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RESEARCH ARTICLE

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Time, climate, and soil settings set the course for reclamation outcomes following dryland energy development

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Abstract

Soil attributes, climate, and time since reclamation have important implications for oil and gas reclamation success on drylands. It is uncertain if reclaimed well pads, on highly degraded drylands, can successfully regain ecological function or meet indicator benchmarks for reclamation. Here, our goals were to assess patterns in reclamation outcomes relative to (1) soil attributes, climate, and time since reclamation; and (2) plant and soil reference benchmarks. We collected a suite of plant, soil, and landscape characteristics from 134 reclaimed well pads on the Colorado Plateau that spanned climate and soil gradients and ranged from 2 to 20 years post-reclamation, then compared characteristics to those from 583 reference plots. On the reclaimed pads, less saline soils, more mesic climates, and longer time since reclamation were associated with favorable reclamation outcomes based on metrics of plant species richness and diversity, plant structure, and cover of important plant functional groups. However, most pads had major departures in 1/4 indicators, suggesting unsuccessful reclamation. Arid warm locations with shallow soils had the greatest percentage of major departures, and noxious plant richness had the greatest departures across soil and climate settings. Our assessment indicates reclamation is failing in key metrics for most pads, and the results highlight the role of environmental conditions in driving reclamation outcomes. These new insights are valuable for ascertaining possible reclamation outcomes and success rates following energy related disturbance, including orphaned wells and renewable energy development. Importantly, the approach used here has applicability for setting benchmarks and outcome standards.

KEYWORDS
benchmark, climate, energy development, indicator, oil and gas, reclamation

1 | INTRODUCTION

Considerable efforts are ongoing to cut emissions and diversify energy sources to address global climate change (Quéré et al., 2019), although energy development continues to grow with substantial ecosystem impacts (Jordaan et al., 2021; McClung et al., 2019). The physical and ecological footprint of energy development is vast and there is uncertainty on where, when, and how these highly disturbed lands can be successfully reclaimed after production has ceased. Energy development can fragment wildlife habitat (Chambers et al., 2022; Howden et al., 2019), increase cover of weedy annual species (Waller et al., 2018), and arrest plant succession (Lupardus et al., 2019). Management actions (e.g., soil amendments, seeding) may improve reclamation, but current research indicates mixed results (Nauman et al., 2017). Recovery may take 50–100 years, if ever, in some ecosystems (Avirmed et al., 2015).

Energy resources in the western US are frequently located in arid and semiarid ecosystems (drylands hereafter (Copeland et al., 2009; Lopez et al., 2021; Sengupta et al., 2018)). Drylands are highly sensitive to climate (Ahlstrom et al., 2015) as well as prone to irreversible land degradation (Barger et al., 2018; MEA, 2005). Extended and severe droughts have become more common, including the ongoing southwestern US "megadrought" (Williams et al., 2022), and have impeded perennial plant establishment and amplified losses of primary production (Dannenberg et al., 2022). These increases in aridity will further challenge reclamation in current drylands following land disturbing activities (Glick et al., 2011), and in areas forecast to transition into drylands in the coming decades (Huang et al., 2016).

In the United States, there is increasing interest in combating the impacts of past and current energy development, and mitigating impacts of future development. For example, the Bipartisan Infrastructure Law ("Infrastructure Investment and Jobs Act", 2021) allocated $4.7 billion toward orphaned and idle well site plugging, remediation, and restoration activities, with implementation underway by Federal, State, and Tribal agencies. Further, there are currently hundreds of thousands of abandoned and current oil and gas wells in US drylands (Allred et al., 2015; Skinner et al., 2022) with an increasing footprint from industrial-scale solar and wind facilities (Loveringa et al., 2022), which have similar environmental impacts and require similar reclamation efforts (Hernandez et al., 2014). Information about reclamation effectiveness, especially in drylands, is particularly important for federal policy and land managers given the vast drylands managed by the federal government (Duniway et al., 2019). Unfortunately, there is a lack of robust scientific information to guide successful reclamation following oil and gas development in drylands, little guidance for siting new developments to maximize reclamation success and minimize long-term impacts (Department of the Interior US, 2018; Interior and Agriculture, 2007), and unlike mining, no national standards or benchmarks for reclamation success (OSMRE 1977; Young et al., 2022).

Defining appropriate benchmarks by which reclamation outcomes are evaluated is critical in assessing reclamation outcomes, particularly when working across a landscape. Evaluation of outcomes have typically been conducted using before-and-after or paired plot comparisons, which are problematic due to landscape and climate variation (Fick et al., 2021). Using networks of reference sites, on the other hand, ensures that spatial and temporal variability in reference indicators is captured (Traynor et al., 2020). One-to-one comparisons may also fail to distinguish between reclamation and restoration by assuming failure if reclaimed sites fail to match undisturbed conditions (Gerwing et al., 2022; Mann et al., In Press).

Determining reclamation success also necessitates defining quantitative benchmarks (Howell et al. 2016; Nauman et al., 2017). Benchmarks are typically created from distributions of indicator values that characterize the natural range of variability expected to occur in a region in the absence of development and are used to evaluate ecosystem conditions and management outcomes (Gibson et al., 2000; Hawkins et al., 2010; Webb et al., 2020). Outcomes of reclamation may be a reflection of climate and soil setting (Bresson et al., 2022; Shackelford et al., 2021), practices (Soulodre et al., 2022), policy (Lupardus et al., 2020), or combinations of factors. Edaphic factors especially, such as soil texture, depth, and salinity, are known to influence or constrain the structure and composition of reclaimed vegetation communities (Monroe et al., 2022; Pennington et al., 2017). Therefore, when evaluating reclamation outcomes, or establishing benchmarks more broadly, land classifications based on concepts of land potential that incorporate the plant–soil-climate system are often used (Herrick et al., 2019). In the United States, this includes the Ecological Site Information System (Caudle, 2013) and more recent efforts to create groups of ecological sites for management and policy decisions at larger scales (Bestelmeyer et al., 2016).

Here, we explore trends in reclamation success on oil and gas pads across gradients in climate, soil settings, and time since reclamation on the Colorado Plateau. We used data from an extensive field sampling campaign that measured indicators of post-reclamation ecological conditions and a network of reference plots monitored by the Bureau of Land Management (BLM), to better understand the abiotic controls over reclamation (Lupardus & Duniway, 2023). First, we determined how reclamation outcomes varied with soil, climate, and time since reclamation. Second, we compared reclamation outcomes to reference locations assessed with monitoring data from the same management units and years as the reclaimed sites, but unimpacted by oil and gas. We accomplished this using climate and predictive soil maps to characterize the general abiotic settings, a linear model framework to assess outcomes, and an ecologically based benchmark-approach to assess site specific outcomes within soil and climate settings (using Ecological Site Groups; ESGs). Finally, we discuss how these results can inform efforts to improve reclamation management more generally.

2 | MATERIALS AND METHODS

2.1 | Study area

We focused on lands impacted by oil and gas development on the Colorado River basin including portions of the Colorado, Arizona and New Mexico Plateaus of New Mexico, Colorado, and Utah ("Plateau" hereafter; Figure 1). The Plateau covers 366,000 km^2 across a broad spectrum of aridity, lithology, topography, and seasonal distribution of precipitation (Duniway et al., 2022; Hereford & Webb, 1992). Plateau ecosystems include shrublands and grasslands, pinyon-juniper and scrub-oak woodlands, subalpine conifer systems, and alpine tundra. Most oil and gas wells on the Plateau are located in the low- to mid-elevation shrubland, grassland, and woodland drylands.

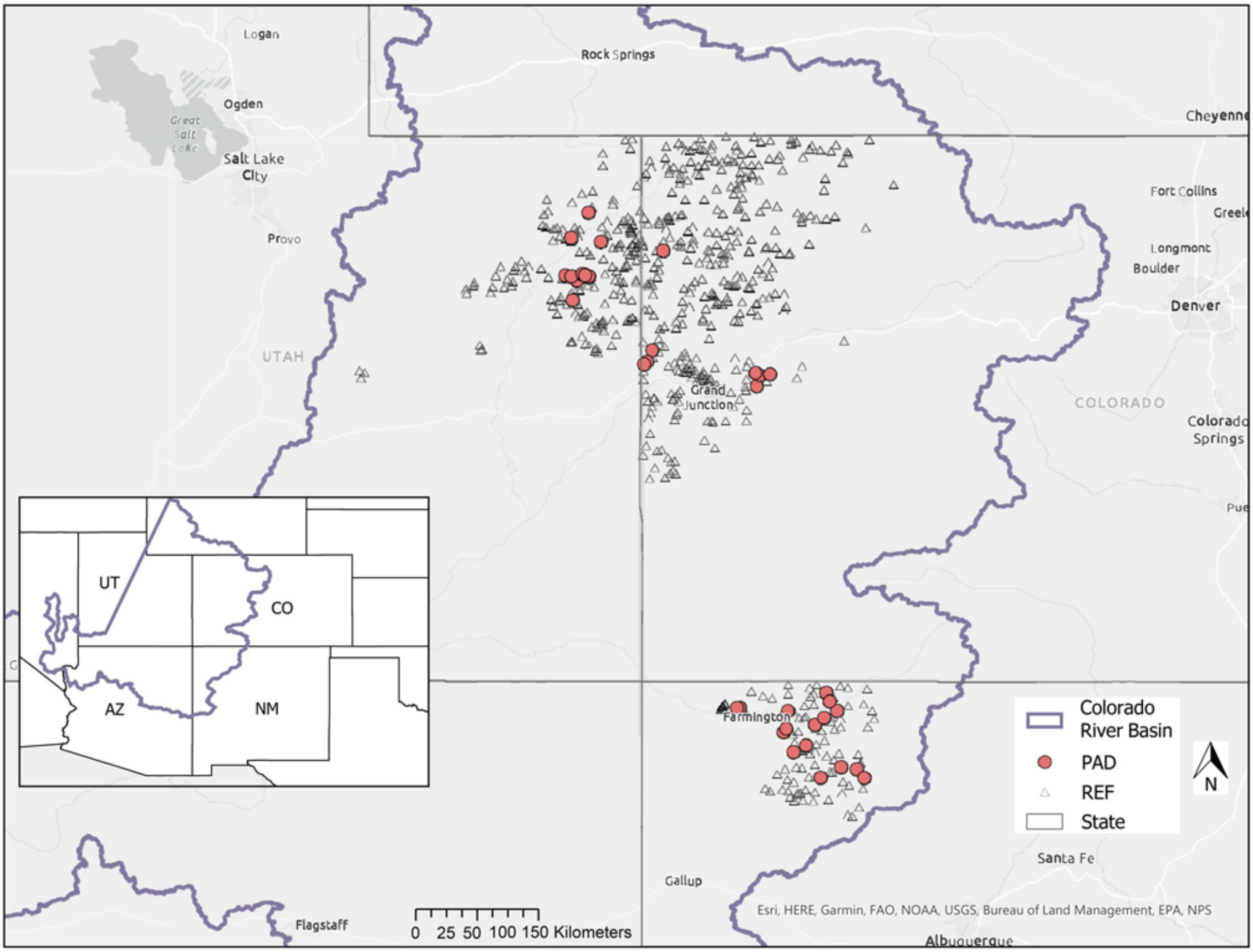

FIGURE 1 Location of study area and distribution of reclaimed oil and gas well pads sampled (PAD; $n = 134$) and Bureau of Land Management Assessment Inventory and Monitoring reference (REF; $n = 583$) locations across the Colorado River basin including portions of the Colorado, Arizona and New Mexico Plateaus of New Mexico, Colorado, and Utah. [Colour figure can be viewed at wileyonlinelibrary.com]

2.2 | Sampling design for well pads

Well location and status data were from the Automated Fluid Minerals Support System (AFMSS; https://reports.blm.gov/reports/AFMSS) from five BLM Field Offices (FOs): Vernal, Utah; Farmington, New Mexico; Grand Junction, Colorado; Little Snake, Colorado; and White River, Colorado, and were limited to wells with a status of "P + A", indicating the operator had been released from liability for the site and "ABD" which indicates the well had been plugged but the operator had not yet been released from liability. We further limited sampling to oil or gas well pads ("pads" hereafter) that were plugged in the year 2000 or later ($n = 725$), then conducted a selection process based on aerial imagery, spatial analysis, and ancillary information provided by collaborating BLM office staff. We also limited sampling to pads without any co-located active wells, where equipment and infrastructure had been removed, and with some evidence or documentation of reclamation. Reclamation activities conducted by operators in the study area commonly include removing infrastructure, recontouring site to blend with surrounding topography, replacing stored topsoil, and revegetating the site by broadcast or drill seeding with a mix of perennial grasses and forbs. We excluded pads that never entered the production phase, were inaccessible (> ~ 3-miles from designated road), were deemed unsafe (> 30% slope), experienced fire in the last decade, or that were less than 0.3 ha in area. We then used a stratified random design to select pads for field visits from a range of management units, soils, climates, and time since reclamation. Pads were stratified by the six FOs; three soil types (based on soil geomorphic units described and mapped in Nauman et al., 2022); three aridity classes calculated within FO and soil type (Zomer et al., 2022); and four time periods since reclamation (from AFMSS; See Table S1 for a complete description of strata). This resulted in 182 possible pads spread across 16 unique strata from which we randomly selected sites for sampling. Finally, sites were rejected in the field based on inaccessibility (e.g., unusable roads) and signs of excessive post-reclamation human disturbance (e.g., equipment, structures, a surplus of trash, evidence of recreational camping).

The authors put great effort into gathering reclamation data, although there was not enough information available on any one reclamation practice (e.g., seeding techniques or mixes, soil storage methods, season of reclamation) to include in the statistical analysis (see Table S2).

2.3 | Pad sampling methods

From July to September of 2020 ($n = 36$) and May–September 2021 ($n = 98$), vegetation composition, structure, and cover data were collected on selected plugged and abandoned oil and gas pads ("Pad" hereafter, total $n = 134$). Data were collected using methods compatible with the BLM Assessment Inventory and Monitoring (AIM) strategy, including line-point intercept (LPI), species inventories, plant height and canopy gap measurements (Table S3; Herrick et al., 2017). With our initial sampling in 2020, we used a hub-and-spoke design with plots centered on the pad (following Herrick et al., 2017). In 2021, we sampled using three evenly spaced, parallel transects such that measurements evenly covered the pad area. Transect length was 25 m, unless the pad was greater than 0.5 ha, in which case 50 m transects were used to better capture variance across the total area. Transects were established perpendicular to the dominant slope, perpendicular to seed rows if present, or perpendicular to a randomly selected azimuth. Fifty evenly spaced LPI points were assessed per transect.

2.4 | Off-pad plot data

To understand how pad conditions compare to lands undisturbed by oil and gas in the BLM FOs sampled, we used data from the BLM AIM program. AIM represents one of the most extensive publicly available plot measurement datasets from US federal lands (Kachergis et al., 2022). The AIM program assesses conditions of BLM lands using standardized methods (Herrick et al., 2017) and a probabilistic sample design. We acquired AIM reference data ("Ref" hereafter) for Colorado, Utah, and New Mexico collected in 2020 and 2021. We then reduced the data to plots within the FOs of interest, within the same soil types and aridity ranges as the pads sampled, and those without fire impacts in the last decade using the Monitoring Trends in Burn Severity Burned Areas Boundaries Dataset for 1984–2020 (Eidenshink et al., 2007). This resulted in a final sample size of $n = 583$ Ref plots.

2.5 | Data analysis and statistical methods

Data generated during this study are available from the USGS ScienceBase-Catalog (Lupardus et. al., 2023). All analyses were conducted in R version 4.2.1 (2022) and RStudio (2022).

2.5.1 | Variable selection

After all soil and vegetation data were collected, indicators were selected based upon common usage in reclamation assessments (Interior, 2007) and were calculated using the "terradactyl" R package (McCord et al., 2022). Our indicators were categorized into plant community metrics (species richness, perennial richness, noxious richness, Shannon diversity, Pielou's evenness), plant structure and cover (woody species height, herbaceous species height, canopy gaps greater than 100 or 200 cm, total foliar cover, bare soil cover), and plant functional group cover (introduced perennial cover, introduced annual cover, native annual cover, perennial herbaceous cover, woody cover). Six explanatory variables (soil sand, clay, and rock content; soil salinity; soil depth class, and site aridity) were chosen to represent the range of climate and soil characteristics sampled and hypothesized to govern site recovery (Table S3). Aridity Index (AI) data were extracted from the Global Aridity Index (AI) Climate Database v2 and converted to Aridity (1-AI) (Zomer et al., 2022). We used recently published 30-m pixel predictive digital soil maps (Brungard et al., 2021; Nauman & Duniway, 2021) to represent selected soil variables at the pads and Ref sites. For each site, we extracted values of percent sand, clay, and rock (indicators of texture) and electrical conductivity (EC, proxy for salinity), for the top 15 cm of the soil column, and used the same approach to extract predictions of soil depth class to estimate depth to root or water restrictive layer. Reclamation time period and administrative unit were additionally included as predictors in analyses (Table S3).

2.5.2 | Non-metric multidimensional scaling (NMS) and Permutational multivariate analysis of variance (PERMANOVA)

We used the "vegan" R package for the following analyses. Using our vegetation data for the Pad and Ref plots, we calculated a Bray–Curtis dissimilarity index using the "vegdist" function. We used NMS to visualize vegetation clusters related to Site Type (Pad/Ref) and to examine correlations between plant community and soil indicators, diversity indicators, and other environmental variables. We used the "metaMDS" function to execute multiple ordinations and looked for stable configurations (Oksanen et al., 2018). We used the function "envfit" to find vector averages of environmental variables (Table S4). We also ran Permutational Multivariate Analysis of Variance (PERMANOVA) using distance matrices and the "adonis" function to determine differences in Pad/Ref vegetation communities. As "adonis" is sensitive to heterogenous dispersion and our sample groups are unbalanced, we used the "betadisper" function to test dispersion between groups.

2.5.3 | Bayesian multilevel (BRM) models

To determine the size of effects of time since reclamation as well as climate and soil variables on ecological indicators we fit multilevel Bayesian linear models (Bürkner, 2018).

Each ecological indicator (y) was modelled separately as:

$$y \quad A + D + EC + Clay + Sand + Rock + \alpha_{Admin} + \alpha_{FSS}$$

where *A* is aridity, *D* is soil depth class, *EC* is soil salinity, *Clay*, *Sand*, and *Rock* are soil texture components, and both α_{Admin} and α_{FSS} are varying intercepts for administrative unit and field season sampled, respectively. We include a fixed slope coefficient for *Time*, but only in models fit to Pad data. To facilitate more direct comparison between parameter estimates, we centered and scaled all explanatory variables except for *Time*, which was centered at 10 years post-reclamation (Schielzeth, 2010). Parameter estimates with 95% posterior credible intervals that did not contain zero were considered to have "non-zero" effects on the response variable. Model fit was assessed by calculating Baye's R^2 and using graphical posterior predictive checks (Gelman et al., 2019).

2.5.4 | Indicator species analysis

We were also interested in knowing which species were both abundant and unique to different reclamation time periods and FOs, therefore we used the time period since reclamation, created previously to stratify the pads, to run an indicator species analysis with the "indicspecies" package (de Caceres et al., 2016; Dufrêne & Legendre, 1997). Indicator species analysis involves calculating an indicator value that quantifies both how specific a given species is to a group, and how abundant that species is within that group (Dufrêne & Legendre, 1997). We used an extension of the indicator value method that allows a given species to be an indicator for multiple groups (de Cáceres et al., 2010).

2.5.5 | Benchmark analysis

To further understand how reclamation outcomes compared to the condition of lands not impacted by energy development, we compared Pad indicators to the distribution of indicator values for Ref data within similar soil-climate settings using Ecological Site Groups (ESGs). We used predictive mapping of ESGs by Nauman et al. (2022) to link each Pad and Ref plot to an ESG. We then developed ESG frequency distributions of reference site indicators (Table S3). Percentiles of the resulting distributions were then used to set benchmarks, against which our Pad data, belonging to the same ESG, were compared and "departures" from reference conditions identified, similar to Traynor et al. (2020) and the quantile approach used by Nauman et al. (2017). Only ESGs with at least 2 pads and 25 Ref were included in this analysis ($n = 6$ ESGs). The sample size ranged between 26–155 Ref plots and 6–28 Pads per ESG. To simplify interpretations, we tallied pads in different "departure classes" from the Ref data. We ranked pads with values greater than the 90th and 70th percentiles of Ref site indicator values as "major" and "minor" departures (respectively) for canopy gap cover (100 and 200 cm), bare soil cover, noxious richness, and introduced cover. We ranked Pad values less than the 10th and 30th percentiles for "major" and "minor" departure (respectively) for total foliar cover, herbaceous cover, woody cover, species richness (perennial and total), evenness, and diversity. Pads not in major or minor departure were classified as having "minimal" departure from Ref plot conditions. The decision on directionality (greater or less than) and the departure cutoffs (e.g., 10th, 30th, 70th, and 90th quantiles) were based on both understanding of ecological processes within these ESGs as well as a review of existing reclamation standards in the Fos, recognizing there are specific species' habitat requirements or other management objectives that will require different benchmarks.

3 | RESULTS

Distributions of all indicators relative to explanatory variables and for both Pads and Ref can be found in Figures S1, S2, S3, and S4.

3.1 | Ordination

The NMS solution with the lowest dissimilarity between Bray-Curtis distances was selected as the final model ($k = 2$, two convergent solutions after 21 tries, stress $= 0.13$). There was some similarity in plant community composition, plant structure, and soil characteristics between both Ref plots and reclaimed pads, though a considerable amount of the Ref plots occupied a unique ordination space (Figure 2).

"Envfit" results (Figure 2, Table S4) indicate all environmental variables (vectors) correlate with at least one NMS axis ($p < 0.05$). A portion of the Ref plots share environmental and vegetation cover characteristics with pads, including higher: aridity, bare soil cover, salinity, noxious plant richness, and introduced annual forb/grass cover. Unshared characteristics of a separate portion of Ref plots included higher species richness (total and perennial), woody height, and woody cover.

PERMANOVA results suggest *site type* (Pad versus Ref), was a significant grouping variable ($F = 72.1$, $R^2 = 0.08$, $p = 0.001$). However, there was heterogeneity of dispersion between *site types* ($p < 0.001$; "betadisper" results in Figure S5), likely because of unbalanced group sizes, thus PERMANOVA *site type* differences were discounted.

3.2 | BRM models

Posterior predictive visualization checks indicated close fit for most models. However, our set of explanatory variables did not predict canopy gap cover, evenness, introduced perennial, or native annual herbaceous cover with high confidence (Figure S6), despite attempts to improve model fit by adding National Land Cover (NLCD) vegetation type classifications and ESGs. For these indicators we focused predominately on the direction of estimates instead of the strength of predictions.

All random and fixed effect estimates, Q5 and Q95, and standard errors are listed in Table S5. In general, estimate variability was very

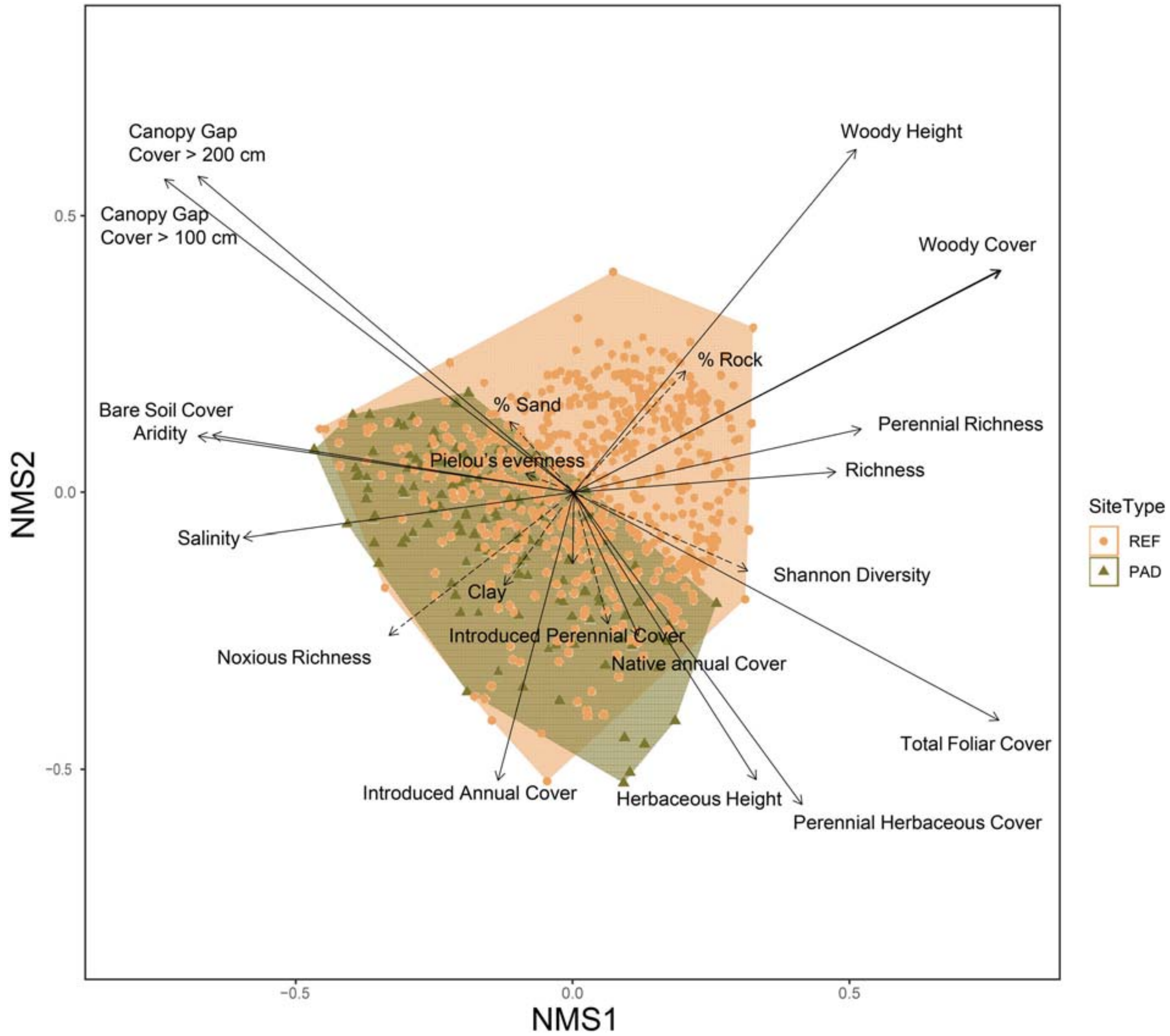

FIGURE 2 Nonmetric Multidimensional Space (NMS) ordination for 134 reclaimed pads (orange circles and hull) and 583 Assessment Inventory and Monitoring (REF; green triangles and hull) plots across the Colorado Plateau. Vectors represent climate, soil, vegetation, and diversity variables significantly correlated with NMS axes. Vectors with a solid line, have an $R^2 > 0.2$, and vectors with a dashed line have an $R^2 < 0.2$. Correlation strength is indicated by arrow length. [Colour figure can be viewed at wileyonlinelibrary.com]

low for bare soil cover and total foliar cover, and very high for noxious richness, Pielou's evenness, and woody indicators (cover and height). In addition, confidence in estimates was generally greater for Ref sites than pads, likely because of greater sample size.

3.2.1 | Effects of soil characteristics

Soil clay, sand, and rock content on both pads and Ref plots were associated with plant community richness and structure more so than functional composition (Figure 3). Pads with more clay had increased estimates of bare soil and lower estimated herbaceous height, while Ref sites with more clay had decreased estimates of woody height and very large canopy gap cover (>200 cm), and increased estimates of noxious plant richness, total species richness, and Shannon diversity. Sandy soils were associated with an increased perennial richness on both Ref and pads. Ref sites with sandy soils additionally had increased estimates of native annuals and decreased estimates of bare soil, woody height, and very large canopy gap cover (>200 cm). On Ref and pads with greater soil rock content, bare soil cover decreased. The Ref sites with rocky soils had higher estimated woody height and very large canopy gaps (> 200 cm), and lower estimated bare soil, noxious richness, and introduced annual cover compared to less rocky sites. Pads on rocky soils had lower very large canopy gap cover (> 200 cm) compared to Ref with rocky soils.

Soil salinity had some of the clearest associations with the indicators, but less so for soil depth (Figure 3). Saline soils were associated with increased perennial richness on both Ref and pads. Pads with more saline soils additionally had decreased perennial herbaceous cover, species diversity, species richness, and species evenness. Ref

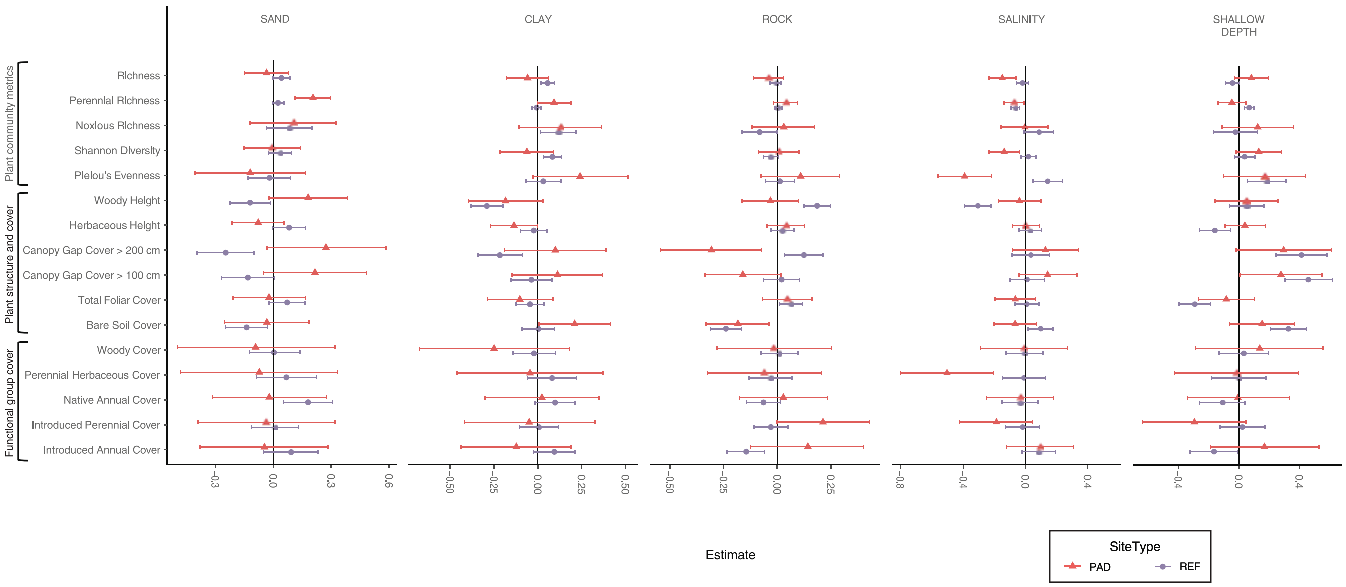

FIGURE 3 Posterior parameter estimates for the effects of soil covariates, including clay content, soil depth, rock content, salinity, and sand content, on functional group cover, plant structure and cover, and plant community metrics. Symbols represent median parameter estimates for reclaimed well pad (PAD) and Assessment Inventory and Monitoring Reference (REF) datasets and bars represent the 5% and 95% confidence intervals for the parameter estimate. Bars intersecting the vertical line at zero designate no significant difference. Overlapping bars designate no significant difference between estimates. All explanatory variables were centered and scaled. [Colour figure can be viewed at wileyonlinelibrary.com]

sites with more saline soils had increased estimated cover of bare soil and species evenness, and a decrease in estimated woody height. Shallow soils were associated with a greater cover of large (>100 cm) canopy gaps on both Ref and pads. Ref sites with shallower soils were additionally more likely to have higher bare soil cover, large canopy gap cover, perennial richness, and species evenness, and lower total foliar cover, introduced annual cover, and herbaceous height than pads.

3.2.2 | Effects of aridity

Our results highlight important differences in vegetation responses to aridity, with some divergence in the association of aridity on pads versus the Ref data (Figure 4). Estimates of total richness, perennial richness, Shannon diversity, and Pielou's Evenness decreased on Ref sites in more arid locations (higher aridity). The only community metric with an aridity association from pads was Pielou's Evenness, which was opposite that on the Ref sites (greater aridity associated with greater evenness). All measures of vegetation cover and structure (height, gaps, total foliar, and bare soil) had associations with aridity that were similar for Ref and pads. In general, more arid sites had shorter vegetation, more large gaps, less total foliar cover, and more bare soil. Of the plant functional group cover indicators (woody, perennial herbaceous, native annual, introduced annual, introduced perennial, and introduced annual), only introduced annual had an association with aridity and only on Ref, with more arid locations having greater cover of introduced annuals.

3.2.3 | Effects of time since reclamation

Our time since Pad reclamation results identified several indicator trends (Figure 5), with perennial richness, Shannon diversity, and Pielou's evenness increasing with increasing time since reclamation. We also saw improvements in measures of vegetation structure and cover over time, including reductions in very large canopy gaps (> 200 cm) and decreases in bare soil cover. For our plant functional group cover indicators, we found higher woody cover and decreased introduced annual cover with more time since reclamation. However, based on parameter estimate slopes, the effects of time were generally relatively small, suggesting slow change in plant community composition, cover, and structure over time.

3.3 | Indicator species analysis

Indicator analysis for time since reclamation (binned: 16–20, 11–15, 6–10, and 2–5 years) and within *Administrative unit* revealed 11 species, both unique and abundant across habitats (Table 1). In New Mexico, pads are consistently regaining several dominant native perennial grasses after just 5 years of recovery, but also have a persistent Russian thistle (*Salsola tragus L.*) invasion. Pads in Colorado are consistently establishing native perennial species (grass and shrub), without introduced species indicated. The native perennial grass, thickspike wheatgrass (*Elymus lanceolatus*), loses dominance after 16 years of recovery. We are left without a clear picture of its replacement, although it could be yellow rabbitbrush (*Chrysothamnus*

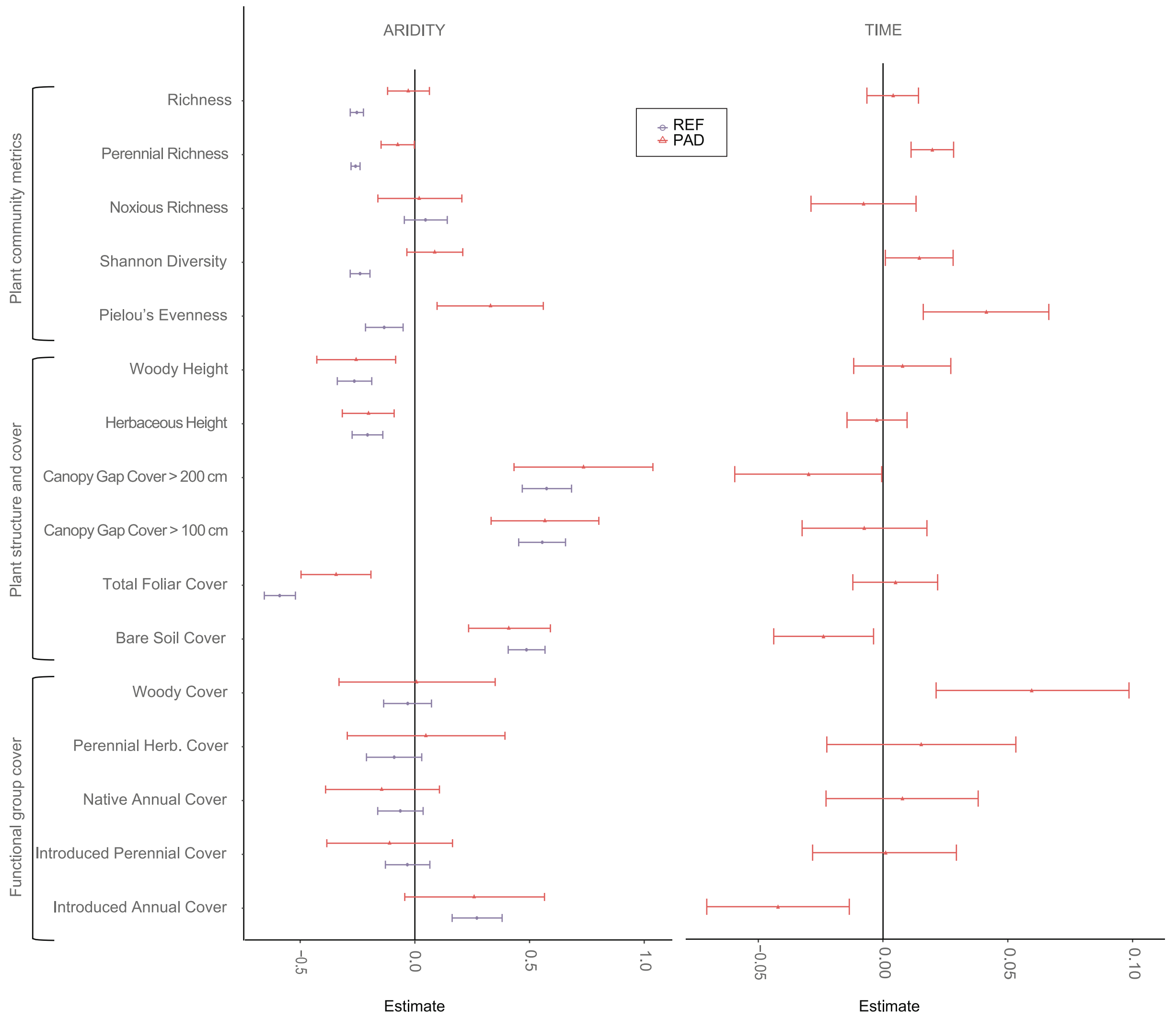

FIGURE 4 (a). Posterior parameter estimates for the effects of Aridity and (b). time since reclamation, on functional group cover, plant structure and cover, and plant community metrics expressed in units of standard deviations, σ. Aridity was centered and scaled while *Time* was median-centered at 10 years post-reclamation. Symbols represent median parameter estimates for reclaimed well pad (PAD, $n = 134$) and Assessment Inventory and Monitoring Reference (REF, $n = 583$) datasets and bars represent the 5% and 95% confidence intervals for the parameter estimate. Bars intersecting the vertical line at zero designate no significant difference. Overlapping bars designate no significant difference between estimates. [Colour figure can be viewed at wileyonlinelibrary.com]

viscidiflorus) which is found on sites 6–20 years post-reclamation. Pads in Utah are persistently invaded with halogeton (*Halogeton glomeratus*). The indicator species results do not show recovery of any dominant native perennial herbaceous species in Utah.

3.4 | Benchmark analysis

When we assessed outcomes for pads relative to the Ref data distribution, we found departure class patterns varied greatly among indicators (Figure 5; see Table S6 for frequency distributions used to set benchmarks). Among the community metrics, we see greater departures in richness indicators than diversity and evenness. Total richness and perennial richness have many more departures in Semiarid Warm Shallow/Deep Rocky and Very Shallow than other ESGs. All ESGs had moderate or major departures in noxious plant richness, with Arid Warm Saline and Arid Warm Shallow standing out with the most departures. Nearly all Arid Warm had major departures in noxious richness, compared to only 50%–70% of sites in the Semiarid Warm.

Indictors of vegetation cover and structure (total foliar cover, bare soil cover, and canopy gap cover), had the most departures in Arid Warm Shallow and Semiarid Warm Finer ESGs. When we compare canopy gap cover (>100 and >200 cm) across arid ESGs, we see no major departures for Arid Warm Saline Upland, while the Arid Warm Shallow had major departures in over 50% of sites. Both Semiarid Upland ESGs had approximately triple the number of pads with major departures in canopy gap cover (>100 and 200 cm) compared to the Semiarid Shallow ESGs.

For plant functional group cover indicators, Arid Warm Saline and Arid Warm Shallow stand out as having greater departures for introduced annual and perennial cover. Every Arid Warm Saline Upland site had departures (no minimal) for introduced annual cover.

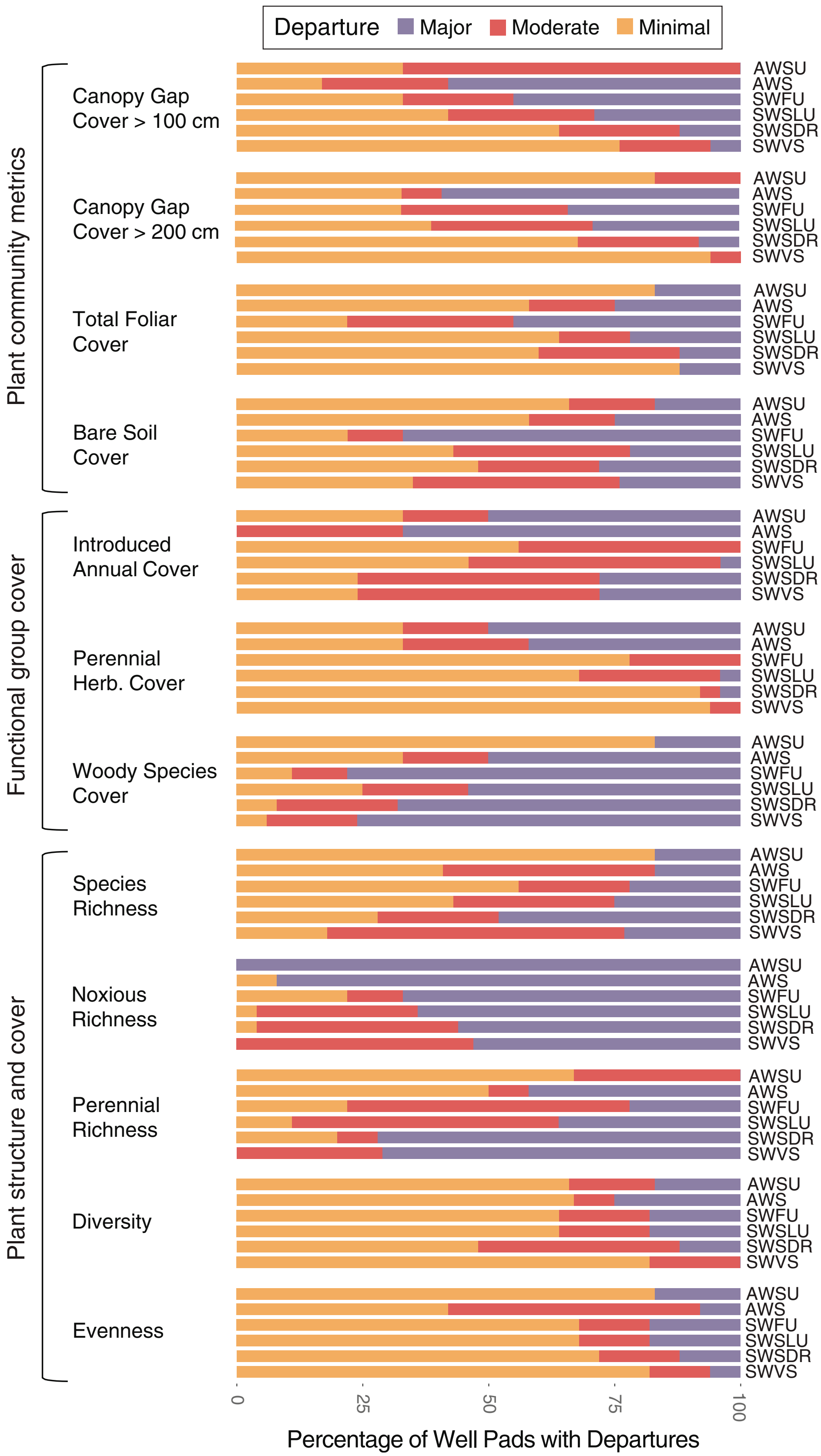

FIGURE 5 Percentage of pads with minimal, moderate, and major departures of indicator values collected on 97 reclaimed pads belonging to six Ecological Site Groups (ESGs) on the Colorado Plateau. Reference indicators calculated for comparison were from 453 Assessment Inventory and Monitoring Reference (REF) plots belonging to the same ESGs. The condition of a well pad site as having "major", "moderate", or "minimal" departure from reference condition, corresponded to the 90th and 70th (canopy gap covers, introduced annual cover, bare soil cover, noxious richness) or the 30th and 10th (total foliar cover, perennial herbaceous cover, woody cover, species richness, perennial richness, Shannon diversity, Pielou's evenness) percentiles respectively. [Colour figure can be viewed at wileyonlinelibrary.com]

Compared to the Semiarid Warm ESGs, the Arid Warm had more than double the number of sites with major departures in introduced annual cover. Perennial herbaceous cover was the indicator with the fewest departures, although departures were higher on arid compared to Semiarid ESGs. The Finer Uplands had no major departures in perennial herbaceous cover or introduced annual cover, but had the most sites with major departures in woody cover of the Semiarid ESGs. Departures in woody cover were high across all ESGs, except

TABLE 1 Indicator species organized by functional group and time since reclamation (16–20, 11–15, 6–10, 2–5 years), for New Mexico, Colorado, and Utah Bureau of Land Management Field Offices (FOs).

		New Mexico FO				Colorado FOs				Utah FO			
Functional group	**Species**	**2–5**	**6–10**	**11–15**	**16–20**	**2–5**	**6–10**	**11–15**	**16–20**	**2–5**	**6–10**	**11–15**	**16–20**
Native perennial Forb	*Chamaesyce fendleri* (Torr. & A. Gray) Small (Fendler's sandmat)			x	x								
Native perennial Grass	*Dasyochloa pulchella* (Kunth) Willd. ex Rydb. (low woollygrass)			x									
	Sporobolus airoides (Torr.) Torr. (alkali sacaton)		x	x									
	Pleuraphis jamesii Torr. (James' galleta)		x	x	x								
	Bouteloua gracilis (Willd. ex Kunth) Lag. ex Griffiths (blue grama)		x	x	x								
	Elymus lanceolatus (Scribn. & J.G. Sm.) Gould (thickspike wheatgrass)					x	x	x					
Native annual forb	*Grindelia squarrosa* (Pursh) Dunal (curlycup gumweed)					x	x	x					
Native perennial Subshrub	*Bassia americana* (S. Watson) A.J. Scott (green molly)			x									
Native perennial shrub	*Chrysothamnus viscidiflorus* (Hook.) Nutt. (yellow rabbitbrush)			x			x	x	x				x
Introduced annual forb	*Salsola tragus L.* (prickly Russian thistle)		x	x	x	x					x		
	Halogeton glomeratus (M. Bieb.) C.A. Mey. (halogenton)									x	x	x	x

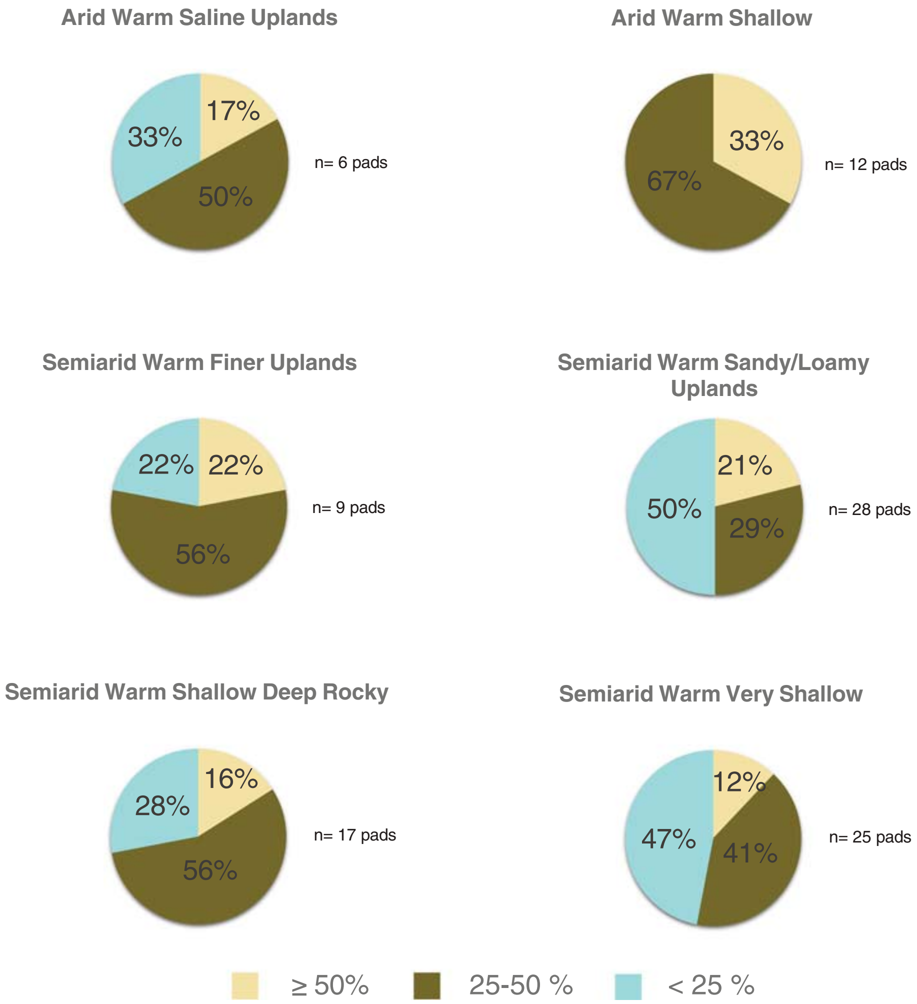

FIGURE 6 Proportion of pads, within six Ecological Site Groups (ESGs), with major indicator departures from reference conditions in ≥50% (6 or more), 25%–50% (3–5), or <25% (0–2) of the indicators shown in Figure 6. A major indicator departure means reclamation has not yet been successful. ESGs include SWVS: Semiarid Warm Very Shallow ($n = 25$); SWSDR: Semiarid Warm Shallow Deep Rocky ($n = 17$); SWSLU: Semiarid Warm Sandy/Loamy Uplands ($n = 28$); SWFU: Semiarid Warm Finer Uplands ($n = 9$); AWS: Arid Warm Shallow ($n = 12$);AWSU: Arid Warm Saline Uplands ($n = 6$). Data here from 97 reclaimed pads and 453 Assessment Inventory and Monitoring reference (REF) plots. [Colour figure can be viewed at wileyonlinelibrary.com]

for the Arid Warm Saline. Arid Warm Shallow had more than double the number of sites with major departures in woody cover compared to Arid Warm Saline Uplands.

When we summed the number of major departures within individual pads (for indicators shown in Figure 5), we found that average percentage of major indicator departures for pads was 33% (4/12 in major departure; Figure 6). When we look within ESGs, the Arid Warm Shallow ESG had the greatest percentage of pads with ≥50% of indicators in major departure, followed by the Semiarid Warm Finer Uplands and Sandy/Loamy Uplands (Figure 6). The Semiarid Warm Sandy/Loamy Uplands also had the greatest percentage of pads with <25% of indicators in major departure. In contrast, the Arid Warm Shallow ESG had no pads in this category, as a majority of pads had an intermediate number of indicators in major departure (the 25%–50% category). There were no pads that had major departures for more than eight of the 12 indicators for which we calculated benchmarks.

4 | DISCUSSION

We conducted one of the most wide-spread field-based assessments of reclamation outcomes following oil and gas development to date. We found aridity, salinity, and time since reclamation were the most important factors governing reclamation outcomes. We also found important plant and soil indicator differences between reclaimed pads and associated reference plots with similar climate-soil conditions (same ESGs), with pads characterized by shallow soils and arid climates (Arid Warm Shallow ESG) containing the most (major) indicator departures.

4.1 | Abiotic drivers of reclamation outcomes

We found that soil salinity was the strongest soil predictor of plant community metrics and functional group cover across both datasets. Compared with plots undisturbed by oil and gas, pads in soil settings with greater salinity had lower plant species richness, diversity, evenness, and perennial herbaceous cover, all important measures of reclamation success (Interior, 2007). This suggests that disturbing highly saline soils magnifies the impacts of soil salinity on recovering plant communities. We attribute this to energy development and activities exacerbating soil salinization (Day et al., 2015; Keiffer & Ungar, 2002) and the challenge elevated salinity poses for plant communities through osmotic stress, ion toxicity, alkalinity stress, and impacts to nutrient cycling (Litalien & Zeeb, 2020). In Utah specifically, our ISA results revealed the introduced annual forb halogeton established itself on pads within the first 5-years and then remained for at least

20 years. While native salt desert communities can tolerate saline conditions in undisturbed soils (Duniway et al., 2022), once established, halogeton alters soil chemistry and soil ecology, possibly creating conditions that favor its growth over native plants (Duda et al., 2003). Seeding pads with salt tolerant, native annuals that demonstrate rapid biomass production may limit survival of halogeton and other undesirable species (Prasser & Hild, 2016). Avoiding development of saline soil locations altogether could also result in fewer pads with unsuccessful reclamation.

Although it is broadly understood that soil texture, rock content, and depth shape drylands of the Colorado Plateau (Duniway et al., 2022), we found these variables significant for only a few indicators for the pads. Interestingly, we also found estimates between Pad and Ref to differ (non-overlapping CI's) and in opposite direction for some indicators, especially for canopy gaps and woody height. We attribute this either lack of or contrasting importance in soil texture, rocks, and depth to the mixing and homogenizing of subsoils and even bedrock during development and reclamation as well as differing plant-edaphic associations post-reclamation compared o relatively undisturbed locations (Lupardus et al., 2020).

Drylands are defined by water limitation (Rodríguez-Iturbe & Porporato, 2007), which is reflected in the association between site aridity and most indicators, both in Pad and Ref datasets. Warming temperatures and associated drying of the Plateau are expected to reduce growth and performance of perennial herbaceous species (Gremer et al., 2015; Hoover et al., 2015; Wertin et al., 2015), and reduce cover and reclamation potential of biological soil crusts (Finger-Higgens et al., 2022; Phillips et al., 2022), among other impacts. Our current research revealed most indicators on pads were negatively impacted by site aridity, relative to typical reclamation goals, with reclaimed pads in more arid settings estimated to have greater bare soil and large canopy gap cover, fewer perennial species, and reduced productivity (strong negative associations of total foliar cover and plant height). The Ref data have similar trends with aridity, although Ref sites showed negative association with community metrics and aridity (reduced richness, evenness, and diversity), and greater introduced annual cover in more arid settings, compared to less arid settings. As temperatures rise, and summer dry seasons become both longer and hotter in coming decades on the Colorado Plateau (Bradford et al., 2020), reclamation benchmarks and standards for ecological recovery are likely to become more difficult to achieve.

4.2 | Time

Current US Federal guidance suggests that reclamation should set a site on a "trajectory" towards a self-sustaining, vigorous, diverse, native plant community, with a density sufficient to control erosion and noxious plant invasion and to re-establish wildlife habitat or forage production (Interior and Agriculture, 2007). Generally, disturbed communities transition from a higher composition of annual to perennial species and from low to high richness through time (Munson & Lauenroth, 2012). The benefits of increasing richness and diversity have been intensively studied and found to both enhance and stabilize ecosystem function through space and time (Hooper et al., 2005). Over the 20-year time-period captured here, sites reclaimed earlier had positive shifts in perennial richness, diversity, and evenness, in addition to vegetation cover and structure and plant functional group cover. Although many changes were modest, for example, increasing from 11 to 14 perennial species over a 20-year period compared to the reference site mean of 21, results confirm a slow yet positive trajectory of recovery post-reclamation.

Site dominance of introduced species and accelerated erosion are both factors shown to limit reclamation trajectories and impact ecosystems effected by energy development and associated roads (Duniway & Herrick, 2011; Gelbard & Belnap, 2003; Waller et al., 2018). Although there were exceptions (e.g., Russian thistlein New Mexico and halogeton in Utah), our results indicate that both introduced species and bare soil were reduced on most older sites, with introduced annuals down ~5% (Figure S2) and woody cover up ~6% (Figure S2). Increased cover of woody species found on our sites, including rabbitbrush, and Fourwing saltbush (*Atriplex canescens* (Pursh) Nutt.) stabilize soils and lessen potential erosion of surface soils by wind (Mayaud et al., 2016; Webb et al., 2021).

4.3 | Benchmarks and reference data

Distribution-based benchmark establishment has been used in both terrestrial and aquatic systems to create data-driven, quantitative, and easily interpretable measures of success (Traynor et al., 2020). Here, we applied this approach to 12 reclamation indicators and across 6 ESGs and found the majority of pads sampled had major departures in 25% or more of the indicators, with indicator departures differing across ESGs. This benchmark-approach highlights challenging soil and climate setting that may need additional reclamation measures more clearly than in our broader statistical modelling. For example, the Semiarid Warm Shallow ESGs stand out as slow to recover, particularly perennial richness and woody cover, and noxious species presence was problematic on all ESGs. We also see indicator specific challenges in some settings, such as reduced perennial richness in Semi-Arid Warm Shallow and Rocky settings. It is likely the typical reclamation approaches are not well suited for these environments and/or shallow and dry conditions are leading these specific ESGs to require more time to recover. These types of interpretations can inform ESG-specific management strategies, including avoiding disturbance on problematic ESGs and specific practices needed in others, such as a more diverse seed mix.

Although there are some exceptions (e.g., Stiver et al., 2015) most ecosystems on the Plateau do not currently have policy-based benchmarks and standards for use in reclamation. For this reason, ecologically comparable lands and data distributions can be used to set reasonable benchmarks (as done here), but it is important benchmarks are not used in isolation from ecological knowledge or existing policy. For example, to prevent woody encroachment in historic perennial grasslands, managers may consider setting woody cover upper limits (Weber-Grullon et al., 2022), as opposed to lower limits in the current study. In contrast, a minimum cover for sagebrush cover are vital for some habitats, and introduced annuals may require seasonal benchmarks to control cheatgrass (*Bromus tectorum*) emergence during sagebrush growing seasons (Williams et al., 2002). Although this type of ecosystem specific research to inform benchmark development for reclamation is generally lacking, with data collection efforts, like we report here, we expect our understanding of post-reclamation ecological dynamics to increase, including how natural variability, climate change, and increasing temperatures can be incorporated into benchmark assessments (Jansen et al., 2022) and inform decision-making at the local, state, and national levels (Carter et al., 2020).

Finally, the potentially degraded conditions of many lands nationally (as much as ~21% of western lands; Herrick et al., 2010) poses a challenge in using broad sampling networks for setting management benchmarks. The high overlap between our reclaimed pads and the BLM AIM sites used as reference in our NMS results suggest land degradation is likely confounding our Pad-Ref comparisons. As the BLM AIM program uses a random sampling frame, including all BLM lands (Kachergis et al., 2022), a robust method for filtering out plots, down to those representing an acceptable ecological or range health condition, will likely improve the accuracy of benchmarks. Further land quality filtering, including individual on-the-ground site assessment, would ensure there is sound reasoning to expect sites are in good condition and represent a management or ecological target. However, from a management perspective, implementing reclamation benchmarks requiring the return of reclaimed sites to a ~ median (30th to 70th percentile) land condition is still a significant improvement (Stefano et al., 2021).

5 | CONCLUSIONS

Our study provides broad scale, ground-based evidence that reclamation outcomes on oil and gas pads are primarily driven by the abiotic setting of the disturbance and time since reclamation. If development and reclamation activities are conducted in arid, saline environments, pads are much less likely to show a positive response to reclamation. Noxious species were a dominate presence on pads, across all sites and abiotic settings. Our results can help define expectations for reclamation and vegetation recovery rates in heterogeneous landscapes and guide reclamation policy, such as bonding release periods. This information also enables prioritization of energy development (including renewables) siting by targeting locations where activities result in successful reclamation and thereby minimize long-term impacts to the land.

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CONFLICT OF INTEREST STATEMENT

There is no conflict of Interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in USGS ScienceBase-Catalog at https://doi.org/10.5066/P94V65T8.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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