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WETLAND RESTORATION

Long-Term Recovery of a Restored Palustrine Wetland: the Role of Monitoring and Adaptive Management

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Abstract
In wetland restoration, adaptive management is a rarely used but potentially effective way to test initial assumptions of factors controlling recovery and adjust ongoing management to encourage ecosystem recovery. Limited development of monitoring practices and governance approaches hinder broader adoption of adaptive management. Reports of adaptive management for small wetlands, in particular, are lacking. We report here on lessons learned from monitoring a 3-ha, restored, palustrine wetland in central Minnesota for 23 years and using this information to guide management. The restoration was undertaken to convert a drained wetland dominated by invasive species to a high-quality meadow and marsh. Invasive species were treated, the drainage-tile system disabled, and 112 native wetland species seeded or planted. We installed a staff gauge for weekly hydrologic monitoring and monuments to delineate 26 vegetation monitoring units that encompassed the entire wetland. Five vegetation surveys were conducted between 2000 and 2019, consisting of comprehensive meanders of each monitoring unit; cover was estimated within each unit for all species observed. Coordination meetings of management staff and scientists were held to review evidence from monitoring that indicated a need to adjust vegetation or water management. Hydrologic monitoring provided evidence that the ecosystem goals needed to be adjusted and vegetation monitoring informed invasive species management. However, the linkage between monitoring and management could have been strengthened with a formal adaptive management plan at the initiation of restoration and with more frequent coordination cycles.

Keywords Wetland restoration · Minnesota · Revegetation · Wetland hydrology · Sedge meadow

Introduction

Restoration of degraded ecosystems is typically an uncertain process. Incomplete knowledge of site resilience, lack of effective methods, organizational constraints, as well as environmental variability, limit the predictability of restoration outcomes (Galatowitsch and Bohnen 2020; Perring et al. 2013; Suding 2011). Ongoing management decisions and actions informed by systematic monitoring (i.e., adaptive management, hereafter AM) has potential to reduce uncertainty over time, but is seldom used in ecological restoration and management despite its potential to improve outcomes and advance practice more generally (e.g., Fabricius and Cundill 2014; Gregory et al. 2006; Westgate et al. 2013). The costs of monitoring, different priorities for managers and scientists, and lack of confidence in assessments as a basis for changing management tactics are among the barriers cited for low adoption of AM (Allen and Gunderson 2011; Gregory et al. 2006). Published reports of AM as part of restoration are few and generally for large or complex projects with experiments designed to support decision-making, i.e., "active AM" (Failing et al. 2013; LoSchiavo et al. 2013; Thom 2000; Weinstein et al. 1997; Westgate et al. 2013; Zedler and West 1996). How to effectively incorporate adaptive management into restorations where multiple replicated, randomized treatments (i.e., true experiments) cannot be contrasted and decisions must be based on observational evidence, i.e., "passive AM", has not received attention. Given that many ecological restorations do not lend themselves to being set up and managed as true experiments, exploring the potential of AM in these so-called passive (or quasi-experimental) contexts is critical.

Drained, freshwater, palustrine wetlands, many of which are small and isolated within agricultural and urban landscapes, have been a focus of restoration interest for more than

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a half-century because of the important services they provide, notably waterfowl habitat and water-quality improvement (Zedler 2003; Zedler and Kercher 2005). These wetlands were once abundant in the glaciated terrain of the midcontinental US (i.e., prairie pothole region). In the US, many of these prairie-pothole, wetland restorations are pursued as individual projects, often supported by grants from conservation organizations (governmental and non-governmental). Even though knowledge of these wetland restorations is often incomplete at the onset of projects, circumstances (both organizational and environmental) are not suited for managing them as experiments.

Yet, facilitating ecosystem recovery requires management that extends many years past the initial phase of physical modifications of hydrologic systems and installation of vegetation or species reintroductions (Aronson and Galatowitsch 2008). High levels of site degradation (e.g., filling or excavation), extensive habitat loss (e.g., regional agricultural drainage), or both, compromise resilience and so the capacity for unassisted ecosystem recovery (NRC 1992). For example, within the intensively agricultural landscapes of the Midwestern US, drained, prairie-pothole wetlands restored only by breaking tile drains or plugging ditches required more than a decade to re-assemble relatively depauperate plant communities; succession was frequently arrested by invasive species (Mulhouse and Galatowitsch 2003). Despite increasing awareness of the challenges associated with relying on wetland restoration as an effective conservation strategy, many efforts continue to be based on overly optimistic assumptions about the likelihood of recovery with little or no monitoring or assessment of management outcomes during recovery (Galatowitsch and Bohnen 2020).

How to pursue wetland restoration so that it is competently aligned with the dynamics of ecosystem recovery is not well-understood and has received minimal empirical attention. The short-term nature of restoration funding (i.e., "projectification", Hodge and Adams 2016) is often a strong deterrent to making commitments beyond the grant period, even if risks to recovery are high (Galatowitsch and Bohnen 2020). In addition, there is little practical guidance for developing sustainable monitoring programs that generate data needed to inform ongoing management decision-making (i.e., AM) (Galatowitsch 2012). As a further impediment, even if informative data are generated, adoption of AM generally requires bridging across teams of people in an organization or among organizations (Allen and Gunderson 2011). The restoration of the tidal Sweetwater Marsh in San Diego demonstrated the value of coupling long-term monitoring with recovery in wetland restoration where active AM is feasible (Zedler 2017). The California Department of Transportation and US Army Corp of Engineers restored a coastal marsh to mitigate the loss of endangered species and wetland habitat and, in collaboration with the US Fish and Wildlife Service and the Pacific Ecological Research Laboratory of San Diego State University, managed the restoration for 20 years using monitoring data to determine if goals were being met and to adjust management strategies as needed. Moreover, the Sweetwater Marsh restoration highlighted the importance of monitoring as a way to capture unexpected outcomes and identify key data gaps critical for management. Examples of AM are needed for the restoration of small, individual wetlands such as prairie potholes, fens, and vernal pools (see Tiner 2003) in order to aid practitioners seeking to implement data-driven decision-making.

Twenty-five years ago, we began restoring a 3-ha palustrine wetland (Spring Peeper Meadow, SPM) at the University of Minnesota's Landscape Arboretum (MLA) with the aim of demonstrating best practices that could improve biodiversity outcomes. Informed by research showing limitations to relying on self-recovery to restore prairie-pothole plant and animal communities (Galatowitsch and van der Valk 1996b; Vanrees-Siewart and Dinsmore 1996), one of our aims was to explore revegetation practices that could be used to accelerate ecosystem recovery. Also at this time, the limitations of short-term commitments to wetland restoration were becoming evident as thousands of wetlands restored on agricultural lands in the late 1980s were being overtaken by a few invasive species (i.e., *Typha* spp. and *Phalaris arundinacea*) (Galatowitsch and van der Valk 1996a). We saw this restoration as an opportunity to explore ways to support ecosystem recovery through AM and to document the benefits of doing so. This restoration needed to be pursued as "passive AM" because the hydrology of SPM was not conducive to experimental manipulations (i.e., variations in hydrology were not possible, Gregory et al. 2006) and because the primary funding sources for the restoration were short-term and uncertain from year-to-year beyond the initial 2-year grant. We report here on what we have learned over two decades of monitoring changes at SPM and using this information to influence management to sustain recovery. In particular, we identify key barriers to and opportunities for AM and offer recommendations for future restorations of small wetlands.

Restoration, Monitoring, and Management Methods

Restoration Context, Goals, and Implementation

The restoration of SPM was initiated as part of a 1995 land purchase extending the boundaries of the MLA, which is part of the University of Minnesota. Funding from a state environmental trust was awarded to the MLA for both land acquisition and wetland restoration. These funds supported the project for its first two years. Additional funds were raised by the

MLA to establish visitor-use infrastructure and to support vegetation management. For twelve years following the initial grants, the MLA assigned a staff member (JB) to manage and monitor the restoration and adjacent lands. Since 2010, staff managing the restoration (neither author) also have many other responsibilities across the 486 ha (1200 ac) MLA. Periodic monitoring (every 4 to 6 years) by campus-based university researchers (the authors) was used to track recovery and provide guidance to MLA operations leadership and staff on strategic use of limited management resources.

Historically, SPM was a headwaters sedge meadow within a landscape dotted with wetlands and surrounded by uplands covered with a mosaic of prairie, savanna, and hardwood forests (Bohnen and Galatowitsch 2005). The wetland had been used for agricultural purposes (pasture and forage production) since the late 1800s, and after tile drainage was introduced in the 1920s, for corn (*Zea mays*) and soybean (*Glycine max*) production. When the restoration was undertaken in 1995, the site was a hayfield where cover was 100% invasive *Phalaris arundinacea*, which established after 1989, when corn and soybean production stopped. The primary goal of the project was to restore the drained field to sedge-meadow and shallow emergent-marsh habitats with hydrology, vegetation, and animal communities similar to high-quality, extant wetlands in the region.

Our previous paper on SPM (Bohnen and Galatowitsch 2005) provides details of the restoration implementation, which we summarize here. Prior to restoring hydrology in 1996, we treated *Phalaris* for two years with multiple herbicide applications. To restore hydrology, we broke sections of tile and installed inline stop-log structures in late fall (October) and seeded immediately (i.e., a dormant seeding). We applied three seed mixes at elevations anticipated to be suited to wet prairie (2.9 ha), sedge meadow (1.1 ha), or emergent marsh (1.9 ha) after reflooding; hereafter these are referred to as the WP, SM, and EM zones, respectively (Fig. 1). In total, 93 species were seeded (not including cover crops). In 1997, coinciding with the emergence of species from the dormant seeding, we installed plants of 32 species (mostly *Carex* spp. in the SM and EM zones). The origin of all seeds, whether sown directly on the site or used to propagate plants, were collected locally, nearly all within 100 km of SPM. In total, we seeded and/or planted 112 wetland species. In the EM zone, 28 species were seeded or planted, while in the SM and WP zones 41 and 33 species, respectively, were seeded or planted. Another 5 native early successional species were sown across the entire wetland to provide initial temporary cover: *Rumex brittanica, Bidens cernua, Bidens vulgata, Persicaria pensylvanica, and Persicaria lapathifolia.*

Monitoring and Management Activities

To facilitate ecological monitoring at SPM, we installed monitoring monuments (coated aluminum poles) in 1996 along 15 transects, which were 30 m apart, north to south. Within a transect, poles were placed at intervals of 30 cm of elevational change east to west. Using the network of poles, we delineated 26 vegetation monitoring units that encompass the entire wetland: 10 WP units, 6 SM units, and 10 EM Units (Fig. 1). Because of the irregular configuration of SPM, the monitoring units ranged in size from 0.04 to .45 ha (averaging 0.19 ha). In 1998, we installed a staff gauge in a deep central part of SPM, accessible from a boardwalk, for hydrologic monitoring. We established 14 photo points, from which images were recorded up to four times throughout the growing season.

Between 1998 and 2005, as part of university research grants, we characterized the water chemistry of SPM and initial establishment of vegetation. Wetland use by birds and amphibians was monitored from 1998 to 2008. Since 2008, we have focused monitoring on vegetation and hydrology, which were central to ongoing management decision-making.

Five vegetation surveys were conducted since 2000 (2000, 2004, 2009, 2013, and 2019). The lead scientist conducting the surveys was the same person for each (JB), with assistance by other observers. Vegetation surveys consist of comprehensive meander searches of each monitoring unit; cover was estimated within each unit for all species observed. Vegetation was surveyed when most species were at peak biomass and identifiable to species (late July–August). In 2000, vegetation was also surveyed in June. We assign cover classes for each species using a modified seven-point cover scale (Mueller-Dombois and Ellenberg 1974). Nomenclature follows Chadde (2013). The initial monitoring program for SPM included both transects of small plots and comprehensive large plots, but small plots left too much unsampled area to inform invasive-species management and so were dropped from the protocol in recent years.

Hydrological data were generated from staff gauge readings collected approximately weekly during the growing season (April through September) from 1998 to 2009. Heavy rains triggered additional readings. After staffing at SPM was reduced in 2009, characterization of site hydrology has been based on fewer staff gauge readings, observations (photo points), and rainfall records from the National Weather Service station (Chanhassen) located 2.9 km from SPM. Groundwater contributions to SPM were not measured. However, seeps on one slope above the marsh were observed after restoration commenced.

Since the initial construction and installation phase of the SPM restoration, management has consisted of invasive species control (regular scouting and treatment), adjusting water levels after extreme high-water events, restoration of surrounding upland habitats, and maintenance of visitor infrastructure (i.e., trails and boardwalk).

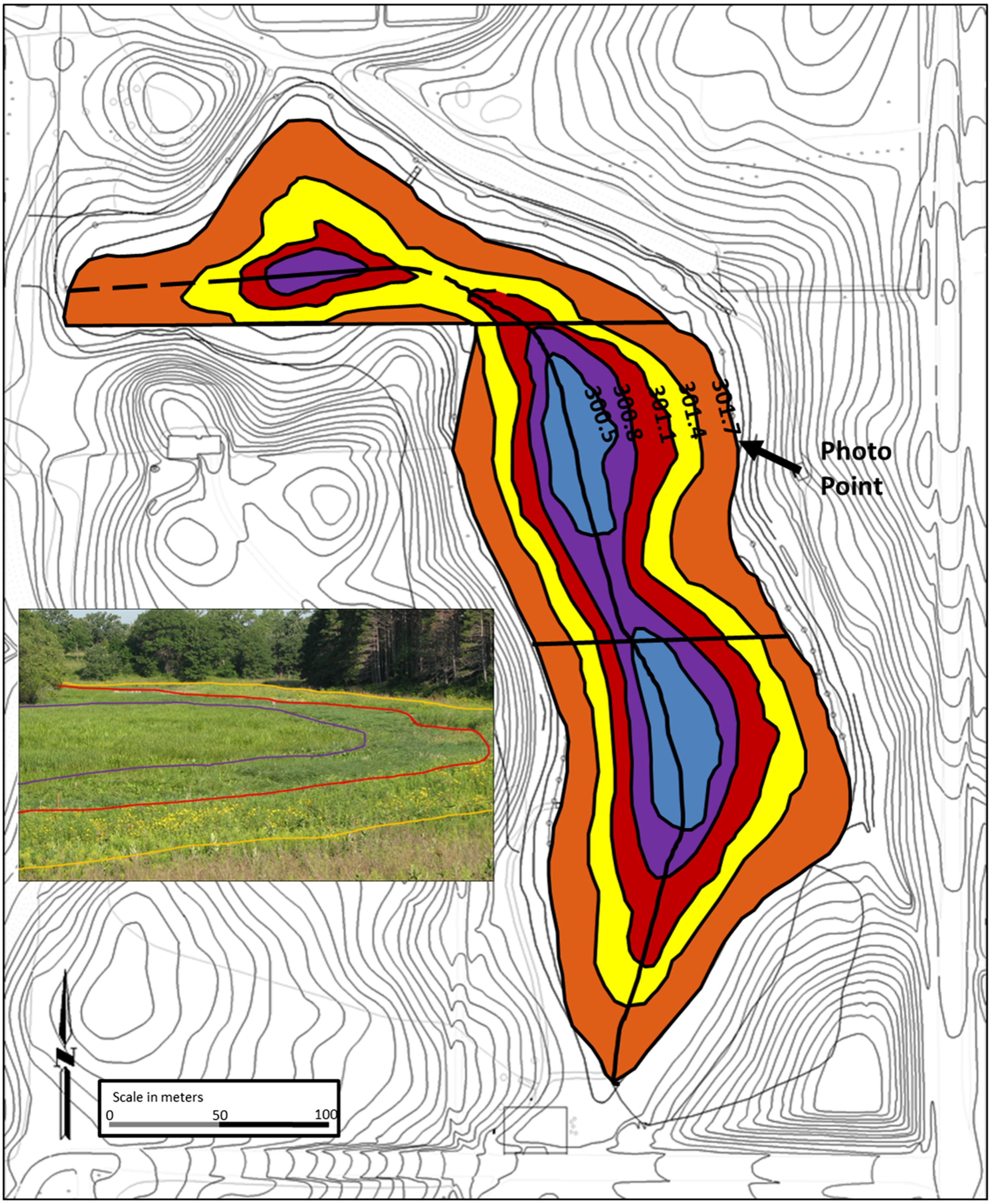


Fig. 1 Elevational zones (meters ASL) delineating the Spring Peeper Meadow restoration site were revegetated with different seed and/or plant mixtures. The zones also correspond to vegetation survey units. The WP zone (orange and yellow) encompasses 10 vegetation survey units, the SM zone (red) - 6 units, and the EM zone (blue and purple) - 10 units. Areas south of the dashed lines were separate plots in the 2000 survey; in subsequent years they were combined with the adjacent plots to the north. Inset photo point image showing the plant community zones was taken from the slope on the east side of the site in the direction noted

Invasive species control efforts in the wetland restoration have primarily focused on three, herbaceous, perennial, invasive, wetland plants (i.e., *Lythrum salicaria*, *Phalaris arundinacea* and *Typha angustifolia*/*T.* x *glauca*). Encroaching woody species, including *Rhamnus cathartica*, *Frangula alnus*, *Fraxinus pennsylvanica*, and *Acer negundo*, were also controlled. Since 2009, the level of effort assigned for SPM management has been informed by changes observed to vegetation and hydrology, as captured during scouting or incidental site visits (MLA staff and university researchers) and following monitoring efforts (researchers).

Analysis and Use of Monitoring Data

The water regime was summarized annually as the inundation duration (% of growing season) in each of the zones, depending on data availability (Table 1). From 1998 to 2009, the records are complete and so inundation duration was estimated for all elevations. After 2009, infrequent staff-gauge records and photo-point images were used to generally categorize water regime based on the presence of standing water in the deepest zone (EM) of the wetland. Interannual changes in inundation duration were compared to changes in monthly rainfall totals and stoplog records, as well as other observations to assess management (e.g., water-level control) and maintenance needs (e.g., stoplog-structure and drain-tile repairs).

After each vegetation survey, we compare changes in six vegetation parameters over time: 1) total number of species, 2) number of species in 13 functional groups, 3) changes in cover of invasive perennial species, 4) changes in cover of common native species, 5) newly detected species, and 6) species losses. Functional groups (i.e., guilds), as described in Aronson and Galatowitsch 2008, were based on life history (annual vs perennial), growth form (graminoid, forb or woody), origin (native vs introduced), and ponding/inundation tolerance.

We use graphical analysis (e.g., tables, graphs, histograms) and descriptive statistics to summarize trends over time and space with a focus on depicting the data in a way that facilitated communication with MLA staff. We provided tracking of changes in abundance and distribution at the species level

Table 1 Hydrological Records - 1997 to 2019. For the first 14 years (1998 to 2009) of the restoration, records related to hydrology were richer and provided a more complete picture of the hydrological status of the restoration. For that period, staff gauge records were collected approximately weekly during the growing season (April 1–October 1). After 2009, staff gauge data were collected less regularly. The % of Growing Season Inundated data were generated from the staff gauge readings. Monthly precipitation totals were obtained from the Chanhassen Weather Station located 3 km from the site to generate growing season and annual total precipitation values. Number of outlet actions summarizes the number of times the water control structure was opened/closed during the season or if NA, no actions were documented. Days outlet set below full pool data are generated. * = Inundation in 1997 was extrapolated from other records. NA = data not collected or not enough data to generate values. Inc. = Incomplete data

	#Staff Gauge Records		% of Growing Season Inundated					Precipitation (cm)				
Year	Growing Season	Annual	EM (300.5)	EM (300.8)	SM (301.1)	WP (301.4)	WP (301.7)	Growing Season Total	Annual Total	Number of outlet actions	Days outlet set below full pool	Photo Point Record (#sets)
1997*	0	0	94	18	3	0	0	64.6	80.1	NA	NA	0
1998	39	53	98	21	10	0	0	57.5	81.2	15	21	0
1999	36	42	100	74	7	0	0	59.1	75.6	4	18	0
2000	32	44	85	62	7	0	0	49.0	73.8	NA	NA	4
2001	28	32	46	31	8	0	0	63.1	85.6	2	Inc	3
2002	40	49	100	100	64	3	0	76.2	93.1	9	15	3
2003	34	35	80	51	28	0	0	45.3	59.5	2	8	3
2004	36	37	100	75	43	15	0	65.2	86.1	2	17	3
2005	48	56	100	89	60	34	0	78.2	107.8	6	32	1
2006	28	33	79	50	25	10	0	52.1	68.0	2	14	3
2007	19	32	56	45	36	25	0	43.8	72.5	1	3	4
2008	24	33	100	84	55	36	0	49.8	67.6	1	17	4
2009	23	25	100	76	44	10	0	44.1	75.9	3	Inc	4
2010	0	0	NA	NA	NA	NA	NA	68.7	92.4	NA	NA	2
2011	0	0	NA	NA	NA	NA	NA	55.5	70.4	NA	NA	0
2012	6	7	84	NA	NA	NA	NA	64.1	83.3	2	Inc	2
2013	6	7	100	NA	NA	NA	NA	67.2	89.1	2	Inc	5
2014	9	9	84	NA	NA	NA	NA	76.4	92.6	1	41	3
2015	7	10	100	NA	NA	NA	NA	62.5	90.0	2	Inc	1
2016	7	9	100	NA	NA	NA	NA	76.7	103.0	1	Inc	1
2017	7	8	84	NA	NA	NA	NA	74.7	96.3	1	Inc	1
2018	0	0	NA	NA	NA	NA	NA	61.0	87.4	NA	NA	2
2019	0	0	75	NA	NA	NA	NA	79.3	111.4	NA	NA	3

for 12 native taxa because they typify the plant communities targeted by the restoration, and in most cases, because we had seeded/planted them. We provided species-level tracking for all invasive species, including *Typha x glauca* and *Phalaris arundinacea*, which established prior to or at the onset of restoration, as well as species such as *Lythrum salicaria, Acer negundo, and Rhamnus cathartica*, which periodically colonized.

Coordination meetings of management staff and researchers served as the main forum for reviewing monitoring results and discussion of management needs. In years when monitoring did not occur, researchers conducted at least one site visit to SPM and reported observations of management concern to MLA staff. Our primary aim with respect to management was to determine if invasive species were increasing in abundance or spatial extent, indicating a need for additional control effort. We also look for evidence suggesting that SPM's water regime was not within a range that supports a diverse marsh and meadow flora. Losses of native species identified species that MLA staff may consider for reintroduction.

Changes to SPM Vegetation and Hydrology over Time (Results)

For 20 years of the 23-year record, data were sufficient to estimate inundation duration (% of growing season) for the deepest zone (EM with upper boundary at 300.5 masl) of the restored wetland. For nearly half these years (9), the EM zone was inundated throughout the growing season (100%), and for another 9 years, between 75 and 99% of the growing season. The two years (2001 and 2007) with the lowest duration of inundation followed several years of low precipitation and/or occurred in years with low precipitation. Growing season and annual total precipitation generally correspond to duration of inundation (Fig. 2), although the long duration of ponding in most years likely also reflected groundwater contributions (unmeasured). Both growing season and annual total precipitation was lower in the first 13 years than in the last ten-year period (Mann-Whitney, $p < 0.05$) when both water level monitoring and management were reduced in frequency (Table 1).

For the 13 years with records sufficient to estimate inundation duration across all zones, all but two years had prolonged inundation of the EM Zone (i.e., >75%). The SM Zone (upper boundary 301.1 masl) was inundated for some percentage of all of these years, with 8 of the 13 years exceeding 25%. The two years with highest duration of ponding in the SM Zone (2002, 2005) had the highest precipitation (growing season and annual). Water-level management was relatively frequent in these two years, as indicated by the number of stop-log manipulations (Table 1).

For 6 of these 13 years, in the WP zone (upper boundary 301.4 masl), inundation duration was greater than 10%. These are not clearly related to precipitation or water-level management (Table 1). Moreover, not all years of relatively long inundation duration at high elevations have corresponding long durations at low elevations (e.g., 2007) suggesting different rates of change in water levels across years. Likewise, for the 5 years with 100% inundation duration in the EM zone, inundation of the WP ranged from 0 to 36%, potentially the result of different annual maximum ponding levels or variability in high-intensity storm events, in combination with water-level management.

In 2000, 4 years post-restoration, 254 species were observed across the WP, SM, and EM zones. Over the past two decades, we detected the colonization of 190 plant species. Of these, 118 were native species: 9 were floating and submersed aquatics, 27 were herbaceous perennial forbs (EM - 1, SM - 10, WP - 16), 5 were perennial graminoids (SM - 4, WP - 1), 38 were herbaceous annual forbs, 6 were upland native perennials, 39 were native annuals, and 32 were woody species. Of the 72 introduced species, there were 33

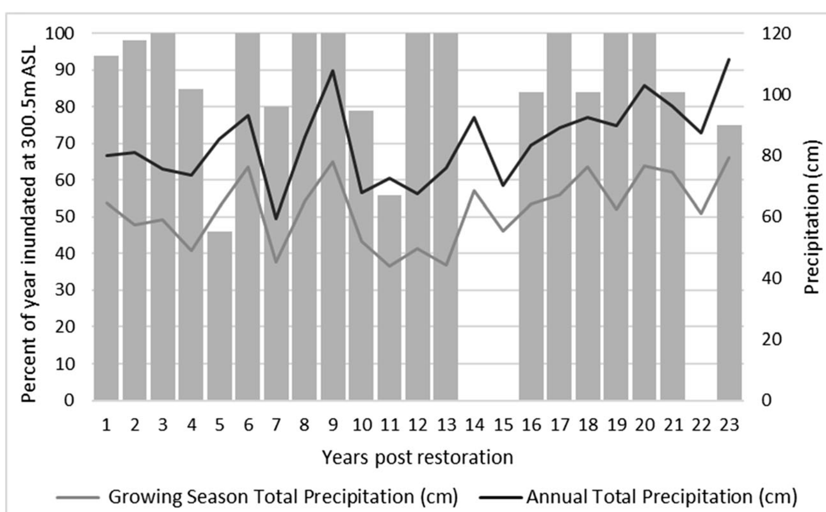


Fig. 2 The percent of the growing season that was inundated at 300 masl (emergent marsh) plotted with growing season total precipitation (cm) and annual total precipitation (cm) from 1 (1997) to 23 (2019) years post restoration. Years with inadequate data are blank for percent of growing season inundated

herbaceous perennials (22 forbs and 11 graminoids), 31 annuals (25 forbs and 6 graminoids), and 8 woody species.

Over time, species richness has steadily declined by 30.7% to 176 species in 2019. While the number of species in the EM Zone has been consistently around 50 species over time, the SM Zone experienced steep initial declines, only half of the 180 species present in 2000 were observed in 2004 (91) (Fig. 3). The richness of the SM zone has remained relatively constant since then. The species richness of the WP has steadily declined from 234 species to 147 species in the past two decades.

Of the 112 species seeded or planted in 1996, 86.6% were documented four years post-restoration; 70.5% were documented 23 years post-restoration (Fig. 4). Nine seeded/planted species (3 in each zone) have not been documented in any survey. Several species established upslope from where they had been sown, as a result of secondary dispersal of seed during high-water conditions or via rhizomatous growth. *Sagittaria latifolia* and *Sparganium eurycarpum* were sown in the EM Zone where they continue to be most abundant, but these species are also common in the SM Zone (Fig. 5). Although sown in the EM, *Carex lacustris* is better represented in the SM and WP. *Calamagrostis canadensis,* sown in the EM and SM zones, has persisted through changes in hydrological condition by expanding and contracting gradually over time.

Whether a species has become abundant in the restored vegetation does not generally correspond to their relative abundance in the seed mix. *Carex cristatella*, *Scirpus atrovirens*, *Eutrochium maculatum*, and *Calamagrostis canadensis* were abundant in the seed mix, each comprising more than 2% of the mix by seed number. Of these species, only *C. canadensis,* (the only rhizomatous species), spread and sustained high cover. Cover of *C. cristatella* and *S. atrovirens* decreased over time, particularly at lower elevations (Fig. 5). *Eutrochium maculatum* abundance has varied over time. Some species, notably *Carex lacustris* and *Sparganium eurycarpum*, that spread vegetatively by rhizomes, have become a dominant component of the plant community. Although neither was rare in the seed mix, both comprised less than 2% of the mix. The cover of both species exceeds 25% across most of the SM and WP Zones (*C. lacustris*) or EM zone (*S. eurycarpum*). *Schoenoplectus fluviatilis*, a species for which no more than 50 seeds were sown, occurred in just two plots in 2000. By 2019, it was documented in 11 of 26 plots. This strongly rhizomatous species is anticipated to continue spreading within the wetland.

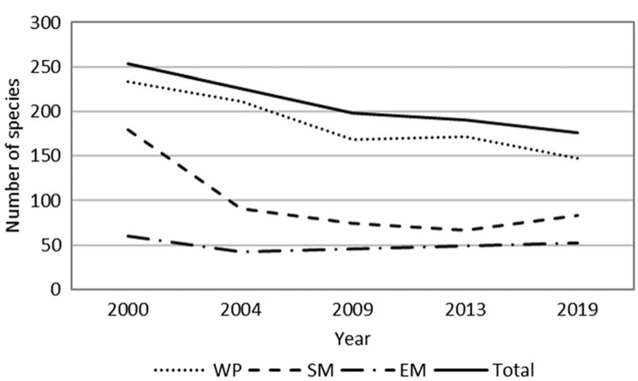


Fig. 3 Changes in total richness and richness of each vegetation zone – Emergent (EM), Sedge Meadow (SM) and Wet Prairie (WP) from 2000 to 2019

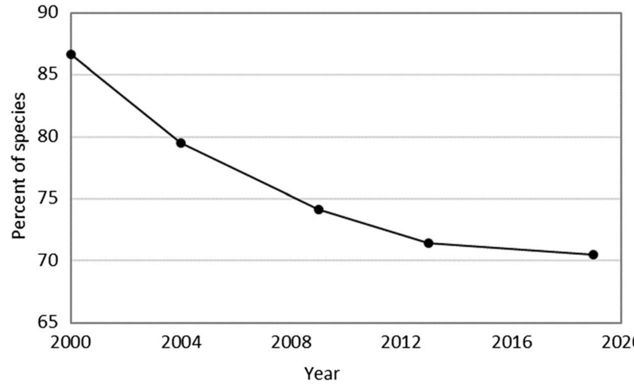


Fig. 4 Percent of the 112 sown or planted species that were represented in the flora from 2000 to 2019

Sedge-meadow perennials (forbs and graminoids combined) was the most diverse native functional group, with 71 total species documented in all surveys. The richness of sedge-meadow perennials declined 21.8% from 2000 to 2019. Nonetheless, sedge-meadow perennials still comprise more than a quarter of SPM's flora (28%). Sedge-meadow perennial forbs and graminoids, as well as native annuals have been the most important functional groups in the SM zone (Fig. 6). In the wet-prairie zone, sedge-meadow perennial forbs, wet-prairie forbs and native annuals were more than half of the species richness in all surveys. The species richness of the emergent zone includes significant representation of floating and submersed aquatics, emergent graminoids and forbs, sedge-meadow perennials, sedge-meadow forbs, and native annuals in all surveys. The richness of introduced species was greatest in the wet prairie (generally 20%).

Eight of the 13 functional groups had fewer species in 2019 than in 2000 (Fig. 7). The greatest change was observed for introduced annuals and introduced perennials, with species losses of 76% and 59%, as well as native annuals (39%). Spring Peeper Meadow's %PNV (percent of total vegetation that are native species representative of the community) increased from 35% in 2000 to 44.3% in 2019, as losses of introduced species exceeded those of native species (Galatowitsch and Bohnen 2020).

Management of the most ubiquitous invasive species, *Phalaris arundinacea and Typha* spp., had been sufficient to limit them each to less than 1% cover across SPM until the period from 2014 to 2019 (Fig. 8). In 2019, *Typha angustifolia/Typha x glauca* were observed to exceed 1%

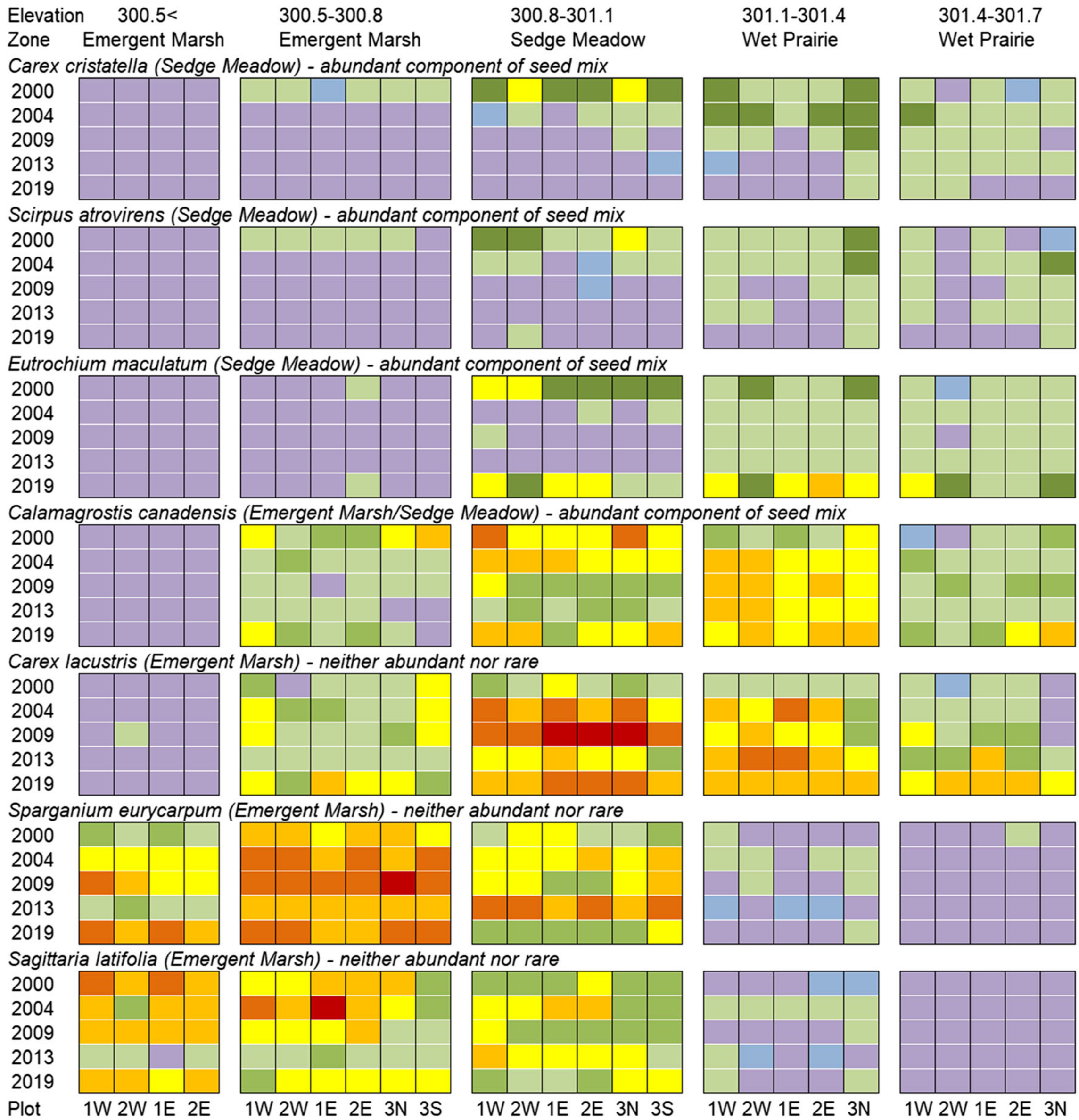


Fig. 5 Cover and distribution of select native species sown in SPM. The zone in which the species was sown is noted in (). Whether the seed was an abundant, rare, or neither abundant nor rare component of the seed mix is noted for each species. Each of the five sets of larger boxes represents zones: Emergent (EM)-2 elevations, Sedge Meadow (SM)- 1 elevation, and Wet Prairie (WP)- 2 elevations. Sampling years are represented on the vertical-axis for each species. The 26 plots are represented on the horizontal axis. Covers by plot are represented for the five sampling periods (small boxes). **2 cont.** Cover and distribution of select native species sown in SPM.

cover in two units of the EM Zone and had increased their distribution from two of ten units in 2013 to 8 eight of ten in 2019. During this same interval, *Phalaris arundinacea* also experienced its greatest increase in distribution and abundance, primarily in the SM and WP zones.

Guidance from SPM Monitoring and Adaptive Management for Restoration of Palustrine Wetlands (Discussion)

All restoration plans, including the one developed in 1994 for SPM, are representations (i.e., models) based on many assumptions about controlling factors (e.g., elevation and hydrology) that are critical for the desired structure and function of the restoration (Thom 2000); these assumptions are tested as a restoration is implemented. When AM guides management decisions, a transparent process exists for determining the extent to which the ecosystem is positively responding to planned interventions and if the initial goals and practices need to be adjusted, i.e., “single-loop” learning (Fig. 9, Galatowitsch and Zedler 2014). Ideally, this process will also facilitate deeper learning (i.e., “double-loop” learning), which may be needed if evidence challenges fundamental assumptions about restoration practice held by the team or key

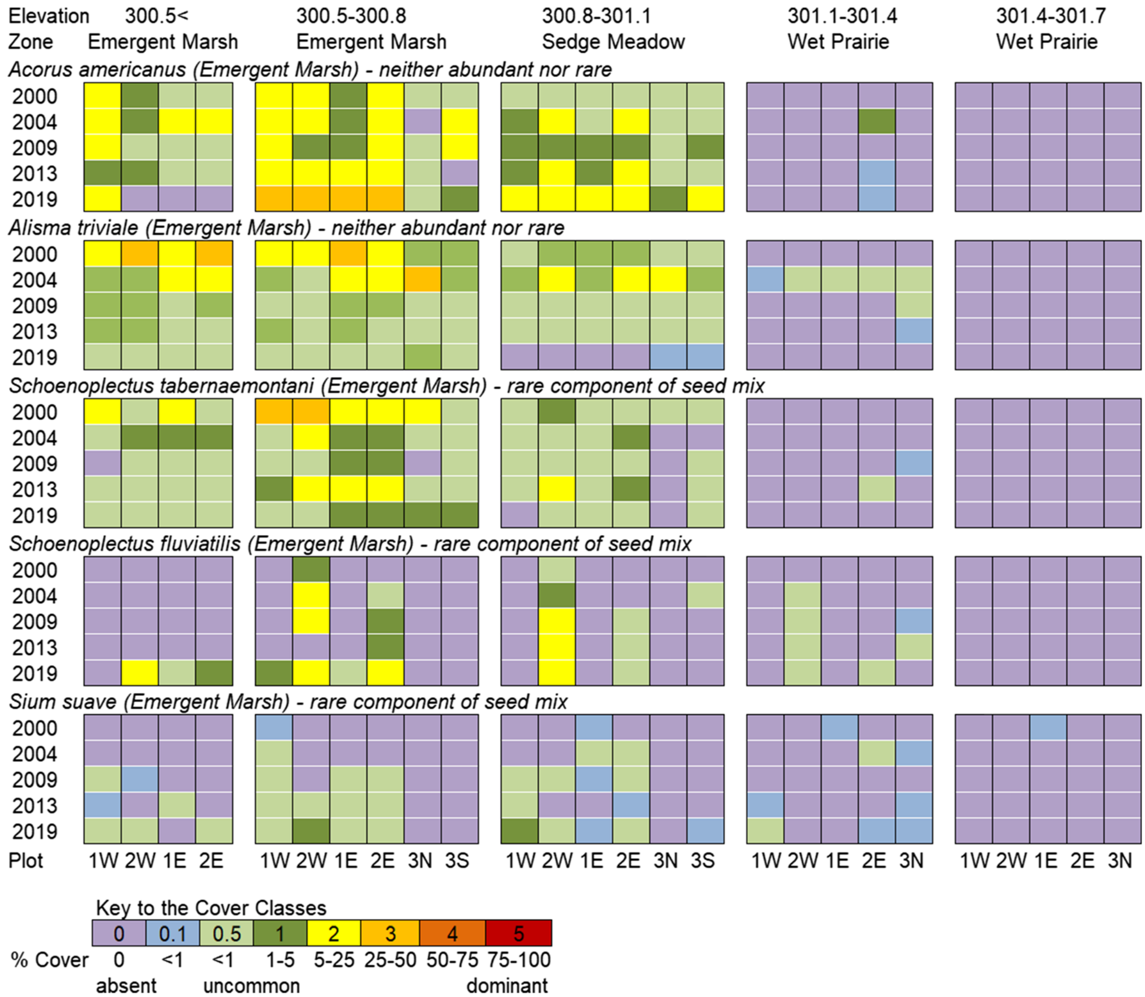


Fig. 5 (continued)

individuals (Fabricius and Cundill 2014). Spring Peeper Meadow illustrates why AM should be considered central to ecological restoration even when managing the project as an experiment (i.e., with replicated, randomized treatments; active AM) is not feasible, and also why it is difficult to effectively implement even on projects that are not large or complex. Both the value and challenges stem from the need to manage through change – both ecological and social – that affects recovery long past the initial implementation of a restoration. At SPM, hydrologic monitoring (as well as general site observations) provided evidence that the ecosystem goals needed to be adjusted to presume emergent marsh, rather than sedge meadow, was a more feasible target community for much of the wetland basin. The extent to which repeated monitoring provided a diagnostic framework to guide long-term recovery, as intended by AM, has been variably effective at SPM. For some aspects of management, notably response to invasive species, monitoring has provided a necessary early-warning signal and accumulation of credible evidence to support decisions that have led to action (Thom 2000; Walters and Holling 1990). Other aspects of management, including management of hydrology and native vegetation, have not been as effectively coupled to monitoring and evaluation at SPM.

Monitoring provided key evidence that guided decisions to adjust goals related to anticipated water regime and wetland plant communities and to test the appropriateness of new goals. Within a few years of implementing the restoration plan, it became clear that despite the small contributing watershed and sedge-peat soils across most of the wetland, SPM was becoming an emergent marsh. Groundwater inputs (seeps) were apparently far greater than had been anticipated, and an elevated roadbed near the outlet buried what was once a broad connection of the meadow to a stream. Hydrologic-monitoring evidence allowed us to refine our conceptual model of SPM system function and adjust our expectations and actions accordingly (Walters and Holling 1990). The management alternatives were to intensively manage the hydrology of the site to achieve an ephemeral water regime or to allow the site to become a shallow emergent marsh. The

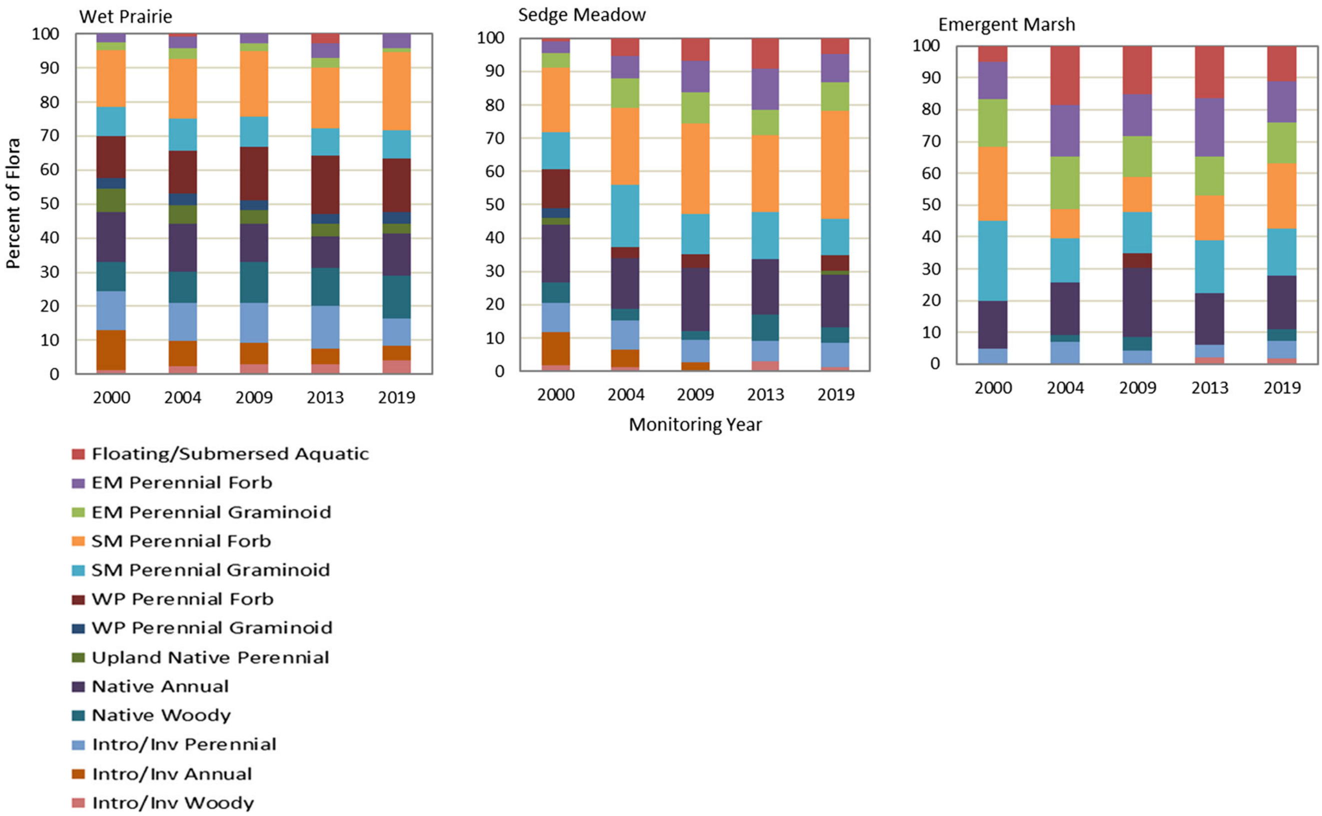
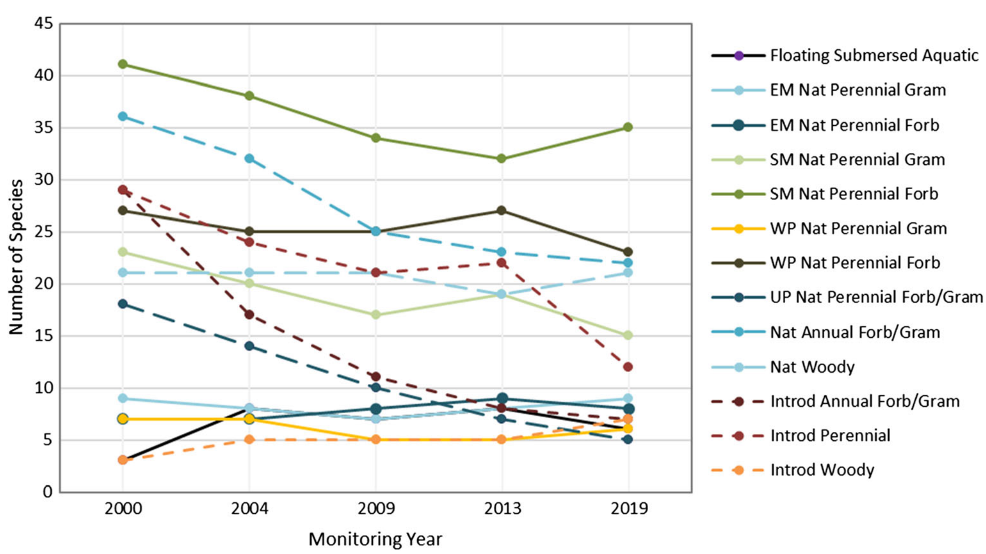


Fig. 6 Percent of the flora comprised by each functional guild in the three zones. A. Emergent Zone, B. Sedge Meadow, C. Wet Prairie.

restoration team opted for the latter, in part, because deciding how much water to remove seemed arbitrary, given the incomplete understanding of the site's historic (i.e., pre-agricultural drainage) water regime. The guiding water management principle adopted was to remove water for two reasons: 1) to prevent over-topping the boardwalk, in the interest of public safety and 2) to prevent high water from killing established native vegetation. Hydrologic records from monitoring show that active management of the outlet structure has resulted in an acceptable emergent-marsh water regime, i.e., the emergent zone is inundated for 75 to 100% of the growing season in most years.

We have been unable to use monitoring data to assess whether water-level management has influenced plant community change consistent with project goals of restoring a wetland with high plant biodiversity. Developing a predictive understanding of the relationship between hydrology and community assembly in restored wetlands has proved

Fig. 7 Changes in species richness by functional group 2000 to 2019



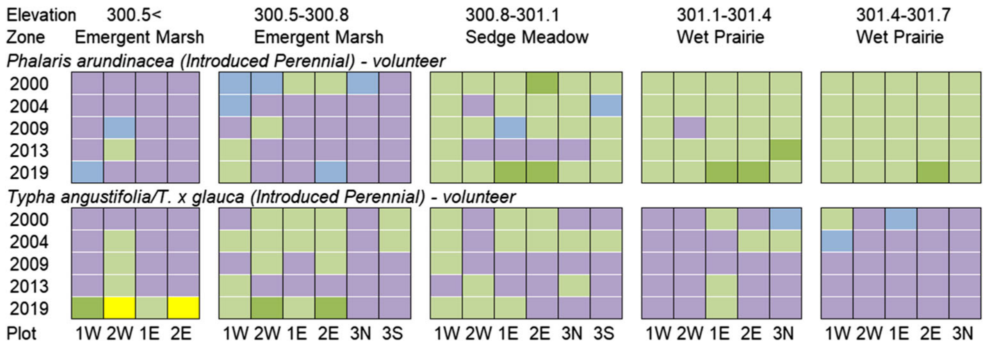


Fig. 8 Cover and distribution of *Phalaris arundinacea* and *Typha angustifolia/T. X glauca*, two invasive wetland perennials that are regularly managed in SPM. Each of the five sets of larger boxes represents zones: EM-2 elevations, SM- 1 elevation, and WP- 2 elevations. Sampling years are represented on the vertical-axis for each species. The 26 plots are represented on the horizontal axis. Covers by plot are represented for the five sampling periods (small boxes). The key to the cover classes is shown below. *Note: Same scale as* Fig. 5

challenging elsewhere, although it is seldom attempted (Sueltenfuss and Cooper 2019). From 1997 to 2009, monitoring data were adequate to relate general changes in vegetation to inundation depth and duration (Table 1). Fluctuations in hydrology over the duration of the restoration resulted in shifts in the plant community that were detected in the floristic surveys and were documented in photo point images taken annually. During this period, site water levels were regularly managed but not using a specific prescription. Consequently, it was not possible to confidently relate changes in hydrologic management to a vegetation response and to refine the prescription over time. Since 2009, only a coarse assessment has been possible; records kept by site managers have been too incomplete to serve as a reliable documentation of actions or to develop technical guidance as recommended by other teams successfully using AM to manage restored wetlands (LoSchiavo et al. 2013). However, during this period monitoring has revealed when inadequate timeliness of water-level management actions have resulted in prolonged high water and emergent-vegetation dieback (2012–2013) or a failure in the outlet structure causing water levels to recede at a greater than expected rate (2018–2019).

Adaptive management in response to monitoring has been most fully operative at SPM for invasive-species management, with clear goals, a conceptual model, and a decision framework (Thom 2000). The goals of monitoring for invasive species were specific from the onset of the restoration: keep all established invasive species below 1% cover and eradicate all newly colonizing invasive species. Generating spatially comprehensive information through formal monitoring every 4 to 6 years, along with evidence of trends in established invasive species (Fig. 8) and locations of newly colonizing invasive species (e.g., *Phellodendron amurense* in 2019) has been useful for adjusting and targeting invasive

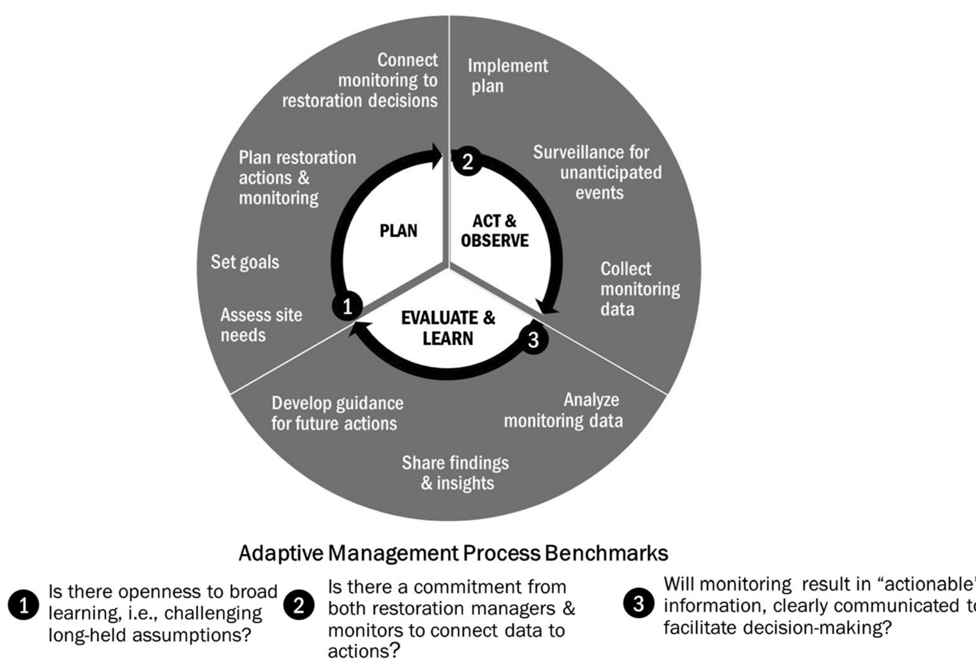


Fig. 9 Adaptive management cycle and benchmarks that should be evaluated prior to the next phase of the cycle. These benchmarks are intended to ensure adaptive management can result in both "single-loop" learning, i.e., improving existing practices, and "double-loop" learning, i.e., challenging existing practices and exploring alternatives (Fabricius and Cundill 2014)

species control efforts. Informal monitoring or scouting by the site manager occurs annually to further guide management efforts. The connection between monitoring and management has facilitated a response to the establishment of three invasive woody species (*Lonicera tatarica* 2009, *Acer ginnala* 2019, *Phellodendron amurense* 2019). However, the spread of invasive species (*Phalaris* and *Typha*) between 2013 and 2019, with 38% of the plots exceeding the 1% threshold, suggests that the monitoring protocol or coordination process needs improvement. The frequency of formal monitoring/evaluation may need to be increased, the scouting protocol may need to be formalized, or the extent to which management is being implemented may require additional tracking. For the first 13 years, the monitoring data were generated and used by the same individuals. In the last ten years, coordination meetings to share monitoring data with the management team are relied on to initiate a cycle of evaluation of site conditions, followed by actions focused on strategic needs. Annual incidental site visits by the research team, with sporadic communication to managers, occurs at SPM, but its influence on management may be limited. The minimal necessary frequency of monitoring and AM cycles may be a function of ecological and social factors. Vegetation change in prairie-pothole wetlands like SPM can occur rapidly in response to disturbances, particularly drawdowns, prolonged inundation, or muskrat herbivory (van der Valk 1989). Commitments to agreed-upon arrangements during coordination meetings can fade over time, with staff turnover or changes in competing management demands. Our experience bears out common governance challenges reported for AM, notably weak organizational understanding of adaptive management and lack of buy-in within the organization (Fabricius and Cundill 2014).

In contrast to invasive-species management at SPM, specific targets intended to trigger action were not established a priori for native vegetation. The revegetation approach for SPM relied on planting and seeding to overcome colonization barriers (i.e., lack of propagule availability from seed banks and dispersal) but then allowed site conditions to determine plant-community composition over time. Consequently, monitoring primarily has, thus far, been used to document but not direct change or refine our conceptual model of the SPM system. Through monitoring, we were able to observe the upward migration of species in response to higher-than-anticipated water levels and the predictable expansion of strongly rhizomatous species (*Carex lacustris, Sparganium eurycarpum, Calamagrostis canadensis*). Propagules of many seeded species were able to disperse to locations that were more optimal for establishment after the hydrology was restored because the seed was broadcast on the surface. Species seeded in the sedge meadow (e.g., *Carex cristatella* and *Scirpus atrovirens*) had dispersed and established at higher elevations, albeit with low cover (Fig. 5). Our monitoring data indicated that a high proportion of species installed (86%) had survived the adjustment to the unplanned water regime. More revealing, though, has been the high interannual variability of some species not apparently connected to changes in site conditions. Taken together, the changes in native vegetation documented at SPM confirm that the project has achieved the goal to re-establish a full complement of vegetation communities, including wet prairie, sedge meadow and shallow emergent marsh. Cover and distribution of native species over extended time frames are highly affected by hydrological change, but managed high-quality wetlands can withstand at least moderate levels of hydrological disturbance. SPM has redeveloped some resilience, with a well-established seed bank and large stands of rhizomatous species which buffer the flora from changes in hydrology that might impact lower quality wetlands more. The site has largely sustained a cover of native species through the shifts in hydrology over its 23-year existence.

The long-term documentation of vegetation change at SPM also illustrates how a project can boost native plant colonization through active revegetation while not managing for highly prescriptive restoration targets. The species richness of unplanted prairie potholes wetlands of comparable age (19 years) is approximately half of that observed at SPM (Aronson and Galatowitsch 2008). Although the number of colonizing species (139) exceeds the number seeded or planted (112), nearly half of those were non-native and very few of the natives were graminoid perennials (5), an important functional group for sedge meadow and wet prairie.

Species loss over time may indicate a quasi-equilibrium in species richness due to competition during vegetation community development (Mouquet et al. 2003). However, species loss, particularly soon after reflooding, may also suggest possibilities for additional species introductions, now that SPM's hydrology is better understood and native vegetation is well-established. The original species list was somewhat opportunistic, consisting of species that were readily available and easily collected in local wetlands. If ongoing management can be counted on to maintain invasive species at low cover, then there may be opportunities to find niches for some species that are typical of high-quality local wetlands and introduce them. Monitoring data over the years has increased understanding of SPM hydrological cycles and how they might particularly affect native annuals and short-lived perennials. With this information, hydrology could be managed to facilitate establishment of a suite of species adapted to periodic drawdowns. Monitoring data also could be utilized to track microniches created by herbivory or microtopography created by muskrat burrowing or old muskrat lodges, where suitable species could be introduced (Diamond et al. 2021; Larkin et al. 2006; Peach and Zedler 2006).

Although the implementation of the SPM restoration was guided by a detailed plan covering revegetation, changes to hydrology, and visitor infrastructure, plans for monitoring and AM initially were considered only at a strategic level prior to project initiation. Durable monuments were designed and installed with the intention of being useful for repeated observations of a broad array of parameters, both biotic and environmental. An AM plan for SPM optimally would have articulated plausible decision scenarios, based on consensus on management options and consequences and key uncertainties in the project team's understanding of the site (e.g., optimizing water level management) (Gregory et al. 2012; LoSchiavo et al. 2013). The SPM team considered that monitoring would provide useful information for decision-making but did not develop a written operational monitoring plan that a priori identified key evidence or thresholds that would trigger action or a change in current practices. Best practice for AM based on the Everglades restoration initiative suggests decision frameworks are useful tools for linking monitoring to thresholds for management options (LoSchiavo et al. 2013; Nie and Schultz 2011; Nie and Schultz 2012).

Formalizing a monitoring plan of this scope and detail for SPM would have triggered assigning responsibilities and securing commitments not only for regular data collection but for a process whereby site managers used the data to make decisions about water and vegetation management (Fig. 9, Failing et al. 2013). In this way, formulating a monitoring plan can be a mechanism to build adaptive capacity (i.e., organizational resilience) of a restoration team, "the capacity of a team to change before the need for change is obvious" (Hamel and Valikangas 2003). Fundamentally, AM needs to be pursued as a social process (Fabricius and Cundill 2014). Attempting to change how an organization approaches a restoration is likely much easier during project planning (vs. later) when resources and expectations are at their highest (Thom 2000). Had the SPM team developed such a plan at the onset of the project, we anticipate that water-level management, in particular, would be less ad hoc, and that with changes in staffing arrangements over time, we may have achieved more consistent follow-through on invasive-species control. Nonetheless, the monitoring and AM procedures that have been used at SPM are likely creating a level of accountability for invasive-species management that would not exist if vegetation changes were not being systematically monitored and shared. While it is not surprising that written monitoring/AM plans were not the norm 25 years ago, it is surprising that they have not yet become a standard of practice and remain rare today.

It may be that the value proposition of monitoring and AM to organizations undertaking restoration is seldom sufficient to motivate essential commitments for ongoing, decision-oriented data collection, for ongoing management and for monitoring and management to be operationally linked. Regardless of prospects to improve restoration practice more broadly, monitoring and AM for an individual project is not feasible without these three components. For small, individual projects like SPM it may be difficult to justify systematic monitoring if there is no plan or commitment for regular, or at least periodic management. The value of the information gathered at SPM mostly benefits the ongoing management of this restoration–whether invasive species control is needed or water level management needs adjusting. SPM's location within an arboretum predisposes it to ongoing management since land management staff are part of the organization and the site has high public visibility. Information from monitoring has helped keep the management needs of SPM on the agenda of an organization whose staff's primary responsibilities are intensive tending of formal gardens. The prospect of ongoing management for a small restoration was sufficiently novel to sustain the commitment of scientists to monitor SPM, even when funds were lacking. That, too, was an organizational predisposition, since the arboretum is part of a university. Generalizable knowledge for improving practice for similar, future wetland restorations is only possible if comparable data from many projects are compiled and analyzed. This requires that the organization funding a restoration is interested in the fate of the project after the grant ends to the extent it establishes monitoring as an expectation and coordinates data acquisition and management (Galatowitsch and Bohnen 2020). For some restoration programs, like the one that funded SPM (Environment and Natural Resources Trust Fund), taking on the responsibilities and costs of data management is beyond its legislated scope. However, organizations that manage large portfolios of land, with many projects, may have the scale and structure to more fully benefit from AM because it can bring to bear data from past restoration efforts to inform proposed projects.

Lack of adoption of AM is frequently linked to a lack of resources, especially for sustaining monitoring programs after initial, typically short-term, project funding has ended (Westgate et al. 2013). Given this common concern, monitoring programs need to be efficient and not strongly compete for staff time, even though early detection of problems and improving decision-making should reduce risks of costly interventions. For invasive species, SPM meander surveys conducted every few years have allowed managers to respond to colonizations of newly arriving species that may otherwise have escaped detection. The SPM case does, however, also highlight that the frequency of monitoring and evaluation can have a strong effect on whether information has the desired management influence. Further, SPM demonstrates the importance of information generated from systematic monitoring (vs casual observations) not connected to formal experiments (i.e., active AM). Systematic observations of native plant distributions over time provided timely evidence of upward migration of species in response to persistently greater inundation than anticipated. SPM revealed the challenges of holding together a monitoring and AM system, even in an organizational context reasonably well-suited to it. At the project scale, SPM highlights the importance of investing in developing monitoring plans to formalize linkages between monitors and managers. For restoration science and practice more generally, SPM demonstrates the need to seek and support new organizational models that allow AM to function collectively, across many individual efforts, many of which are not especially large or well-funded for the long-term.

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Authors Contributions SM Galatowitsch and JL Bohnen both contributed to the establishment and implementation of the research, analysis of results, writing of paper.

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Data Availability Monitoring data are available upon request to corresponding author.

Code Availability N/A

Declarations

Ethics Approval N/A

Consent for Publication N/A

Consent to Participate N/A

Conflicts of Interest/Competing Interests N/A

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