta government develops for AEMERA.

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Appendix I. Study Site Descriptors

Table A1. Description of the 18 Study Sites

Site ID	UTM Zone	Easting	Northing	License	Land description	Spud year	Certification year	Age class
1	12	436581	5550405	141682	NW-20-13-14	1989	1990	20
2	12	435240	5551773	184388	NW-30-13-14-4	1996	2005	10
3	12	412464	5581280	139753	SE-27-16-17-4	1989	1993	20
4	12	428048	5540877	201188	NW 21-12-15 W4	1997	2003	10
5	12	426549	5542805	152641	NW 29 12 15 W4	1992	1996	20
6	12	414093	5535961	183173	NE 1 12 17 W4	1996	2004	10
7	12	414393	5535589	84734	SE-1-12-17 W4	1980	1983	30
8	12	439965	5532126	176601	SW 27 11 14 W4	1995	2005	10
9	12	382837	5571404	132322	SE 26 15 20 W4	1988	2003	10
10	12	414455	5534818	96691	NE 36 11 17 W4	1982	1992	20
11	12	451206	5545481	83488	NW 2 13 13 W4	1980	1983	30
12	12	438786	5549398	117348	SE 21 13 14 W4	1985	1986	30
13	12	455186	5552518	139581	SE 31 13 12 W4	1989	1992	20
14	12	419484	5537647	90874	NE 9 12 16 W4	1981	1983	30
15	12	443161	5527678	141685	NW 12 11 14 W4	1989	1996	20
16	12	426563	5538365	203375	SW 17 12 15 W4	1997	2005	10
17	12	439655	5532008	99456	SW 27 11 14 W4	1982	1983	30
18	12	456020	5553640	154416	NW 32 13 12 W4	1992	2001	10

Appendix II. Vascular plant species identified in this study.

Table A2. List of vascular plant species included in this study and whether they were sampled within the 0.25 m^2 quadrats and their native status.

Species_ID	Genus	Species	Common	Sampled in quadrat?	Non-native?
Achimill	*Achillea*	*millefolium*	Common Yarrow	Yes	No
Agrocri	*Agropyron*	*cristatum* ssp. Pectiniforme	Crested Wheat Grass	Yes	Yes
Agrosca	*Agrostis*	*scabra*	Tickle Grass	Yes	No
Allitex	*Allium*	*textile*	Prairie Onion	Yes	No
Andrsep	*Androsace*	*septentrionalis*	Fairy Candelabra	Yes	No
Anteapr	*Antennaria*	*parvifolia*	Low-Everlasting Pussy-toes	Yes	No
Arabgla	*Turritis*	*glabra*	Tower Mustard	No	No
Arabhol	*Boechera*	*holboellii*	Reflexed Rock Cress	Yes	No
Arctuva	*Arctostaphylos*	*uva-ursi*	Bearberry/ Kinnikinnick	No	No
Arteabs	*Artemisia*	*absinthium*	Absinthe	No	Yes
Artecan	*Artemisia*	*canadensis*	Sagebrush	Yes	No
Artefri	*Artemisia*	*frigida*	Pasture Sage	Yes	No
Artelud	*Artemisia*	*ludoviciana*	Prairie Sage	No	No
Astr Spp	*Astragalus*	*Spp*	Milk Vetch Spp	No	No
Astrbis	*Astragalus*	*bisulcatus*	Two-grooved Milk Vetch	No	No
Astrcic	*Astragalus*	*cicer*	Cicer Milk Vetch	No	Yes
Astrcra	*Astragalus*	*crassicarpus*	Ground plum	Yes	No
Astrdas	*Astragalus*	*agrestis*	Purple Milk Vetch	Yes	No
Astrpec	*Astragalus*	*pectinatus*	Narrow-leaved Milkvetch	No	No
Astrstr	*Astragalus*	*laxmannii* var. robustior	Ascending Purple Milk Vetch	No	No
Axyrama	*Axyris*	*amaranthoides*	Russian Pigweed	No	Yes
Boutgra	*Bouteloua*	*gracilis*	Blue Grama Grass	Yes	No
Bromano	*Bromus*	*anomalus*	Nodding brome Grass	No	No
Bromine	*Bromus*	*inermis*	Smooth Brome	Yes	Yes
Bromtec	*Bromus*	*tectorum*	Downy Chess Grass	Yes	Yes
Carefil	*Carex*	*filifolia*	Thread-leaved Segde	Yes	No

Species_ID	Genus	Species	Common	Sampled in quadrat?	Non-native?
Carepen	*Carex*	*pensylvanica*	Sun-loving Sedge	Yes	No
Careste	*Carex*	*duriuscula*	Low Sedge	Yes	No
Ceraarv	*Cerastium*	*arvense*	Mouse-ear Chickweed	Yes	No
Chenalb	*Chenopodium*	*album*	Lamb's Quarters	Yes	Yes
Chryleu	*Leucanthemum*	*vulgare*	Ox-eye Daisy	No	No
Chryvill	*Heterotheca*	*villosa*	Hairy Golden Aster	No	No
Cirsarv	*Cirsium*	*arvense*	Canada Thistle	No	Yes
Cirsflo	*Cirsium*	*flodmanii*	Flodman's Thistle	Yes	No
Comaumb	*Comandra*	*umbellata*	Bastard Toad-flax	No	No
Convarv	*Convolvulus*	*arvensis*	Field Bindweed	Yes	No
Creptec	*Crepis*	*tectorum*	Annual Hawksbeard	Yes	Yes
Descpin	*Descurainia*	*pinnata*	Green Tansy Mustard	Yes	No
Descsop	*Descurainia*	*sophia*	Flixweed	Yes	Yes
Elymlan	*Elymus*	*lanceolatus*	Northern Wheat Grass	Yes	No
Elymrep	*Elymus*	*repens*	Quack Grass	Yes	No
Elymtra	*Elymus*	*trachycaulum*	Slender Wheat Grass	Yes	No
Erigcae	*Erigeron*	*caespitosus*	Tufted Fleabane	No	No
Erigpum	*Erigeron*	*pumilus*	Hairy Daisy	No	No
Erysasp	*Erysimum*	*asperum*	Prairie Rocket	No	No
Erysche	*Erysimum*	*cheiranthoides*	Wormseed Mustard	No	Yes
Eurolan	*Krascheninnikovia*	*lanata*	Winter Fat/White Sage	No	No
Fesc Spp	*Fescue*	*Spp*	Fescue Grass Spp	No	No
Festcam	*Festuca*	*campestris*	Foothills Rough Fescue	Yes	No
Festsax	*Festuca*	*saximontana*	Rocky Mountain Fescue	Yes	No
Gaurcoc	*Gaura*	*coccinea*	Scarlet Butterfly-weed	Yes	No
Gleched	*Glechoma*	*hederacea*	Ground-ivy	No	Yes
Grinsqu	*Grindelia*	*squarrosa*	Gumweed	Yes	No
Hapllan	*Pyrrocoma*	*lanceolata* var. laceolata	Lance-leaved Pyrrocoma	No	No

Species_ID	Genus	Species	Common	Sampled in quadrat?	Non-native?
Haplspi	*Xanthisma*	*spinulosum*	Spiny Ironplant	No	No
Hespcom	*Hesperostipa*	*comata*	Needle and Thread Grass	Yes	No
Hespcur	*Hesperostipa*	*curtiseta*	Western Porcupine Grass	No	No
Hetevill	*Heterotheca*	*villosa*	Golden Aster	Yes	No
Hierumb	*Hieracium*	*umbellatum*	Narrow-leaved Hawkweed	No	Yes
Hordjub	*Hordeum*	*jubatum*	Foxtail Barley Grass	Yes	No
Kochsco	*Kochia*	*scoparia*	Summer Cypress/ Burning Bush	No	No
Koelmac	*Koeleria*	*macrantha*	June Grass	Yes	No
Lactsca	*Lactuca*	*serriola*	Prickly Lettuce	Yes	No
Lappsqu	*Lappula*	*squarrrosa*	Blue-bur	Yes	No
Leyminn	*Leymus*	*innovatus*	Hairy Wild Rye Grass	Yes	No
Liatpun	*Liatris*	*punctata*	Dotted Blazing Star	Yes	No
Lich Spp	*Lichen*	*Spp*	Lichen Spp	Yes	No
Linavul	*Linaria*	*vulgaris*	Yellow Toad-flax	Yes	Yes
Linuusi	*Linum*	*usitiatissimum*	Flax	No	No
Lithinc	*Lithospermum*	*incisum*	Narrow-leaved Puccoon	No	No
Lupipus	*Lupinus*	*pusillus*	Annual Lupine	No	No
Lycoann	*Lycopodium*	*annotinum*	Stiff Club-moss	Yes	No
Machgri	*Xanthisma*	*grindelioides*	Toothed Ironplant	No	No
Mammviv	*Mammillaria*	*vivipara*	Ball Cactus	Yes	No
Medilup	*Medicago*	*lupulina*	Black Medick	Yes	Yes
Medisat	*Medicago*	*sativa*	Alfalfa	Yes	Yes
Melioff	*Melilotus*	*officinalis*	Yellow Sweet Clover	Yes	Yes
Mononutt	*Monolepis*	*nuttalliana*	Spear-leaved Goosefoot	No	No
Muhl Spp	*Muhlenbergia*	*Spp*	Muhy Grass Spp	No	No
Nassvir	*Nassella*	*viridula*	Green Needle Grass	Yes	No
Oenocae	*Oenothera*	*cespitosa*	Rock Rose	No	No
Opunpol	*Opuntina*	*polyacantha*	Prickly-pear	No	No

Species_ID	Genus	Species	Common	Sampled in quadrat?	Non-native?
			Cactus		
Orobfas	*Orobanche*	*fasciculata*	Clustered Broom-rape	No	No
Oxytser	*Oxytropis*	*sericea*	EarlyYellow Loco-weed	No	No
Oxytspl	*Oxytropis*	*splendens*	Showy Loco-weed	No	No
Pascsmi	*Pascopyrum*	*smithii*	Western Wheat Grass	Yes	No
Pens Spp	*Penstemon*	*Spp*	Beard-tongue Spp	No	No
Pensalb	*Penstemon*	*albidus*	White Beard-tongue	No	No
Pensgra	*Penstemon*	*gracilis*	Lilac-flowered Beard-tongue	No	No
Petapur	*Dalea*	*purpurea* var. purpurea	Purple Prairie Clover	No	No
Phlohoo	*Phlox*	*hoodii*	Moss Phlox	Yes	No
Planpat	*Plantago*	*patagonica*	Pursh's Plantain	Yes	No
Poaari	*Poa*	*arida*	Plains Bluegrass	No	No
Poacom	*Poa*	*compressa*	Canada Bluegrass	No	Yes
Poapra	*Poa*	*pratensis*	Kentucky Bluegrass	Yes	No
Poasan	*Poa*	*secunda* ssp. secunda	Sandberg Bluegrass	Yes	No
Portole	*Portulaca*	*oleracea*	Purslane	No	No
Potearg	*Potentilla*	*drymocallis*	White Cinquefoil	No	No
Potefru	*Dasiphora*	*fruticosa*	Shrubby Cinquefoil	No	No
Potehip	*Potentilla*	*hippiana*	Woolly Cinquefoil	No	No
Potepen	*Potentilla*	*pensylvanica*	Prairie Cinquefoil	No	No
Psorlan	*Psoralidium*	*lanceolatum*	Scurf Pea	Yes	No
Raticol	*Ratibida*	*columnifera*	Prairie Cone-flower	Yes	No
Rosaaci	*Rosa*	*acicularis*	Prickly Rose	Yes	No
Rosaark	*Rosa*	*arkansana*	Prairie Rose	No	No
Salskal	*Salsola*	*kali*	Russian Thistle	No	Yes
Seladen	*Selaginella*	*densa*	Prairie Selaginella	Yes	No
Soncarv	*Sonchus*	*arvensis*	Perennial Sow-thistle	Yes	Yes
Soncasp	*Sonchus*	*asper*	Spiny Annual Sow-thistle	Yes	Yes

Species_ID	Genus	Species	Common	Sampled in quadrat?	Non-native?
Sphacoc	*Sphaeralcea*	*coccinea*	Scarlet Mallow	Yes	No
Stel Spp	*Stellaria*	*Spp*	Chickweed Spp	Yes	Yes
Sympocc	*Symphoricarpos*	*occidentalis*	Buckbrush	No	No
Taraoff	*Taraxacum*	*officinale*	Common Dandelion	Yes	Yes
Therrho	*Thermopsis*	*rhombifolia*	Golden Bean	Yes	No
Thlaarv	*Thlaspi*	*arvense*	Stinkweed	Yes	Yes
Tragdub	*Tragopogon*	*dubius*	Goat's-beard	Yes	Yes
Trifhyb	*Trifolium*	*hybridum*	Alsike Clover	Yes	Yes
Trifpra	*Trifolium*	*pratense*	Red Clover	No	Yes
Verbtha	*Verbascum*	*thapsus*	Common Mullein	No	Yes
Viciame	*Vicia*	*americana*	American Vetch	Yes	No

Appendix III. Entity database relationship diagram

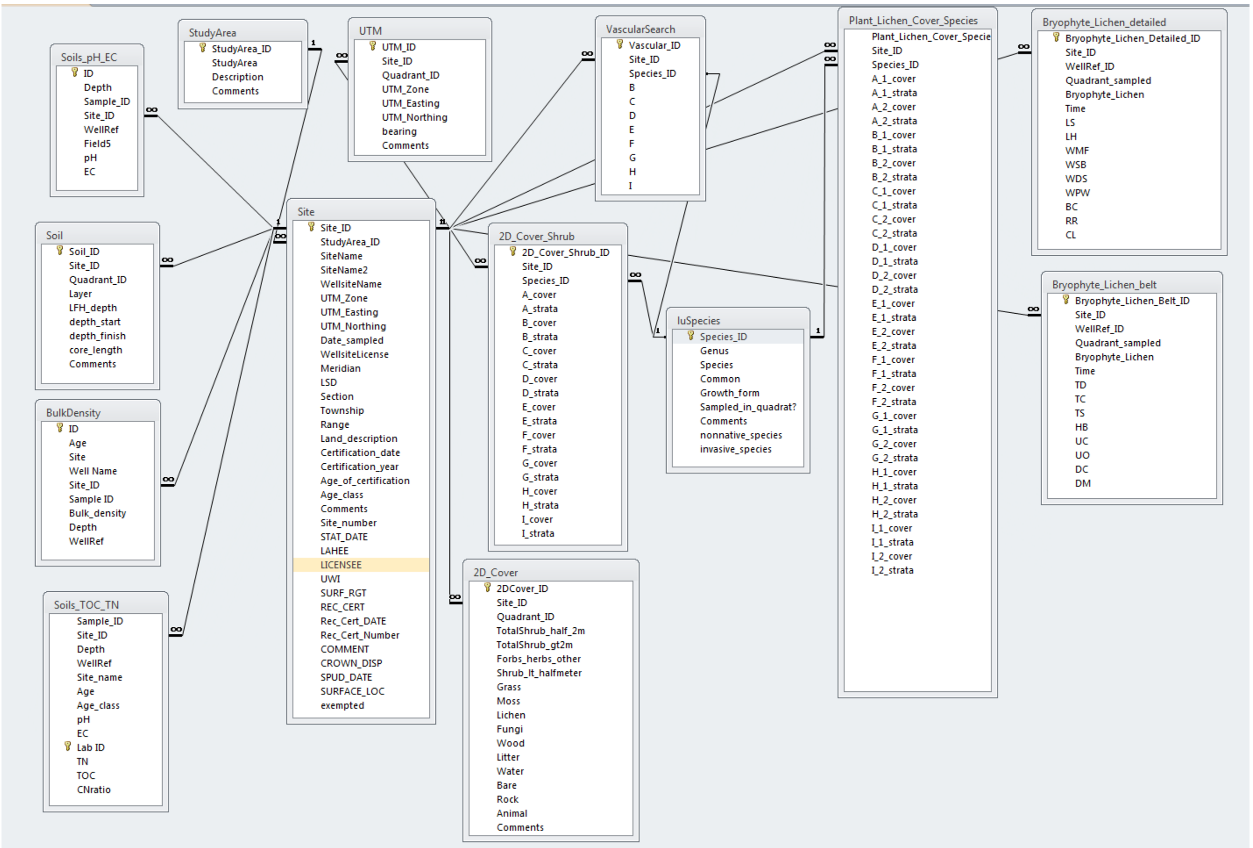

Fig. A3-1. Entity relationship diagram for the MS Access database where the Dry Mixedgrass ERM data are stored.