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RESEARCH ARTICLE

Wetland restoration: can short-term success criteria predict long-term outcomes?

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Worldwide wetland loss over the past 50 years has made wetland conservation a public policy priority, leading to an increase in wetland restoration programs. However, predicting long-term restoration outcomes remains difficult. The monitoring of these programs rarely exceeds 5–10 years, forcing wetland managers to rely on short-term success criteria that may be criticized by the scientific community. Our objective was to assess the significance of four short-term success criteria (*Carex* ssp. shoot density, *Salix* ssp. survival, invasive species cover, and hydrologic dissimilarity to reference sites) used in a restoration program of 12 wetlands monitored for 5 years post-restoration in predicting restoration outcomes 15 years post-restoration. We defined the success of restoration efforts after 15 years using a cluster analysis-based approach, and the clusters were described using principal coordinate analysis and Tukey's post hoc honest significant difference test. Finally, we assessed the pertinence of each short-term success criteria in predicting long-term restoration outcomes using Pearson correlation tests and spatial regressive models. Our results demonstrate that stress-based short-term success criteria can be reliable predictors of longer-term success for communities with shallow water tables, whereas target-species-based short-term success criteria are not. Hydrologic dissimilarity to the reference site was appropriate for willow-sedge community outcome predictions, while invasive species cover was best for sedge community outcome predictions. For communities in drier habitats, such as the willow-herb community, none of the tested short-term success criteria were significant predictors of long-term restoration outcomes, and further research is required to identify suitable short-term success criteria.

Key words: long-term restoration, monitoring, plant communities, short-term success criteria, wetland restoration predictions

Implications for Practice

- Short-term success criteria can be valuable tools for identifying projects with a risk of failure in the early stages of restoration. These criteria can help managers implement reinforced monitoring, adaptive management, and corrective measures.
- Short-term success criteria do not replace long-term monitoring or success assessment. Rather, they can complement them as a tool to help managers avoid undesirable outcomes and achieve restoration goals.
- Our results can be used to guide restoration strategies for plant communities close to the *Scheuchzerio palustris-Caricetea fuscae* and *Betulo carpaticae-Alnetea viridis* phytosociological classes.

Introduction

Wetlands cover 8–9% of the world's land area and are among the most functionally important ecosystems (Zedler & Kercher 2005; Davidson et al. 2018). They provide 43% of global ecosystem services important for human health and well-being (Davidson et al. 2019). Worldwide, wetlands have declined by nearly 70% since 1900 (Davidson 2014), and 35% since 1970 (Darrah et al. 2019). Despite the significant degradation that has already occurred, anthropogenic impacts continue to threaten the integrity and functioning of wetlands (Asselen et al. 2013; IPBES 2019). Most wetland loss is due to conversion to agricultural or urban uses through ditching, drainage, and dewatering (Patino & Estupinan-Suarez 2016; Zou et al. 2017; Robertson et al. 2019).

Wetlands are priority ecosystems for conservation, integrated into many levels of public policy, planning, and regulation on a global scale (Mitsch & Gosselink 2015; Tillman & Matthews 2023). For example, permits allowing wetlands disturbance often require

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the implementation of mitigation measures such as conservation, restoration or creation of wetlands, and this has led to an increase in wetland restoration programs (Gaucherand et al. 2015; Moreno-Mateos et al. 2020).

Many studies of restoration outcomes focus on vegetation composition changes over time (Matthews & Spyreas 2010; Boscutti et al. 2017). Yet, our ability to predict long-term plant community development in restored ecosystems using ecological monitoring data remains limited and imperfect (Brudvig et al. 2017; Barnard et al. 2019; Sueltenfuss & Cooper 2019) because vegetation composition can be highly variable following restoration (Laughlin et al. 2017; Atkinson et al. 2022; Oliver et al. 2023). In addition, long-term monitoring data from restoration projects are rarely available or published, making it difficult to predict the multi-decade-long trajectories of restored ecosystems (Wortley et al. 2013). A meta-analysis of 621 restored or created wetland sites worldwide found that 49% were monitored for 5 years or less, while less than 1% were monitored for 10 years or more (Moreno-Mateos et al. 2012).

Many authors have criticized the extensive use of vegetation-related criteria as indicators of successful wetland restoration (Matthews & Endress 2008; Littlewood et al. 2014; Smith et al. 2017). Others have indicated that it would be preferable to use stressors as defined by Grime (1979), such as hydrological conditions or biological invasion, as short-term indicators of success rather than relying solely on vegetation composition (Ogden et al. 2005; Hughes et al. 2011). These assumptions are consistent with recent studies that have highlighted the importance of hydrological regime (Sueltenfuss & Cooper 2019; Mosanghini et al. 2023) and biological invasion (Li et al. 2021; Goetz et al. 2022) as important factors of restoration outcomes for many wetland ecosystems. Some authors have also pointed out that early trajectories of restored ecosystems may not reflect long-term outcomes and that indicators from these early stages may lead to a misinterpretation of overall project success or failure (Aoyama et al. 2022; Hallett et al. 2023).

The United Nations Decade on Ecosystem Restoration highlights the need for early-stage tools and performance standards to guide restoration projects and ensure the long-term success of wetland restoration programs (Zedler 2000; Cadier et al. 2020; Herb & Finlayson 2023). The identification of indicators that can assess the success or failure of restoration projects at an early stage of the restoration process would be highly valuable since it could guide project changes or alterations that could increase long-term project success.

In this study, we tested the potential of four short-term success criteria to predict the long-term outcome of the restoration of three plant communities in 12 mountain wetlands near Telluride, Colorado, United States, at 5 and 15 years after restoration. We tested two vegetation-related criteria: (1) "*Carex* ssp. shoot density" and (2) "*Salix* ssp. survival," (3) one biological invasion-related criterion, "invasive species canopy cover," and (4) one hydrological criterion, "hydrologic dissimilarity to the reference site." We hypothesized that these criteria would be useful to predict long-term restoration results. Specifically, we asked: (1) Could short-term success criteria be used to predict long-term restoration outcomes? (2) Were biological invasion-related and hydrologic criteria better than target species-related criteria for predicting long-term restoration outcomes?

Methods

Study Sites

Our study focused on 12 wetlands located in the Telluride Ski & Golf Club (TSG) area, in the Town of Mountain Village, Colorado, at an elevation of 2900 m asl (37°56′19″N, 107°51′55″W). The average daily maximum and minimum temperatures during January, the coldest month, are 2.9 and −14.8°C, respectively. July, the warmest month, has average daily maximum and minimum temperatures of 24.0 and 5.3°C, respectively. The region has an average annual rainfall of 852 mm, almost half of which falls during the summer months of May through September (Table S1).

In 1993, the TSG constructed a golf course that partially or completely buried the 12 wetlands under 1–5 m of mineral soil and sediment. Sections of the impacted sites were restored, and wetland areas that were not directly impacted were used as reference sites (Fig. 1). All restored and reference wetland occur on a set of benches created by post-Pleistocene Silver Mountain landslide deposits (Howe 1909). The reference sites selected in 1998 had not undergone the filling associated with the construction of the golf course. Thus, vegetation and substrate observed in 1998 remained identical to what occurred prior to the construction of the golf course.

The TSG area has been modified by human activity, resulting in landscape fragmentation, including the construction of infrastructure such as roads, buildings, and golf courses. However, the Town of Mountain Village, Colorado, where the golf course is located, developed a wetland and watershed management plan in 1996 to protect the remaining wetlands and restoration sites and to limit changes in groundwater recharge, level and flow, or nutrient introductions (Telluride Mountain Village 1996). Table S2 presents characteristics of the study wetlands, including restored and reference areas, dominant plant communities, average restored plot distance to the nearest reference community, and average distance between restored plots.

Restoration Project

Construction of a golf course by the TSG in 1993 resulted in the filling of 28 ha of wetlands without the required federal permits. Subsequently, the U.S. District Court of Colorado ordered the company to restore 14 ha of the impacted wetlands, which must be monitored for 5 years. Between 1998 and 2000, 12 wetlands were restored after 2 years of pre-restoration site analysis.

The 12 restoration wetlands were located within or adjacent to the golf course. The restoration goals were to: (1) restore the vegetation that existed prior to development (historical ecosystems); (2) integrate these wetlands into the landscape, by connecting them to the local natural groundwater flow system and being self-sustaining, requiring no further action after the

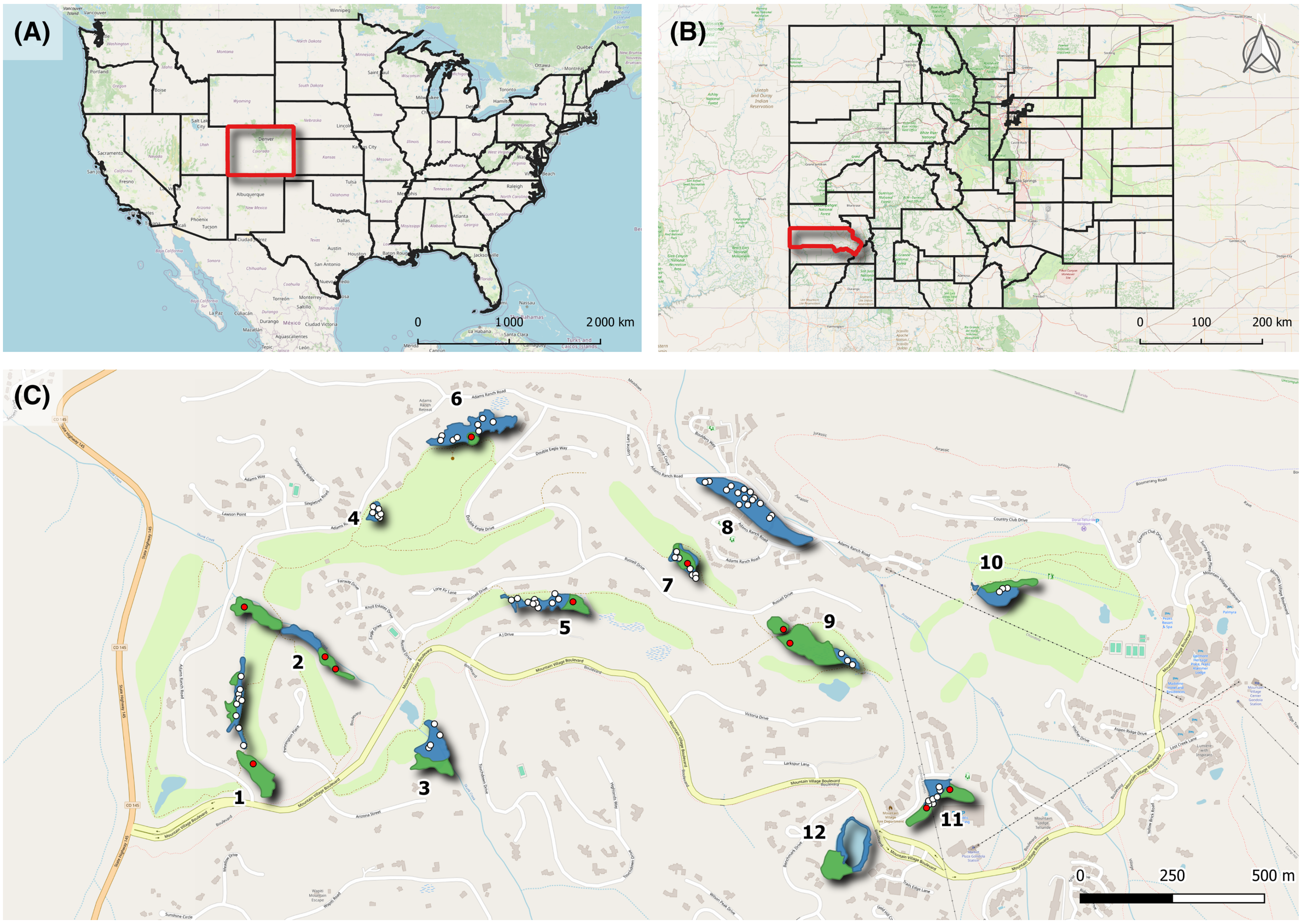

Figure 1. Location of study area in southern Colorado (A) in San Miguel County (B). Numbers from 1 to 12 correspond to the 12 studied wetlands located within the golf course in Mountain Village (C). Blue polygons represent the restored area and green polygons the reference area. White dots represent the restored plots and red dots represent the reference plots.

restoration was complete; (3) create restored ecosystems that do not conflict with local recreational activities, primarily skiing and golf. The objectives for hydrologic regime and vegetation composition were developed using reference sites.

To define realistic reference sites, each was selected within the area of influence of the golf courses. This was done to ensure that the water table and plant communities of the restoration and reference sites would be influenced by the same conditions. Furthermore, reference sites were selected based on their plant communities and hydrologic conditions during 1996–1998. Restoration projects followed the steps shown in Figure 2 and were implemented from 1998 to 2000. For a detailed description of the restoration program, see Cooper et al. (2017).

Each restored wetland was designed to support one to three target plant communities (Fig. S1), each with a distinct hydrologic regime. The three communities were: (1) dominated by *Carex utriculata* and/or *C. aquatilis* in areas with shallow water tables (<20 cm in mid to late summer); (2) dominated by *Salix monticola*, *S. brachycarpa*, and *C. utriculata* and/or *C. aquatilis* in areas with water table depth 20–50 cm below the ground surface; and (3) dominated by mainly *S. monticola* and *S. brachycarpa*, other shrubs such as *Ribes lacustre* and herbaceous species including *Calamagrostis canadensis*, *Geum macrophyllum*, *Conioselinum scopulorum*, *Geranium richardsonii*, and other species (Table 1) in areas with deeper summer water tables (>50 cm). The target community for each plot was determined by water table analysis using 2 years of water table monitoring post-earthwork, but prior to planting (1996–1998). Plant species nomenclature follows Weber and Wittmann (2012).

To assess the restoration projects, several success criteria were developed, including the depth and variation of the water table, the survival and growth of planted *Salix* ssp., the rate of *Carex* ssp. spread via tillers, and the canopy cover of invasive plant species. These success criteria were designed to be measurable metrics and allow us to characterize and contrast restored versus reference sites. These criteria reflect important characteristics of the targeted plant communities, including structuring plant species, major threats, and key abiotic conditions. Between 2003 and 2004, these criteria were met on a sufficient area of restored wetland to consider the restoration program successful. In 2013, we revisited every wetland to

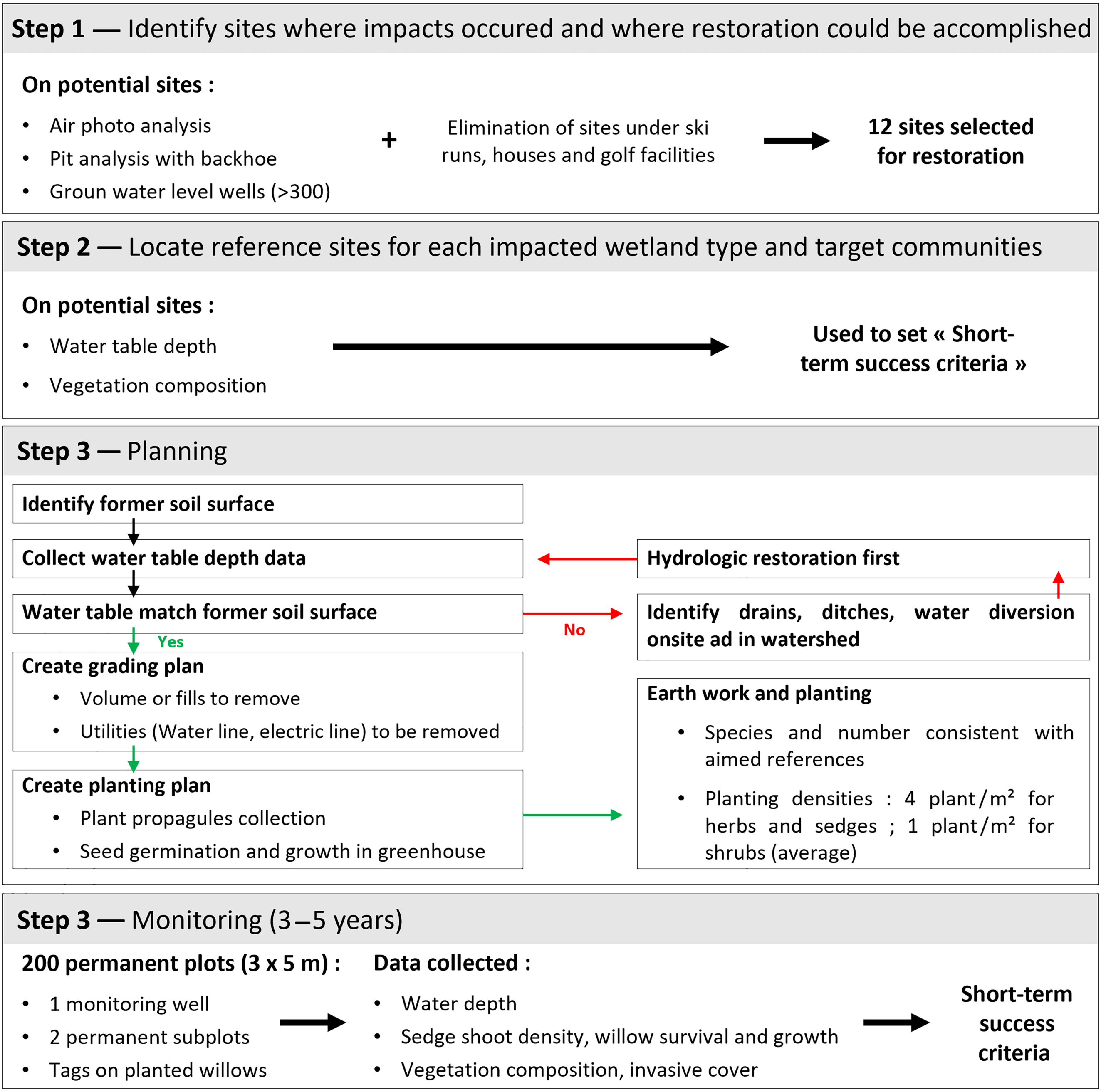

Figure 2. Steps taken for the restoration of 12 wetlands within the Telluride Ski & Golf Club (TSG) from 1998 to 2001.

assess the success criteria 15 years after the restoration project was implemented.

Monitoring

We established 5–15 random plots within each restored wetland. Each plot was 3 × 5-m^2. We established similar plots at reference sites. A groundwater monitoring well was installed in each plot along one of the 5-m sides. Each plot contained two randomly placed 40-cm diameter subplots to measure the density of *Carex* ssp. shoots, and to assess the survival and growth rates of tagged *Salix* ssp.

Vegetation composition was quantified annually from 1998 to 2003 by recording ocular estimates of canopy cover by species using cover classes, according to the Braun-Blanquet system (1: 1–5%, 2: 6–25%, 3: 26–50%, 4: 51–75%, cover; Braun-Blanquet 1932). In 2013, we were able to locate 72 restored plots and 11 reference plots. Vegetation composition was analyzed in these plots in 2013. The density of *Carex* spp. shoots, and the height and survival of *Salix* spp. were measured

Table 1. Vascular plant species introduced during restoration program in each type of target wetland plant community. Dominant species for each stratum (highest planted quantity) are indicated in bold text.

Community	*Species planted*
Sedge	***Carex utriculata*** and *C. aquatilis*
Willow-sedge	***Salix monticola***, *S. geyeriana*, *S. brachycarpa*, ***C. utriculata***, and *C. aquatilis*
Willow-herb	***S. monticola***, ***S. brachycarpa***, *S. geyeriana*, *S. bebbiana*, *S. drummondiana*, *Alnus incana*, ***Ribes lacustre***, *Lonicera involucrata*, *Pentaphylloides floribunda*, ***Calamagrostis canadensis***, ***Geum macrophyllum***, ***Geranium richardsonii***, ***Conioselenium scopulorum***, *Glyceria striata*, *C. microptera*, *Mertensia ciliata*, and *Ligularia bigelowii*

in each restored subplot on an annual basis from 1998 to 2003. From 1998 to 2003, groundwater levels were monitored on a weekly basis from late May through October on both restored and reference plots. This was done using a water level meter.

Data Analysis

All analyses were performed using the R 4.2.0 software (R Core Team 2023). We used data from plots that have been consistently monitored since 2003 and 2013. This includes 72 restored and 11 reference plots.

A hierarchical cluster analysis (HCA) was performed on the 2013 plant composition data from restored and reference plots to identify vegetation types using the R base package (R Core Team 2023), the Gclus package (Hurley 2019), and the custom function Hcoplot by Borcard et al. (2018). The HCA assigned each plot to a cluster based on the distance between plots using Ward's minimum variance method, which minimized variance between clusters and within each cluster. Distance between each plot was calculated with a Bray–Curtis distance matrix.

The number of clusters was determined using two approaches. First, the fusion level of the dendrogram, where long horizontal lines precede steep increases, indicates cut levels using the R base package (R Core Team 2023). Second, we used the IndVal index (Dufrêne & Legendre 1997) to integrate a specific fidelity measure and propose an optimal number of clusters and significant alternatives using the Labdsv package (Roberts 2023). The final number of clusters selected was the one identified as most relevant by both methods.

A restored plot was considered to have successfully restored vegetation if it was grouped in a cluster dominated by reference plots of the same plant community. Conversely, a restored plot was considered unsuccessful if it was grouped into a cluster dominated by reference plots of a different plant community. A restored plot within a cluster without reference plots was also considered unsuccessful. Each cluster was then characterized using the 2013 *Carex* spp. cover, 2013 *Salix* spp. cover, the 2013 herbaceous plant cover, the 2013 invasive plant cover, and the 2001 average water table depth. An analysis of variance and a Tukey's post hoc honest significant difference (HSD) test were performed to assess significant differences between cluster characteristics using the packages MultCompView (Graves et al. 2023) and Dplyr (Wickham et al. 2023). Results were plotted using GGplot2 (Wickham et al. 2024) and Ggpubr packages (Kassambara 2023).

Principal coordinates analysis (PCoA), an ordination method that makes minimal assumptions about the data and attempts to preserve the distance relationships between individuals, was performed with a Bray–Curtis dissimilarity index using the 2013 vegetation composition as the distance metric to represent a plot's dissimilarity in a two-dimensional space using the Vegan package (Oksanen et al. 2022). The results of the HCA were then integrated and plotted with the results of the PCoA to provide a comprehensive picture of vegetation composition using the packages GGplot2 (Wickham et al. 2023), Ggpubr (Kassambara 2023), and Dendextend (Galili 2015). The PcoA first axis was analyzed using a Pearson correlation test between plot coordinates on this axis and the 2001 mean water table depth of each plot using the R base package (R Core Team 2023) and packages GGplot2 (Wickham et al. 2024) and Ggpubr (Kassambara 2023).

We assessed the reliability of short-term success criteria measured 5 years after restoration to predict the outcomes of the restored communities 15 years after restoration. To do so, we employed both a Pearson correlation test using the R base package (R Core Team 2023) and spatial autoregressive models (SAMs), a method similar to generalized linear models that aims to minimize spatial autocorrelation issues (Pebesma & Bivand 2023) using the SpatialReg package (Bivand et al. 2024). Success in 2013, as defined above, was a binomial response variable extracted from the cluster analysis while the four short-term success criteria, 2003 *Carex* ssp. shoot density, 2003 *Salix* ssp. survival, 2003 invasive plant cover, and 2001 hydrologic dissimilarity, were used as continuous explanatory variables in the SAMs.

The quality of the SAMs was then assessed with two metrics commonly used to evaluate the goodness of fit of logistic regression and other models: the McFadden's pseudo-r^2 and the Akaike's information criterion (AIC). Subsequently, the SAMs were employed to compute plot-based success or failure predictions for each of the 72 restored plots. The number of true and false positives, as well as true and false negatives, was calculated by comparing the outcomes of the predictions with the 2013 success.

The hydrological dissimilarity to the reference sites in SAMs was calculated using the Euclidean distance based on the weekly water table depth data from May to August 2001, thereby allowing for the incorporation of annual variations in hydrological conditions. The year 2001 was selected for its suitability as a representative sample of the weather patterns observed over the Telluride area between the years 1998 and 2013. This choice was based on an analysis of precipitation, snowfall, and temperature data (Table S1).

The measure used for all our analyses is the Euclidean distance between a given restored plot and the least hydrologically dissimilar reference plot with the targeted vegetation. Calculation of Euclidean distance between all restored plots and reference plots was done using the Vegan package (Oksanen et al. 2022) and the custom function DissRef3 provided by Durbecq et al. (2020).

Results

Success Criteria

Significant variations were observed in the 2003 success criteria values, depending on the plant communities targeted.

The density of *Carex* ssp. shoots exhibited significant variability among the communities in 2003 (Fig. 3A). The willow-sedge community exhibited the highest mean density, with an average of 46.4 ± 18.6 individuals/m^2. The willow-herb community exhibited the lowest mean density, with an average of 19.9 ± 21.4 individuals/m^2, which was significantly different from the willow-sedge community. The sedge community had intermediate shoot density, averaging 29.8 ± 13.0, but was not significantly different than the willow-sedge and willow-herb communities.

The survival of *Salix* ssp. in 2003 exhibited a notable degree of variability among the communities (Fig. 3C). The willow-herb community exhibited the highest survival rate, with an average of 89.0 ± 21.3%. The willow-sedge community exhibited the lowest survival rate, with an average of 71.5 ± 31.1%, which was significantly different from the willow-herb community. In the sedge community, the short-term success criterion was set at zero, as no *Salix* spp. were planted.

The cover of invasive plant species in 2003 exhibited a significant level of variability among the different communities (Fig. 3D). The willow-herb community exhibited the highest invasive cover, with an average of 22.0 ± 22.6%. The willow-sedge and sedge communities exhibited significantly lower invasive cover, with an average of 4.0 ± 7.1% and 5.9 ± 9.7%, respectively. These values were significantly different from those observed in the willow-herb community.

Hydrological dissimilarity, as Euclidian distance, in 2001 was not significantly different among the communities (Fig. 3B). The sedge community had an average dissimilarity of 119.0 ± 84.1, willow-sedge had an average dissimilarity of 111.0 ± 68.8, and willow-herb had an average dissimilarity of 79.5 ± 55.6. All communities had overlapping interquartile ranges and medians, indicating no statistically significant differences.

Plant Community Restoration Outcomes

We identified four groups of plots (Fig. 4A) organized along the first axis of the PCoA (Fig. 4B), which was significantly correlated ($r = 0.62$; $p < 0.001$) with mean water table depth (Fig. 5). Cluster analysis indicated that the restoration program had an overall success rate of 55% after 15 years. However, this success rate was highly variable depending on the target community. It was 62% for the sedge community, 73% for the willow-sedge community, and 33% for the willow-herb community.

Cluster C1 was characterized by sedge and willow-sedge community reference plots (Fig. 4) and included restored plots with the shallowest water tables, averaging 13.9 ± 24.7 cm and dominated mainly by *Carex utriculata*, with an average of 80% cover (Fig. 6A). This cluster was also characterized by a

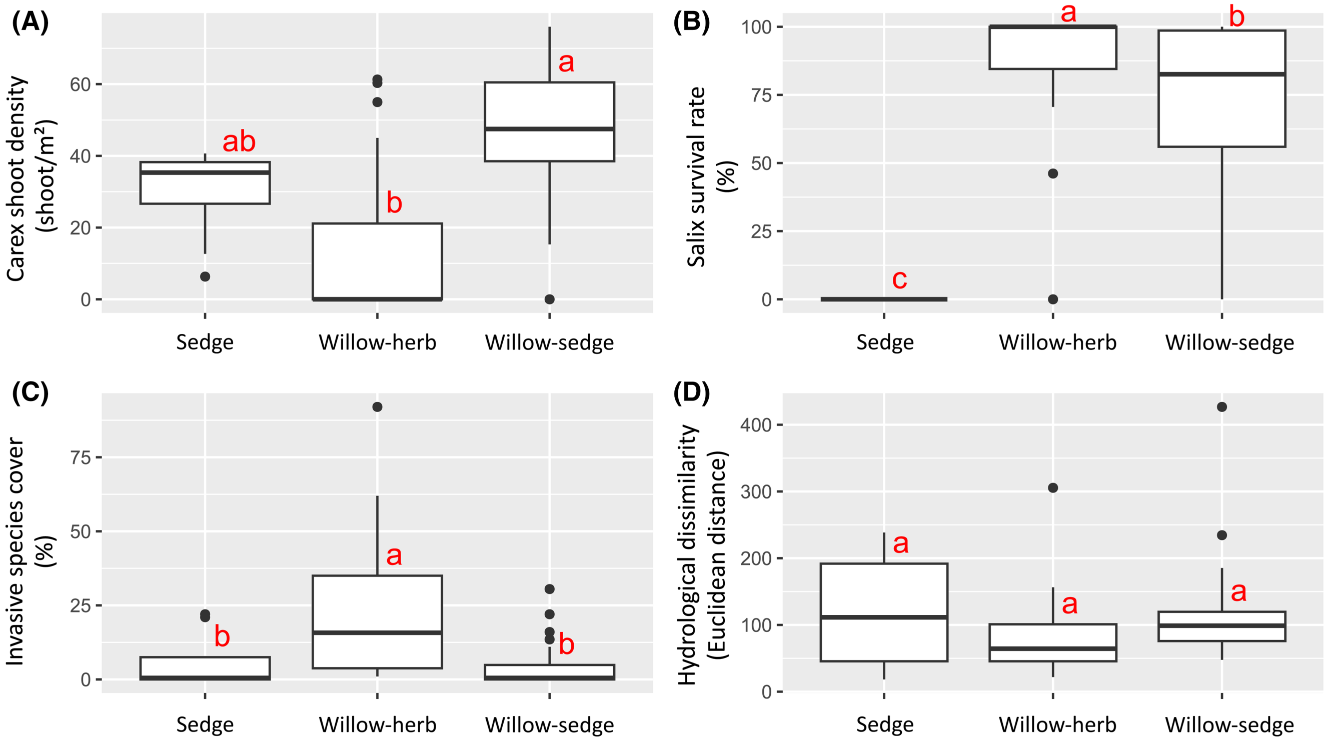

Figure 3. Boxplots and Tukey's post hoc HSD test of *Carex shoot density* (A), *Salix survival rate* (B), invasive plant cover (C) in 2003 and hydrological dissimilarity (D) in 2001 for each targeted community. Red letters indicate significant differences between groups (*p* value <0.05). Each box represents the lower quartile, the median (bold line), and the upper quartile ($n = 4$). The vertical lines correspond to a 95% CI.

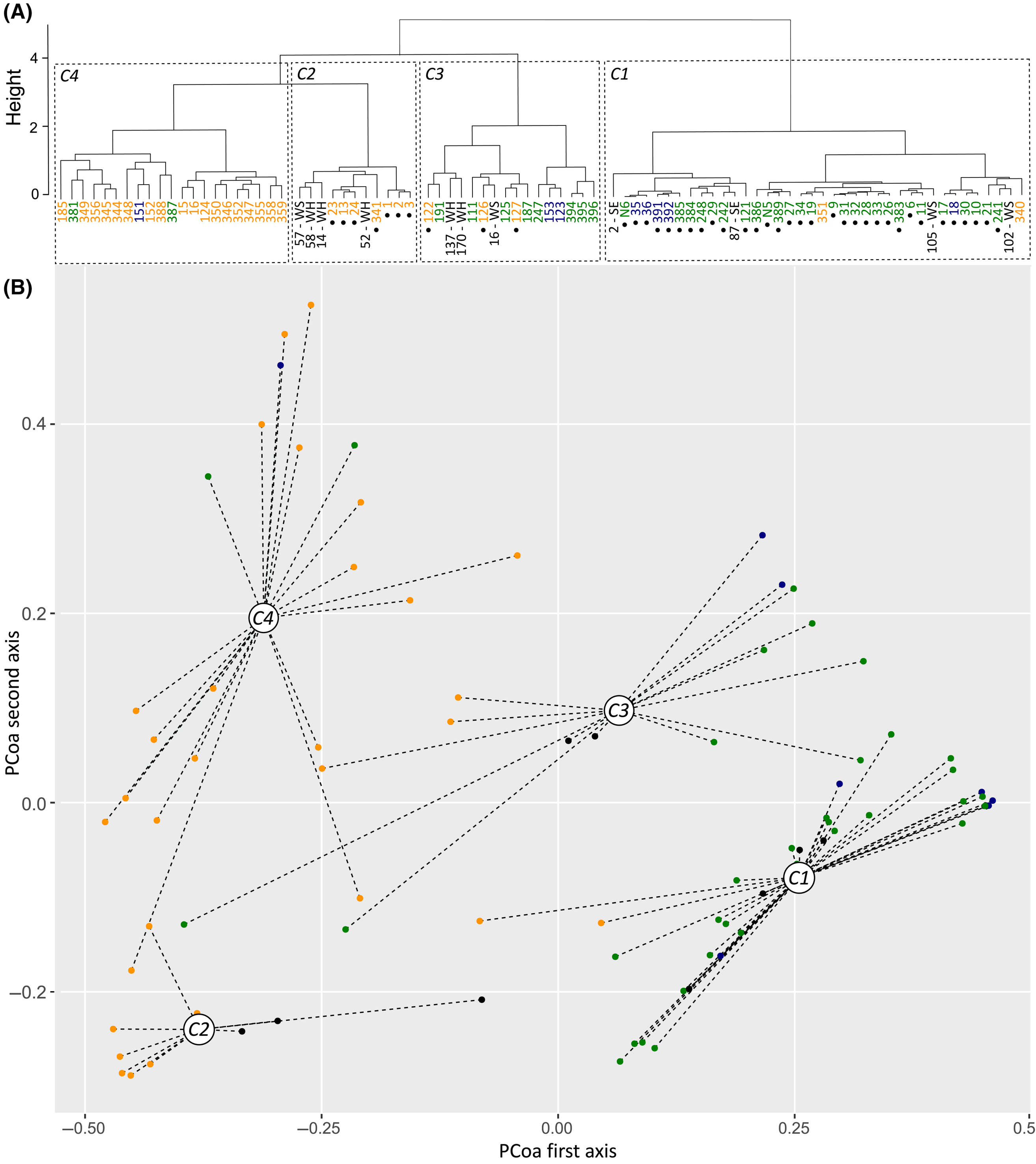

Figure 4. Hierarchical clustering analysis of 2013 vegetation composition using a Bray–Curtis dissimilarity matrix and Ward's minimum variance method (A) and principal coordinates analysis (B). Each plot is color-coded to represent community types. Black indicates reference plots (n = 11), followed by community type identifiers ("WS" for willow-sedge, "WH" for willow-herb, and "SE" for sedge). Restored plots (*n* = 72) are orange for willow-herb, green for willow-sedge, and blue for sedge. Black dot in front of restored plots' ID indicates successful restoration outcomes.

23% average cover of *Salix* species, such as *Salix monticola* (Fig. 6B), a 7% average cover of herbaceous species, mainly *Poa palustris* and *Equisetum arvense*, and a 2% average cover of invasive species, mainly *Cirsium arvense* (Fig. 6C & 6D). Within this cluster, 94% of the restored plots achieved their assigned restoration objective.

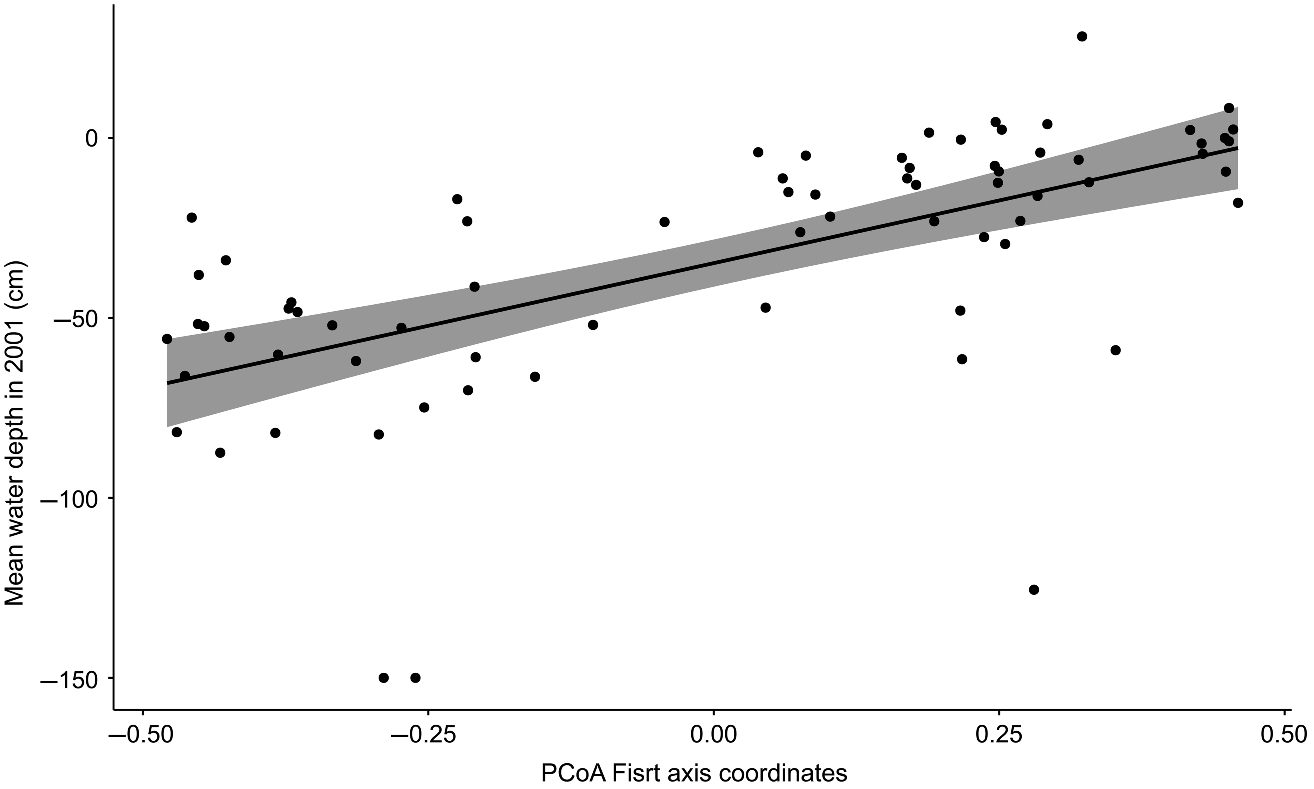

Figure 5. Pearson correlation between 2001 mean water depth measured in the restored plots and their coordinates on the first axis of the PCoA ($n = 72$, $r = 0.62$; p value <0.001).

Within cluster C1, further subdivision could be made based on dominant plant species (Fig. 7). The first subcluster (C1a) contained only sedge community reference plots and was dominated by *C. utriculata* with an average cover of 81% and a very low mean coverage of 3% *Salix* species, mainly *S. monticola*. The second subcluster (C1b) contained only willow-sedge community reference plots and was co-dominated by the same *Carex* and *Salix* species as in cluster C1a, but with average cover for each of 79 and 34% (Fig. 8).

Cluster C2 was characterized by willow-herb community reference plots (Fig. 4) and included restored plots with the deepest water tables, averaging 63.8 ± 15.6 cm. These plots were dominated by *S. monticola* with an average cover of 82% (Fig. 6B). This cluster was also characterized by a high cover of herbaceous species, mainly *E. arvense*, Cowbane (*Oxypolis fendlerii*), and *Calamagrostis canadensis*, with a total average cover of 45% (Fig. 6C), a 5% average cover of *Carex* species, mainly *C. utriculata* and 11% average cover of invasive species, mainly *Taraxacum officinale* (Fig. 6A & Fig. 6B). Within this cluster, 100% of the restored plots achieved their assigned restoration objective.

Cluster C3 was characterized by willow-herb community reference plots (Fig. 4) and consisted of restored plots at the interface between clusters C1 and C2 with an intermediate water table averaging 21.2 ± 24.6 cm. This cluster was characterized by a high cover of herbaceous species, such as *E. arvense* and Tracy rush (*Juncus tracyi*), with total cover averaging 36% (Fig. 6C), and a 40% average cover of *Carex* species, mainly *C. utriculata*, and a 24% average cover of *Salix* species, mainly *S. monticola* (Fig. 6A & Fig. 6B). The average cover of invasive species, such as Oxeye daisy (*Leucanthemum vulgare*), within this cluster was limited to 6% (Fig. 6D). Within this cluster, 25% of the restored plots achieved their assigned restoration objective.

Cluster C4 contained no reference plots (Fig. 4) and included restored plots with deep water tables averaging 61.0 ± 34.4 cm in summer. This cluster was characterized by 45% average cover of herbaceous species, such as Common yarrow (*Achillea millefolium*) (Fig. 6C), and by a 6% average cover of *Carex* species cover, mainly *C. utriculata* (Fig. 6A). However, the *Salix* species cover of this cluster, mainly *S. monticola*, was less important than that of cluster C2 with an average of 24% (Fig. 6B). This cluster stood out from the others because of its high cover of invasive species, mainly *Phleum pratensis* and *L. vulgare*, with an average of 34% (Fig. 6D). None of the restored plots within this cluster achieved their assigned restoration objective.

Success and Failure Prediction

The relevance of our short-term success criteria for predicting restoration success 15 years after restoration was highly variable (Tables S3 & S4). *Carex* ssp. shoot density had the highest Pearson correlation coefficient with overall restoration success ($r = 0.358$; $p = 0.002$). The SAM using this criterion also had the lowest AIC (77.530) and the highest McFadden's r^2 (0.095). Using *Carex* ssp. shoot density as an explanatory variable, the

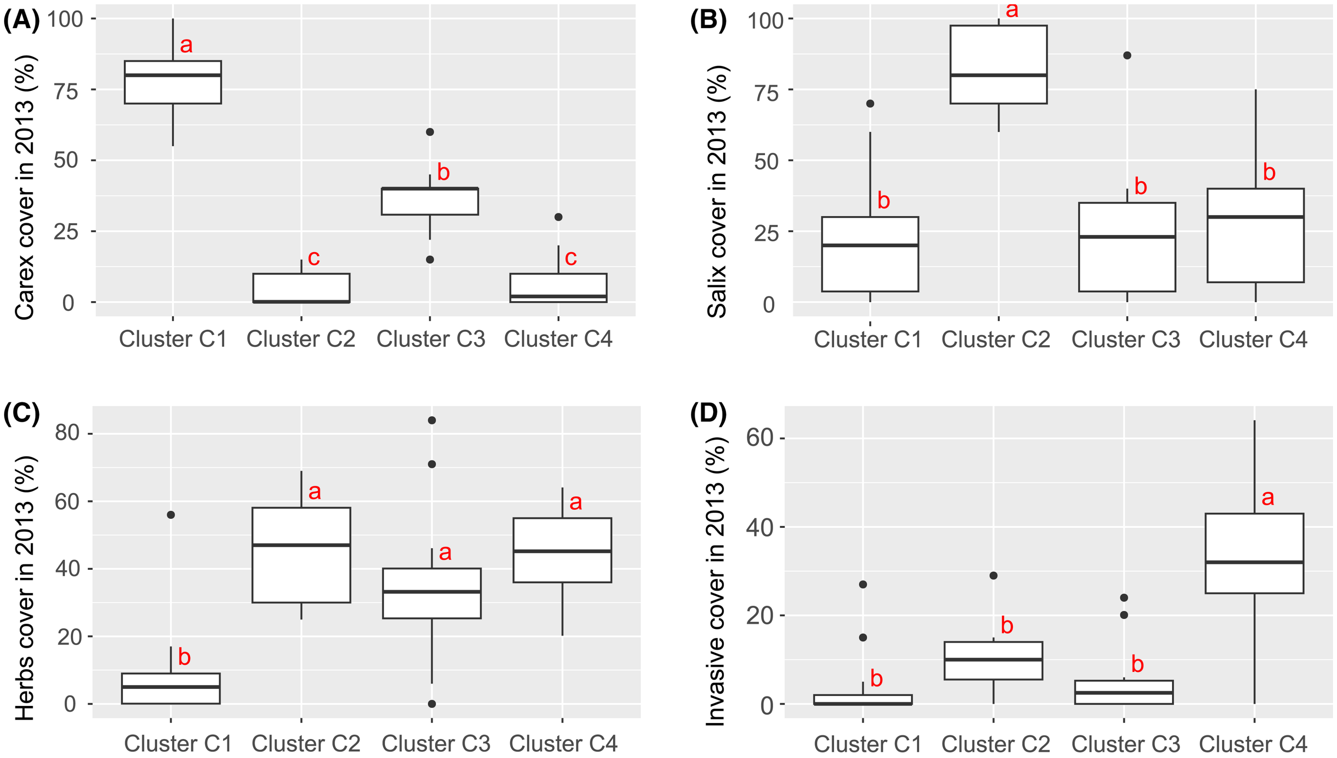

Figure 6. Boxplots and Tukey's post hoc HSD test of *Carex* (A), *Salix* (B), herbs (C), and invasive species cover (D) in 2013 for each cluster identified by the hierarchical clustering analysis. Red letters indicate significant differences between groups (p value <0.05). Each box represents the lower quartile, the median (bold line), and the upper quartile ($n = 4$). The vertical lines correspond to a 95% CI.

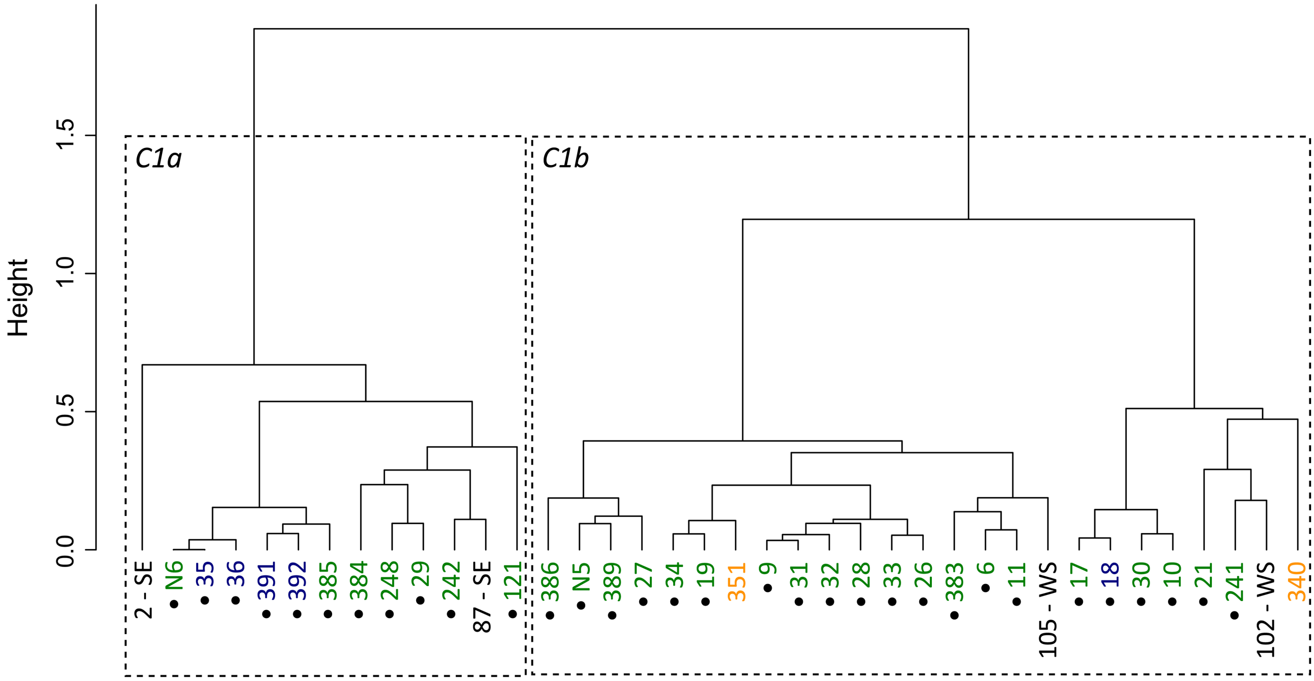

Figure 7. Hierarchical clustering analysis of 2013 vegetation composition using a Bray–Curtis dissimilarity matrix and Ward's minimum variance method and. Each plot is color-coded to represent community types. Black indicates reference plots ($n = 4$), followed by community type identifiers ("WS" for willow-sedge, and "SE" for sedge). Restored plots ($n = 34$) are orange for willow-herb, green for willow-sedge, and blue for sedge. Black dot in front of restored plots' ID indicates successful restoration outcomes.

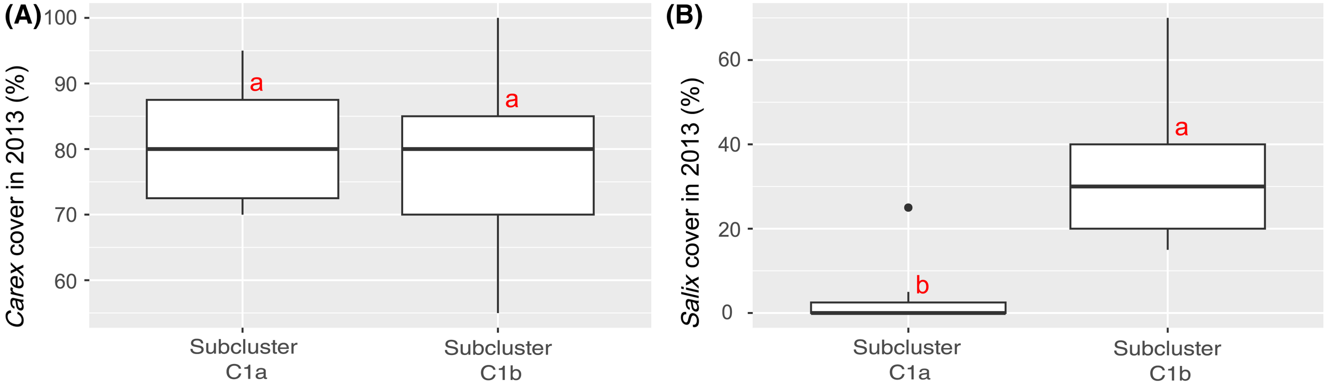

Figure 8. Boxplots and Tukey's post hoc HSD test of *Carex* (A) and *Salix* (B) cover in 2013 for each cluster identified by the hierarchical clustering analysis. Red letters indicate significant differences between groups (p value <0.05). Each box represents the lower quartile, the median (bold line) and the upper quartile ($n = 4$). The vertical lines correspond to a 95% CI.

model predicted 41 successes and 31 failures. Analyzing the predictions, we observed 48 accurate predictions (true positives and true negatives) and 24 false predictions (false negatives and false positives), which represented a 67% accuracy.

For the sedge community, invasive species cover had the highest correlation coefficient with restoration success ($r = -0.750$; $p = 0.032$). The SAM analyzing invasive species cover had the lowest AIC (−162.895) and the highest McFadden's r^2 (0.597). Using invasive species coverage as an explanatory variable, the model predicted six successes and two failures, which is consistent with the observed results (no false positives or false negatives).

For the willow-sedge community, hydrological dissimilarity had the highest correlation coefficient with restoration success ($r = -0.397$; $p = 0.020$). The SAM using hydrological dissimilarity as an explanatory variable was the one with the lowest AIC (33.095) and the highest McFadden's r^2 (0.143). Using hydrological dissimilarity as the explanatory variable, the model predicted 30 successes and four failures. We observed 28 accurate predictions (true positives and true negatives) and six false predictions (false negatives and false positives).

For the willow-herb community, none of the short-term success criteria had a significant Pearson correlation with restoration success. However, the SAM using *Salix* ssp. survival as the explanatory variable had the lowest AIC (40.992) and the highest McFadden's r^2 (0.010). Using *Salix* ssp. survival as the explanatory variable, the model predicted 0 success and 30 failures. Analyzing the predictions, we observed 20 accurate predictions (true positives and true negatives) and 10 false predictions (false negatives and false positives).

Discussion

We demonstrated that several of our short-term success criteria could be used as important predictors of long-term wetland restoration program success. Stress-related short-term success criteria, such as hydrological dissimilarity and invasive species canopy cover, were more effective in predicting long-term wetland restoration outcomes than target-vegetation-related success criteria, such as sedge shoot density or willow survival. However, our short-term success criteria could only be used to predict success for plant communities with shallow average water table depths (<50 cm), such as the sedge and willow-sedge communities. For communities with deeper average water tables (>50 cm), such as the willow-herb community, none of the studied short-term success criteria were significant predictors of restoration outcomes.

Sedge Community

For the sedge community, the canopy cover of invasive species was the only short-term success criterion that could be used to predict long-term restoration outcomes with a high accuracy rate (100%). It has been demonstrated that the presence of invasive species is an obstacle to the success and sustainability of restoration efforts targeting wetland plant communities (Kettenring & Adams 2011; Weidlich et al. 2020; Charles et al. 2023) especially in Cyperaceae-dominated communities (Li et al. 2021). Moreover, it has been reported that interspecific relationships, especially competition, are an obstacle to the success of Cyperaceae species during the restoration process (Qi et al. 2021). Several authors also emphasized prior restoration of proper hydrologic conditions as a primary driver of wetland plant community restoration (Cooper et al. 2017; Qi et al. 2021; Charles et al. 2023). However, for sedge plant communities, we did not find hydrological dissimilarity to be a significant predictor of long-term outcomes. This result, contrasting with previous research, may be explained by the hydrological dissimilarity in our data, that was too small to affect sedge community restoration outcomes in our restoration program.

Conducting a complementary study using a dataset where the hydrological regime significantly differs from the reference could be important to expand our results on the suitability of hydrological dissimilarity as a short-term success criterion. The last short-term success criterion studied for sedge plant communities, *Carex* ssp. shoot density, did not prove to be useful for predicting restoration outcomes in the early stage of restoration. This aligns with previous research (Littlewood et al. 2014) demonstrating that restoring the dominance of a particular species did not necessarily result in a systematic shift of the vegetation toward the target plant community. Our research highlights the importance of focusing on known drivers or obstacles of target plant community dynamics to predict restoration outcomes at an early stage of a restoration program.

From a structural, functional, and edaphic point of view, the sedge community can be compared to the *Scheuchzerio palustris-Caricetea fuscae* phytosociological class (Tüxen 1937), and our results could be extended to communities within this class. An extrapolation to communities of the *Phragmito australis-Magnocaricetea elatea* (Klika & Novák 1941) class could also be considered at lower elevation.

Willow-Sedge Community

For the willow-sedge community, hydrological dissimilarity was the only short-term success criterion that could be used to predict long-term restoration outcomes with a high accuracy rate (82%). It is well known that the hydrologic regime plays an important role in the final composition of restored wetland communities (Casanova & Brock 2000; Richards et al. 2020; Charles et al. 2023). In particular, willow-dominated communities are known to be dependent on the presence of an appropriate ecological niche, especially for water requirements (Mosner et al. 2011; Goetz et al. 2022). As noted above, the presence of invasive species can hinder the success and sustainability of restoration efforts (Kettenring & Adams 2011; Weidlich et al. 2020; Charles et al. 2023). However, unlike sedge communities, willow-sedge communities are less susceptible to long-term colonization by invasive plant species. Planting fast-growing tall *Salix* species is widely used as a method to control the establishment and spread of invasive species through interspecific competition (Lee et al. 2010; Dommanget et al. 2019). These considerations explain why invasive species canopy cover was not found to be an efficient short-term predictor of restoration outcomes for these communities. As we found for sedge communities, short-term criteria based on target species, *Salix* ssp. survival and *Carex* ssp. shoot density, were not reliable long-term success predictors for the willow-sedge community. In addition to the importance of hydrological conditions as a structuring factor of community species composition, our work emphasizes the critical role of restoring a specific hydrological regime, determined using reference sites, to improve and predict the success of wetland community restoration.

From a structural, functional, and edaphic point of view, the willow-sedge communities can be compared with some hydric communities of the *Betulo carpaticae-Alnetea viridis* phytosociological class (Huml et al. 1979), and our results could be extended to communities within this class. An extrapolation to communities of the *Carici elatae-Salicetea cinereae* class (Passarge & Hofmann 1961) could also be considered at lower elevation.

Willow-Herb Community

None of the tested criteria were significantly correlated with restoration success for the willow-herb community. This suggests that other factors may play a crucial role in determining the successful restoration of this community. Numerous authors emphasized that the dispersal and availability of seeds and ramets may influence wetland restoration success (Aavik & Helm 2018; Garrouj 2019; Stryszowska-Hill et al. 2023). Metrics such as proximity to similar ecosystems or a persistent seed bank might be considered as potential short-term success criteria, as well as other metrics related to stress and disturbance. However, our restoration program did not rely on seedling establishment from wind-blown seeds, as willows were planted as rooted cuttings. Now that tall willows are present, significant seed rain does occur, and we have found large numbers of willow seedlings in suitable habitats.

Restoration programs often require early evaluation within administrative timelines. Nunes et al. (2016) found that only 31% of restoration projects were assessed for periods exceeding 5 years, and merely 14% for periods exceeding 10 years post-restoration. However, in the assessed willow-herb community, all successful plots 15 years after restoration were considered failures 5 years after restoration due to the abundance of invasive species. The growth of willows, which established a continuous tall canopy in these plots, led to a significant decrease in invasive species cover over time, resulting in many plots being considered successfully restored by our HCA. This misalignment between administrative and ecological timelines (Aavik & Helm 2018; Cayton et al. 2023; Stryszowska-Hill et al. 2023) is significant since some ecosystems can take decades to centuries to fully recover (Rydgren et al. 2020). Our work highlights that, for some communities, it may not be pertinent to try to predict restoration outcomes after only 5 years. Considering that time is a key factor in achieving ecosystem restoration, a longer time frame should be considered (Woodcock et al. 2011; Moreno-Mateos et al. 2020).

From a structural, functional, and edaphic point of view, the willow-herb communities can be compared with some mesic communities of the *B. carpaticae-A. viridis* phytosociological class (Huml et al. 1979), and our results could be extended to communities within this class. An extrapolation to communities of the *S. purpurae* class (Moor 1958) could also be considered at lower elevation.

Short-Term Success Criteria Significance

In accordance with the criticism of restoration assessment metrics based on vegetation composition and target species (Smith et al. 2017; Yabe et al. 2021), we found that relying solely on short-term success criteria focused on target plant species, such as *Salix* ssp. survival or *Carex* ssp. shoot density, is insufficient for predicting long-term restoration outcomes of wetland plant communities. Instead, stress related metrics, such as hydrological dissimilarity and canopy cover of invasive species, provided a more accurate approach for assessing and predicting wetland restoration outcomes for the three studied communities.

Canopy cover of invasive species was a significant criterion for wetland communities sensitive to interspecific competition with limited or no shrub and/or tree cover. However, hydrological dissimilarity proved to be a significant criterion for wetland communities that are less sensitive to biological invasions due to the presence of fast-growing shrubs and/or trees that limit full sun establishment opportunities for invasive species. For communities in drier habitats, none of the short-term success criteria studied were pertinent. Thus, it is important to conduct further research to determine if other criteria could perform this role. This could include studying proximity to similar ecosystems suitable for propagule dispersal to the restoration site or seed bank persistence in local or translocated soils.

The significance of our short-term success criteria also depends on the contingencies of the pressures and constraints experienced by restoration and reference sites. It is well established that anthropogenic pressures, in particular nutrient inputs and changes in land use, can exert a profound influence on the dynamics of plant communities (Hedwall et al. 2019; Muehleisen et al. 2023) and on restoration outcomes (Audet et al. 2015).

The objective of utilizing reference sites within the golf course's influence area was to ensure that all sites were subjected to comparable pressures and constraints, thereby enabling the comparison of their trajectories. Moreover, the management plan introduced in 1996 focused on preventing changes in groundwater recharge, water table depth and dynamics, or nutrient introductions (Telluride Mountain Village 1996). Consequently, the indirect impact of golf course management on restored and reference wetlands is expected to be minor.

In the event of an unforeseen perturbation with significant localized impacts, such as infrastructure construction, river diversion, or chemical contamination, our short-term success criteria may become less relevant, as they would no longer be the primary vector for restored site trajectory.

Impact of Global Warming on Predictions

The impact of global warming on the short-term success criteria found over the course of the present 15-year study is probably limited. First, in the same wetlands, Cooper et al. (2017) found that water table depths measured in 2003 were strongly correlated ($r = 0.70$) to those measured in 2013, suggesting similar soil saturation for a given site. Additionally, plant communities are known to respond to warming with at least a 10- to 15-year delay due to lags in the life stages of plant species (Alexander et al. 2018).

However, on longer time scales, global warming could have a significant impact on the short-term success criteria tested here. Several studies have demonstrated the effects of global warming on the dynamics of invasive species (Huang et al. 2011; Liu et al. 2017). Similarly, increasing drought severity is expected to significantly affect water table levels (Cook et al. 2020; Vicente-Serrano et al. 2020). Consequently, longer-term predictions will require us to better consider and integrate changing climate conditions when defining short-term success criteria for wetland restoration projects.

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Supporting Information

The following information may be found in the online version of this article:

Table S1. Comparison of meteorological values (precipitation, snowfall, and temperature) in the Telluride Mountain Village area between 1998 and 2013 and 2001.
Table S2. Characteristics of the 12 wetlands studied.
Table S3. Pearson correlation coefficient (r) and p value (p) for each computed Pearson correlation test on each target plant community.
Table S4. McFadden's pseudo r^2 (r^2) and Akaike information criterion (AIC) for each computed binomial Spatial Autoregressive Model.
Figure S1. Photographs of the (a) sedge community, (b) willow-sedge community and (c) willow-herb community.

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