Status and Trends of Wetlands and Deepwater in Minnesota: 2006 to 2020

DEPARTMENT OF NATURAL RESOURCES

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Cover photo: A fen (a type of emergent wetland) at Maplewood State Park. Photograph by A. Kendig.

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Contents

Abstract

Wetlands provide essential functions for humans and wildlife, but wetland area can be lost through draining, filling, excavating, or drought. Following the loss of approximately half of Minnesota's historical wetland area, Minnesota's Wetland Conservation Act set the goal of no net loss of wetlands beginning in 1991. To track the state's adherence to this goal, the Minnesota Department of Natural Resources established the Wetlands Status and Trends Monitoring Program beginning in 2006. Here, we report the changes in wetland and deepwater area between 2006 and 2020 using aerial photography of 3750 plots placed randomly throughout the state and revisited every three years. Over this time, Minnesota experienced a net gain of 43,389 acres of wetland and deepwater, with the greatest gains occurring recently (2015-2020). Most of the area gained and lost was in emergent wetlands and the greatest source of wetland and deepwater area was agricultural land. Over 100,000 acres of forested wetland transitioned to emergent or scrub-shrub wetland, ~19% of which is projected to return to forested wetland. Direct drivers of wetland change explained 39%-82% of wetland gains and 88%-100% of wetland losses while indirect drivers explained the remainder. Wetland gains due to direct drivers are associated with greater precipitation. Minnesota is achieving its goal of no net loss of wetland quantity. Yet, some wetland functions that may be lost with declines in wetland classes, such as forested wetlands, may not be replaced completely through gains in wetland area.

A poor fen (at type of emergent wetland) in Chippewa National Forest. Photograph by A. Kendig.

Introduction

Wetlands sit at the intersection of terrestrial and aquatic environments, providing unique habitats and a suite of ecosystem functions that are valued by society (Keddy et al. 2009). For example, wetlands in Minnesota are breeding habitats for waterfowl and amphibians (Swanson and Duebbert 1989, Hecnar 2004), and some of Minnesota's rarest flora and fauna are associated with wetland habitats (MN DNR 2022a). Peatlands across Minnesota serve as important carbon storage (Weishampel et al. 2009, Chaudhary et al. 2020) and wetland floodplains help stabilize river hydrology and mitigate flood impacts (Hey and Philippi 1995, Riedel et al. 2005). Wetlands can also help control nutrient pollution (Hansen et al. 2018, Boardman et al. 2019). Approximately 25% of Minnesota is covered by wetlands and deepwater (Kloiber 2010).

European settlement and the intensification of agriculture drove the removal of approximately 6.37 million acres of wetland in Minnesota by the 1980's (Dahl 1990, Rhemtulla et al. 2007). In more recent decades, Minnesota lost wetlands and lakes from its prairie pothole region (western and southwestern portions of the state) (Genet and Olsen 2008, Oslund et al. 2010, Dahl 2014). This historical and ongoing loss of wetland area prompted the creation of Minnesota's Wetland Conservation Act (WCA) of 1991, which aims to maximize the quantity, quality, and biological diversity of Minnesota's wetlands through "no net loss", restoration and enhancement, avoiding impacts, and replacing wetland values upon impact (Minnesota Administrative Rule 8420.0110 Subpart 1).

The Minnesota Department of Natural Resources (DNR) established the Wetlands Status and Trends Monitoring Program (WSTMP) in 2006 to evaluate the achievement of WCA goals (Kloiber 2010, Kloiber and Norris 2013, 2017). This program is modeled after the federal Wetland Status and Trends project, which is led by the U.S. Fish and Wildlife Service (USFWS 2023). Here, we present the results from WSTMP from 2006 to 2020.

Methods

Study design

We evaluated changes in land cover for 3,750 one-square-mile (640 acre) plots located randomly throughout Minnesota. Plot locations were selected with a generalized random tessellation stratified (GRTS) design (Stevens and Olsen 2004). GRTS designs achieve randomness and spatial balance over the sample frame, which in this case was the state of Minnesota. Plots were divided into three panels, each of which was surveyed once every three years beginning in 2006. Five cycles of three-year samples were completed between 2006 and 2020. The original sample size for WSTMP was 4,990 plots, which included a fourth panel that was sampled annually (Kloiber 2010). Data were collected from all 4,990 plots through 2017 before budget limitations required reducing the sample size. In 2016, a power analysis was performed to evaluate potential sample sizes using wetland change data from the first three cycles. Power was calculated as the proportion of p-values of Wilcoxon signed rank tests that were less than 0.05 from 1000 samples of the dataset with replacement. A new sample size of 3,750 plots was chosen, and plots were removed in the reverse order of the GRTS design, which maintained the randomness and spatial balance of the remaining plots. Here, we report results from only the

3,750 plots for all cycles. Change analyses for 2006 to 2011 (Kloiber and Norris 2013) and 2006 to 2014 (Kloiber and Norris 2017) using 4,990 plots were previously reported.

Data collection

We obtained aerial imagery of each plot by flying aircrafts at approximately 6,700 ft altitude during spring (snow-free and leaf-off). For the baseline imagery, we used 645-format, true-color film (41 x 56 mm frame size), which was subsequently scanned at 2,400 dots per inch and georeferenced to create a digital image with a ground sampling resolution of approximately two feet (Kloiber 2010, Kloiber et al. 2012). For subsequent imagery, we used a digital, 50 mm Phase One camera with a resolution of 100 megapixels, approximately 7" ground resolution. Stereo images obtained for the baseline (2006-2008) were mapped by land cover and classified into six wetland classes (forested, scrub-shrub, emergent, aquatic bed, unconsolidated bottom, or cultivated), six upland classes (urban, rural development, agricultural, natural, silviculture, other), deepwater, or artificially flooded wetland (Table 1). We used additional imagery, such as fall leaf-color imagery collected by the MN DNR, to help classify wetlands. Man-made wetlands (i.e., where water was intentionally detained or exposed through excavation, damming, berms, etc.) were indicated as such but were included with natural wetlands of the same class in the analyses presented here.

To quantify changes in wetland area, images of each cycle were compared to the images and mapped areas from the previous cycle. Where wetlands expanded or were created, new polygons were created that had the wetland attribute for the most recent cycle, but also retained the non-wetland attribute for the previous cycles. Where wetlands contracted or were lost, new polygons were created with the applicable non-wetland attribute for the most recent cycle, but also retained the original wetland attribute from the previous cycles. After the baseline mapping, only changes in wetland and deepwater area were tracked (gains and losses in both). We assessed whether changes to or from wetland or deepwater were caused by "direct" or "indirect" drivers, where direct drivers could be identified using the imagery, such as a new road, a drainage structure, beaver activity, or a change in agricultural practices, and indirect drivers could not. When classification errors from previous cycles were identified, we corrected the prior classifications. Field verification of the baseline dataset demonstrated that wetlands were correctly distinguished from non-wetland 94% of the time and wetlands were correctly classified 89% of the time (Kloiber 2010).

Because we were unable to collect aerial imagery in spring 2020 due to the Covid-19 pandemic, we used alternative imagery sources. We used imagery collected by other organizations or we collected imagery at different times for plots that were not 100% deepwater, which we omitted due to negligible temporal changes. We used 2019-2021 DigitalGlobe satellite imagery of 698 plots, 2019 and 2021 USDA National Agriculture Imagery Program (NAIP) aerial imagery for 84 plots, and we collected imagery in fall 2019 of 68 plots, in fall 2020 of 12 plots, in spring 2021 of 368 plots, and in spring 2022 of one plot. The DigitalGlobe imagery was collected between April and October, and imagery for approximately 459 plots was obtained between mid-April and the end of May, when we normally collect data. USDA NAIP imagery was collected between June and August.

Table 1: Land cover classes used to classify polygons in WSTMP (adapted from Kloiber et al. 2012, Kloiber and Norris 2013).

System	Class	Description
wetland	aquatic bed (AB)	>30% cover of floating or submerged vegetation most of the growing season
	Cultivated (CW)	ineffectively drained wetland in actively cultivated fields with flooding >7 days
	Emergent (EM)	>30% cover of erect, rooted herbaceous vegetation most of the growing season (e.g., marshes, wet meadows, fens, some open bogs)
	Forested (FO)	>30% cover of trees or shrubs >20 ft tall (e.g., floodplain forests, forested swamps, forested bogs)
	scrub-shrub (SS)	>30% cover of trees or shrubs <20 ft tall (e.g., shrub swamps, some open bogs)
	unconsolidated bottom (UB)	open-water (<30% vegetation cover), <20 acres, <6.6 ft deep at low water, and lacking wave-formed or bedrock shorelines
deepwater	Deepwater (DW)	≥20 acres permanently flooded open water (lakes, rivers, streams), and open-water wetlands with windswept shoreline or >6.6 ft deep at low water
artificially flooded	artificially flooded wetlands (AF)	manipulated water levels (e.g., aquaculture, sewage treatment ponds, wetland treatment systems, mine tailing ponds, swimming pools)
upland	Agricultural (A)	cropland, pasture, orchards, nurseries, farm buildings, and abandoned agriculture that's not maturing toward a natural condition
	Natural (N)	non-managed forested and wooded land, grassland, prairies, long-term fallow lands, and upland conservation lands
	rural development I	human development without street/road network and outside cities/towns (e.g, recreation, mining, commercial/industrial facilities, roads ≥33 ft wide)
	Silviculture (S)	>30% closed canopy wooded land that's managed for wood/wood products
	urban development (U)	cities and towns that have street/road network and a mixture of commercial/industrial, residential, or park areas
	other upland (O)	all uplands not otherwise classified (e.g., barren land, land in transition)

Data analysis

We analyzed all data in R, version 4.2.2 (R Core Team 2022). We estimated statewide areas with the Horvitz-Thompson estimator, where the inclusion probability for each plot (0.044) was the number of plots divided by the area of the sample frame in square miles (84,856). We estimated variance with the local neighborhood variance estimator (Stevens and Olsen 2003), which takes the spatial location of plots into account. We report variance as 95% confidence intervals (hereafter, 95% CI). These estimators were implemented with the *spsurvey* package (Dumelle et al. 2023). For plots on the border of Minnesota, area outside of the state was considered as a separate land cover class that was not included in estimates of total or percentage area. Change in wetland and deepwater area was calculated first as the difference between consecutive monitoring cycles or the first and last monitoring cycles for each plot. Area that transitioned from a non-wetland land cover class to a wetland or deepwater land cover class was considered a “gain”, reverse transitions were considered a “loss”, and the difference between gains and losses were considered a “net” change. Plot-level differences were then extrapolated to the state-level using the estimators described above. Transitions between wetland and deepwater were not considered losses or gains because the same waterbody can include both deepwater and wetland, and changes in area between the two can be considerable due to annual variation in weather (Kloiber et al. 2012). We similarly estimated areas for each of four ecological provinces as defined by MN DNR’s Ecological Classification System (MN DNR 2023). Because the provinces were not used to stratify the samples, samples sizes vary by province and are reported. The three monitoring panels are similarly represented within each province (Table S1), where unequal representation may cause bias in province-scale estimates due to temporal variation in wetland and deepwater area.

We evaluated changes in wetland area due to precipitation. Precipitation data were obtained for each plot in each month using the *prism* package in R (Hart and Bell 2015). PRISM climate data are spatially continuous modeled estimates of weather metrics, such as the monthly total precipitation used here. We summed monthly precipitation totals (rain + melted snow) between consecutive monitoring periods, starting with July and ending in March. For example, the cumulative precipitation for the consecutive monitoring periods of 2006 and 2009 (i.e., panel one in monitoring cycles one and two) included July 2006 through March 2009. We fit two generalized linear mixed-effect models using the *glmmTMB* package in R (Brooks et al. 2017). In the first model, the response variable was a binary indicator for whether a plot had gained wetland or deepwater area between each consecutive monitoring period and in association with each type of driver (direct/indirect). Because we did not want to include plots where gains in wetland or deepwater area were not possible, we only included plots where a gain of any size and any driver had been observed at least once over the study. Each plot was replicated eight times within the dataset (two driver types by four consecutive monitoring periods). The explanatory variables in the model were cumulative precipitation, driver type, and their interaction. There was a random intercept for plot and the response distribution was binomial. Model fit was assessed using residual diagnostic plots with the *DHARMa* package (Hartig 2022). In the second model, we repeated this same process for losses of wetland or deepwater area.

Results

Wetland distribution and classes

Most statewide surveyed area was upland, followed by wetland, deepwater, and artificially flooded wetland (Table 2). Most wetland and deepwater is concentrated in the Laurentian Mixed Forest Province (LMF, Fig. 1), where these waterbodies make up nearly 41% of the province's area (Table 2). The Eastern Broadleaf Forest Province (EBF) contains the second largest area of wetland and deepwater, followed closely by the Prairie Parkland Province (PP). Despite having the smallest total area of wetland and deepwater of all the provinces, nearly a quarter of the Tallgrass Aspen Parklands Province (TAP) is composed of these waterbodies (Table 2).

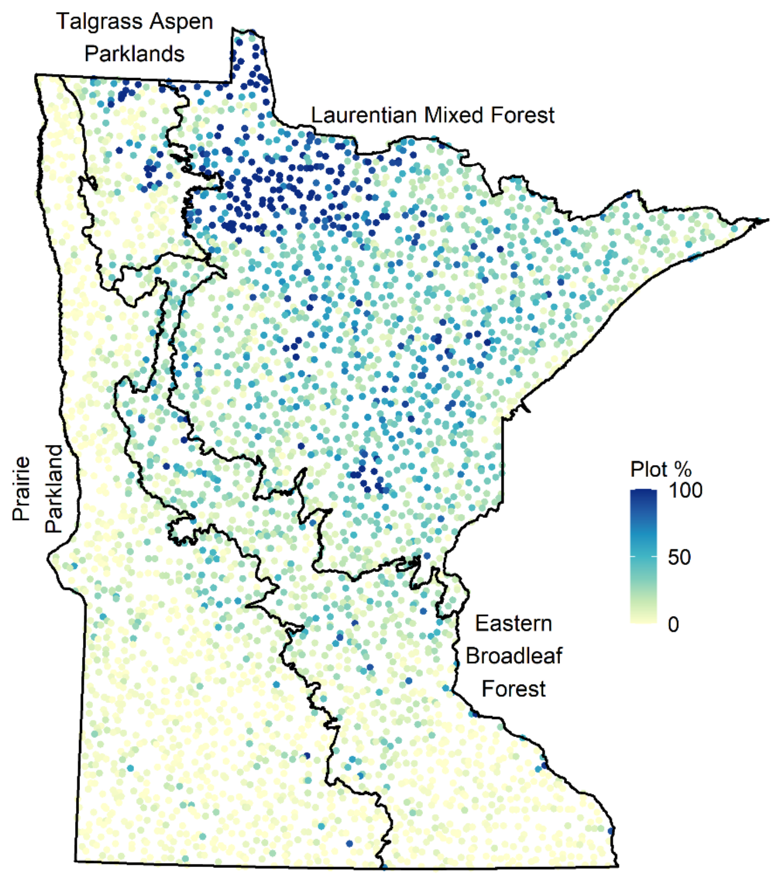

Figure 1: The percentage of plot area with wetland or deepwater for each sample plot in the 2018-2020 monitoring cycle.

Table 2: Estimated statewide or province area in thousands of acres (with 95% CI) and percentage of statewide/province total area for four land systems during the 2018-2020 monitoring cycle.

	Upland		Wetland		Deepwater		Artificially flooded	
Scale	**Acres (95% CI)**	**%**	**Acres (95% CI)**	**%**	**Acres (95% CI)**	**%**	**Acres (95% CI)**	**%**
statewide	40,888 (40,634–41,142)	75.68	10,653 (10,432–10,874)	19.72	2,453 (2,288–2,618)	4.54	36 (7–65)	0.07
PP	14,902 (14,812–14,993)	92.97	921 (861–981)	5.75	205 (161–248)	1.28	2 (1–3)	0.01
TAP	2,219 (2,141–2,298)	76.97	640 (564–715)	22.18	8 (5–11)	0.28	16 (-8–41)	0.57
EBF	10,100 (9,994–10,205)	84.43	1,485 (1,403–1,567)	12.41	376 (307–444)	3.14	3 (0–5)	0.02
LMF	13,667 (13,469–13,865)	59.02	7,608 (7,426–7,790)	32.86	1,864 (1,721–2,008)	8.05	16 (-1–32)	0.07

In the 2018-2020 monitoring cycle, forested wetlands comprised the largest statewide area of wetlands, approximately four million acres, followed by emergent, deepwater, and scrub-shrub (Fig. 2, Table S2). Unconsolidated bottom, aquatic bed, and cultivated wetlands comprised the smallest statewide areas. For all wetland/deepwater classes except cultivated wetland, the largest areas were in the LMF province. The largest area of cultivated wetland was in the PP province. The most common wetland class in the LMF province was forested wetlands and the most common class in the PP, TAP, and EBF provinces was emergent wetland. The second most common wetland class in the PP and EBF provinces was deepwater while the second most common class in the LMF and TAP provinces was scrub-shrub.

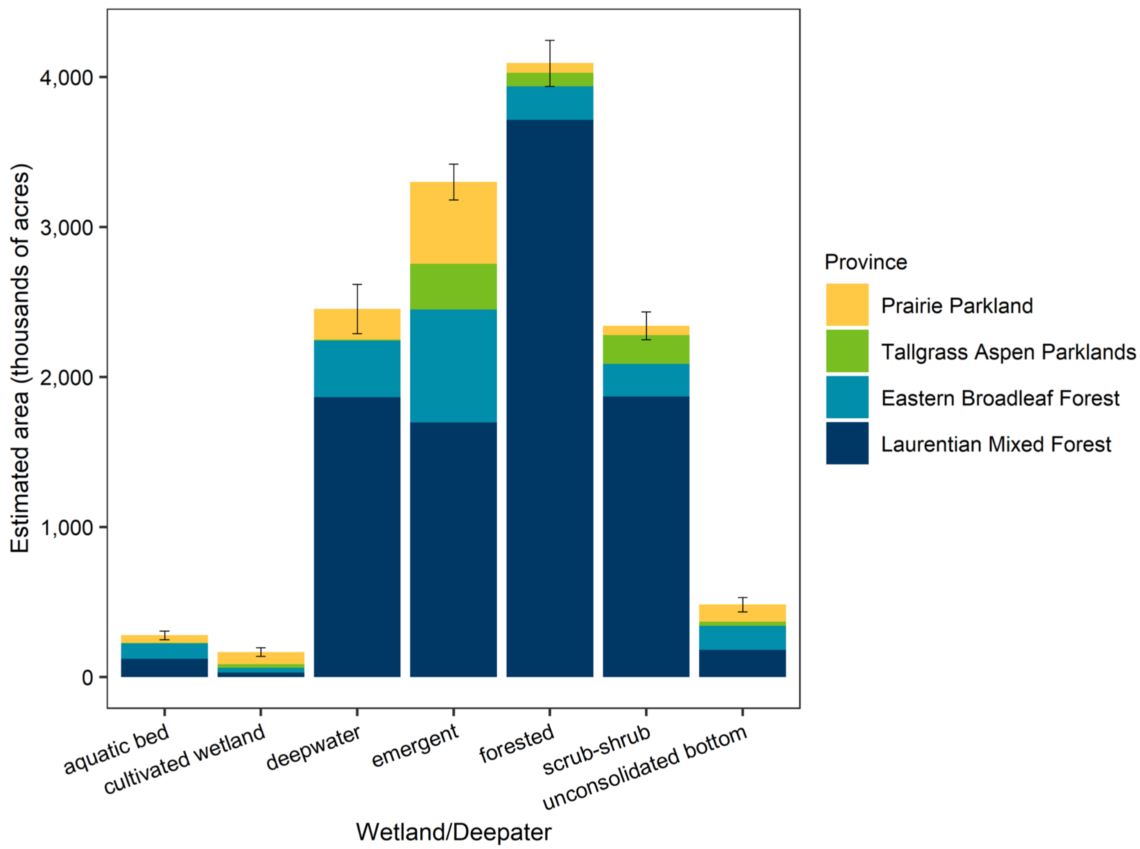

Figure 2: Estimated statewide area and 95% CI in thousands of acres of each wetland/deepwater class in the 2018-2020 monitoring period. Bars are comprised of estimated area for each province. Values are in Table S2.

Overall wetland change

Between the first and fifth monitoring cycles, Minnesota gained an estimated 50,737 (95% CI: 38,961–62,513) acres of wetland and deepwater, which was 0.39% (95% CI: 0.30%–0.48%) of wetland/deepwater area in the first monitoring cycle. Minnesota lost an estimated 7,348 (95% CI: 5,127–9,570) acres of wetland and deepwater, which was 0.06% (95% CI: 0.04%–0.07%) of initial wetland/deepwater area. Therefore, Minnesota experienced an estimated net gain of 43,389 (95% CI: 31,445–55,333) acres of wetland and deepwater (0.33%, 95% CI: 0.24%–0.42%, of initial wetland/deepwater area).

Gains exceeded losses in each of the ecological provinces (Fig. 3-4). The PP province had the greatest net gain in wetland/deepwater area, with ~19,200 acres (Fig. 4, Table S3). There was a net gain of ~29,300 acres of emergent wetlands statewide. Unconsolidated bottom wetlands had the second largest change with a net gain of ~10,200 acres. Cultivated wetlands increased ~2,600 acres, mostly in the PP and EBF provinces. All other classes had net gains less than 1,000 acres. Smaller sample sizes in the TAP province led to greater uncertainty around change estimates.

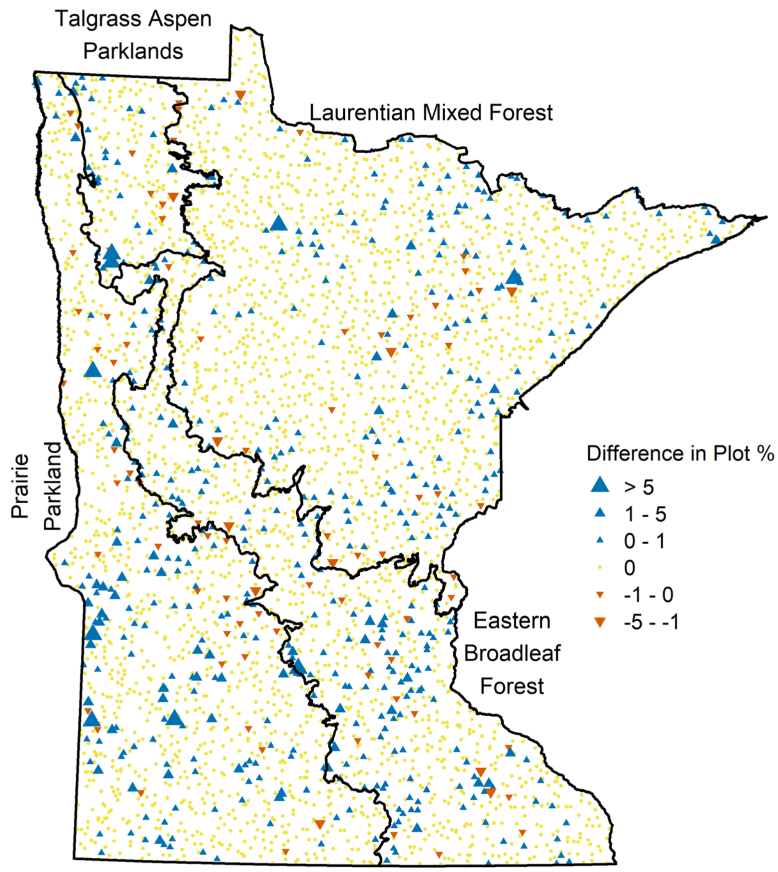

Figure 3: Change in wetland and deepwater area to or from upland and artificially flooded wetland between the first and fifth monitoring cycles (final % plot area – initial % plot area).

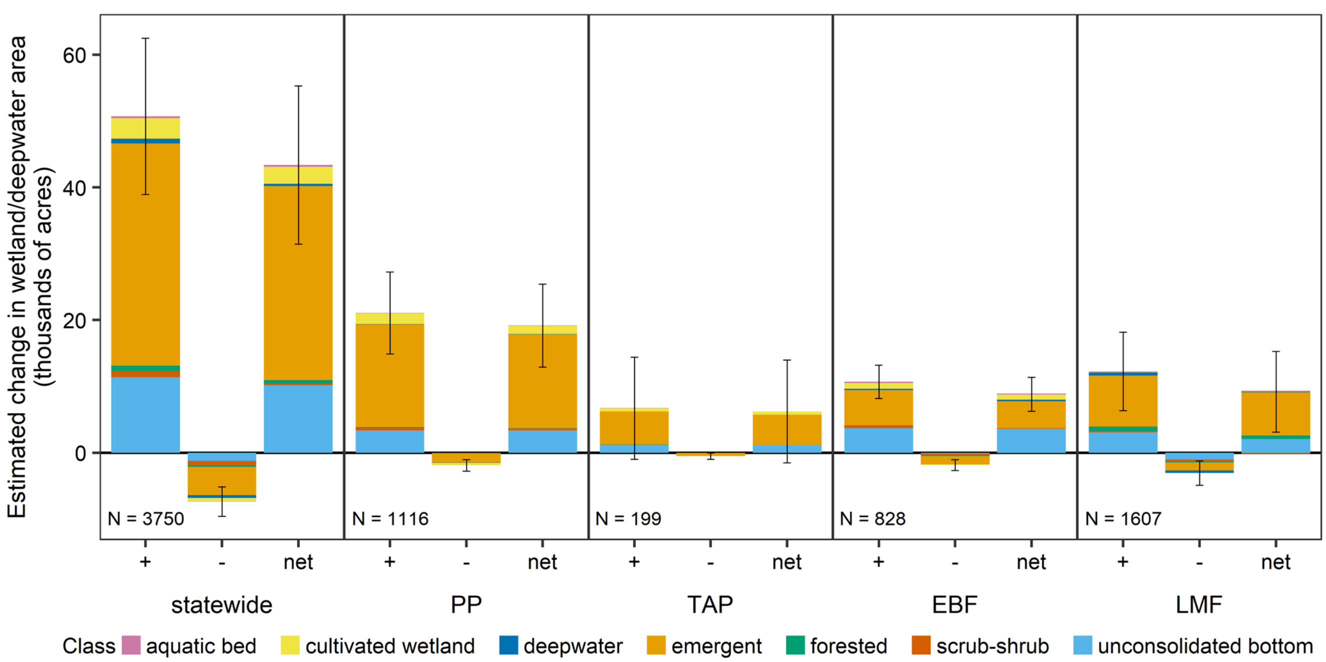

Figure 4: Gain, loss, and net change in wetland/deepwater area for the state and each province between the first and fifth monitoring cycles, color-coded by wetland/deepwater class. Error bars represent 95% CI for the total gains, losses, and net changes. N is the sample size. Values are in Table S3.

The primary source of wetlands and deepwater statewide was agricultural land, with a net gain of ~24,700 across the PP, TAP, and EBF provinces (Fig. 5, Table S4). Natural upland was a secondary source of wetlands and deepwater in these provinces and the primary source in the LMF (net gain: ~12,400 acres). Most of the wetland and deepwater area lost in the state became agricultural land or rural development. The largest losses to agricultural land were in the PP province while the largest losses to rural development were in the LMF province.

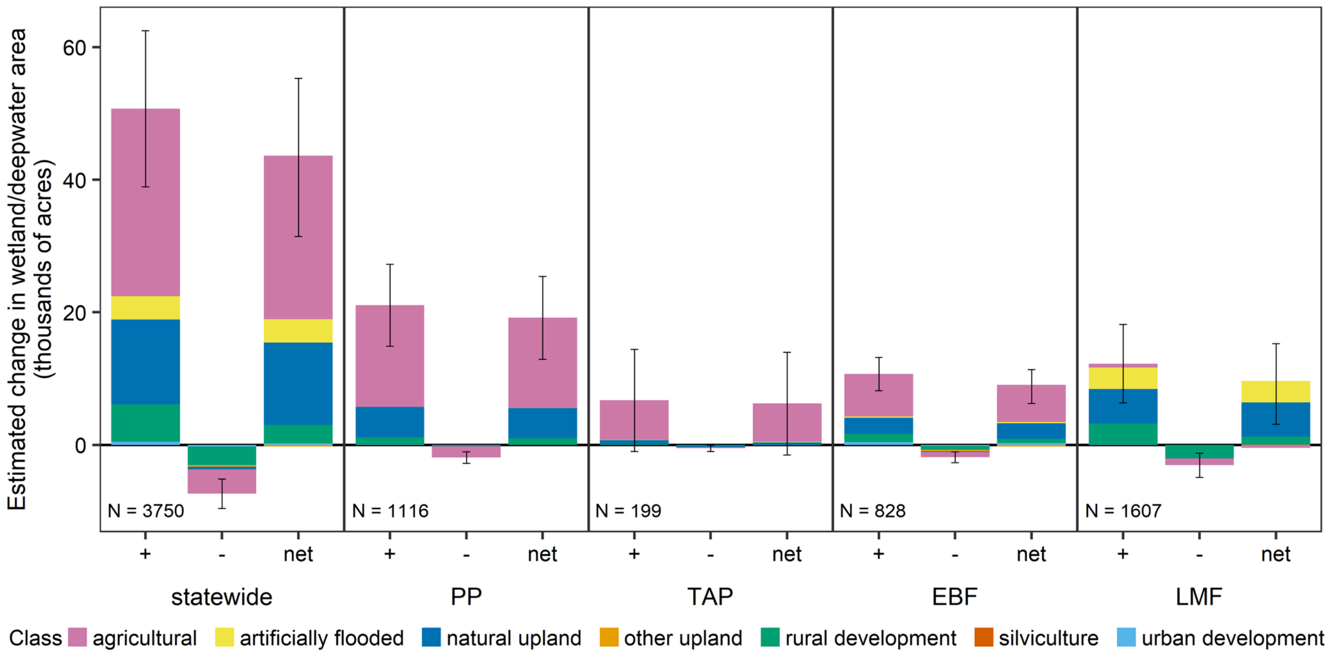

Figure 5: Gain, loss, and net change in wetland/deepwater area for the state and each province between the first and fifth monitoring cycles, color-coded by the non-wetland class that became wetland/deepwater (gains) or that wetland/deepwater became (losses). Error bars represent 95% CI for the total gains, losses, and net changes, which are the same as the values in Fig. 4. N is the sample size. Values are in Table S4.

Rate of wetland change

Wetland/deepwater gains exceeded losses across all four consecutive monitoring cycles (Fig. 6, Table S5). In addition, wetland/deepwater losses have been generally declining over time. Between the first (2006-2008) and second (2009-2011) monitoring cycles, Minnesota lost an estimated 2,506 (95% CI: 1,150–3,863) acres of wetland/deepwater. Between these cycles, forested wetlands, scrub-shrub wetlands, and deepwater had net losses. The greatest wetland/deepwater loss occurred between the second (2009-2011) and third (2012-2014) cycles (3,327 acres, 95% CI: 2,173–4,481). Emergent and unconsolidated bottom wetlands accounted for the largest losses but gains in both wetland classes offset losses. Between the third (2012-2014) and fourth (2015-2017) cycles, Minnesota lost an estimated 1,485 (95% CI: 716–2,253) acres. Emergent and unconsolidated bottom wetlands had net gains and forested and scrub-shrub wetlands had net losses. The greatest gain occurred between the fourth (2015-2017) and fifth (2018-2020) cycles. Minnesota gained an estimated 27,029 (95% CI: 19,231–34,828) acres and lost an estimated 1,107 (95% CI: 359–1,856) acres (net change: 25,922, 95% CI: 18,086–33,758). The greatest gains were in emergent and unconsolidated bottom wetlands, both of which had relatively small losses. There were also gains in each of the other wetland classes and deepwater.

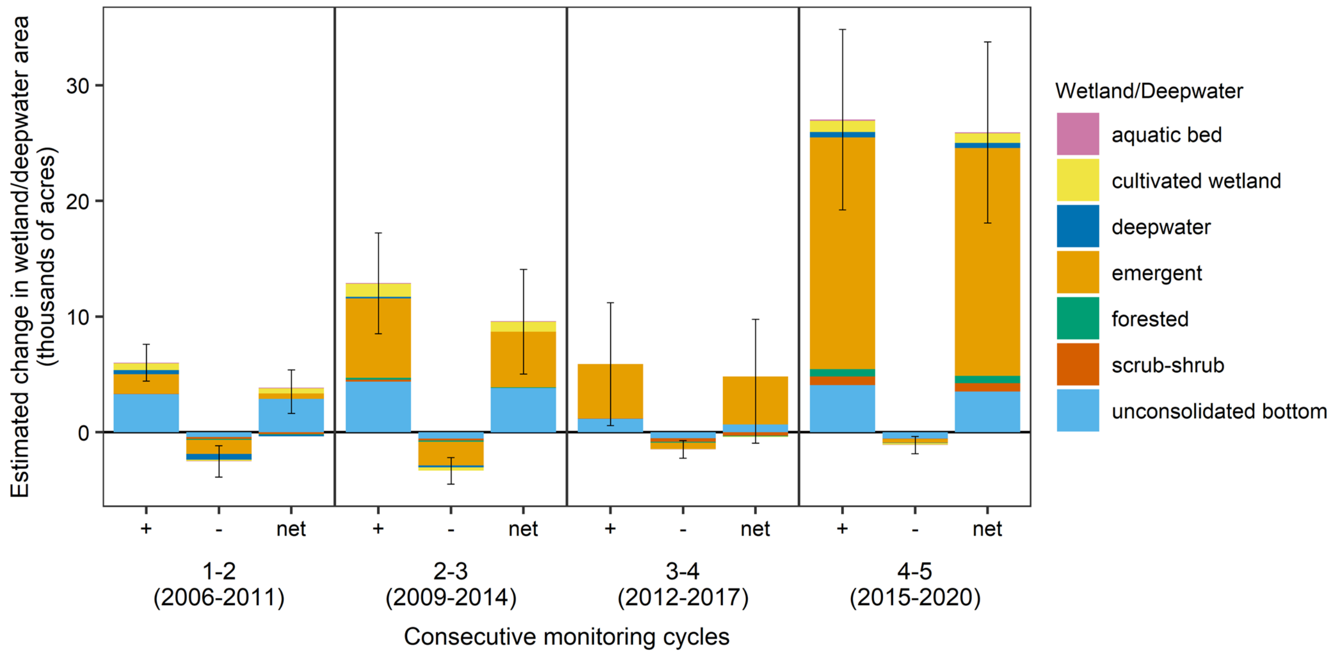

Figure 6: Change in statewide wetland/deepwater area between consecutive monitoring cycles, color-coded by wetland/deepwater class. Error bars represent 95% CI for the total gains, losses, and net changes. Values are in Table S5.

Wetland transitions

The largest observed wetland class change between the first and fifth monitoring periods was from forested wetland to emergent wetland, followed by scrub-shrub wetland to forested wetland and forested wetland to scrub-shrub wetland (Table 3). Transitions among deepwater, aquatic bed wetland, and unconsolidated bottom wetland, which are associated with shifts in water levels, water clarity, and plant growth, were also notable. Emergent wetland had large shifts to and from cultivated wetland, scrub-shrub wetland, and unconsolidated bottom wetland. Agricultural land and natural upland transitioned to all wetland classes and often contributed the largest areas. All wetland classes transitioned to rural development.

The types of wetland and non-wetland transitions that drove change in wetland area between monitoring cycles were relatively consistent. For all consecutive cycle pairs, the largest change among wetland classes was from forested wetland to emergent wetland (Tables S6-S9). For the first two cycle comparisons (1-2 and 2-3), the largest area of wetland lost to non-wetland was emergent wetland to agricultural land (Table S6-S7). For the last two cycle comparisons (3-4 and 4-5), the largest area of wetland lost to non-wetland was unconsolidated bottom wetland to rural development (Tables S8-S9). The largest wetland area gained from non-wetland was agricultural land to emergent wetland in the second and fourth consecutive cycles (Tables S7, S9). From the first to the second cycle, the largest transition from non-wetland to wetland was agricultural land to unconsolidated bottom wetland (Table S6). From the third to the fourth cycle, the largest transition from non-wetland to wetland was artificially flooded wetland to emergent wetland (Table S8).

Table 3: Change in estimated statewide area (acres) of each wetland and non-wetland class between the first (2006-2008) and fifth (2018-2020) monitoring cycles. See Table 1 for abbreviation meanings. Boxes are shaded by area changed with larger values represented by more blue and less yellow colors. Horizontal and vertical lines separate wetland from non-wetland classes. Area that transitioned from one non-wetland class to another (bottom right) is omitted. Total area in thousands of acres for the first and fifth monitoring cycles are in the right column and bottom row, respectively. Transitions between consecutive monitoring periods are in Tables S6-S9.

2018-2020 Cover → 2006-2008 Cover ↓	AB	CW	DW	EM	FO	SS	UB	A	AF	N	O	R	S	U	total (x 1000)
AB	22,8192	8	6,981	4,083	0	9	10,692	1	0	33	0	12	0	0	250
CW	0	137,856	0	13,771	121	1,346	3,200	349	0	0	0	92	0	42	157
DW	17,452	0	2,443,178	7,162	0	80	275	0	0	26	0	390	0	0	2,469
EM	3,432	23,298	1,473	3,127,503	6,612	24,455	21,411	2,573	0	268	230	1,013	0	151	3,212
FO	635	571	237	89,632	4,039,282	37,872	2,242	148	0	0	16	94	0	20	4,171
SS	126	2,012	79	11,436	43,552	2,275,039	1,681	516	0	20	0	115	0	26	2,335
UB	26,239	77	87	11,608	21	83	430,186	56	0	53	0	1,096	0	10	470
A	76	1,782	10	20,882	84	781	4,697	↑ wetland/deepwater gains							
AF	0	0	0	3,510	0	0	7								
N	168	1,265	267	6,902	708	161	3,332								
O	0	0	0	0	0	0	0	← wetland/deepwater gains							
R	78	0	471	2,039	0	0	3,034								
S	0	0	0	11	0	0	0								
U	1	0	0	168	0	0	301								
total (x 1000)	276	167	2,453	3,299	4,090	2,340	481								

Transitions from forested wetland

To evaluate the long-term effects of transitions from forested wetland to emergent or scrub-shrub wetland (Table 3), we examined the subsequent cover types of polygons that underwent these changes (Fig. 7, Table S10). We could track the fate of 112,617 acres over one monitoring period (three years) following forested wetland transition and found that 67% was emergent wetland, 25% became scrub-shrub wetland, and 8% returned to forested wetland. We tracked the fate of 82,355 acres over two monitoring periods (six years) following the forested wetland transition and found that 46% was emergent wetland, 43% was scrub-shrub wetland, and 10% was forested wetland. Finally, we tracked the fate of 43,505 acres over three monitoring periods (nine years) following the forested wetland transition and found that 31% was emergent wetland, 49% was scrub-shrub wetland, and 19% was forested wetland. For the wetland area we could track for nine years, the transition to forested wetland occurred primarily in the first three years and the transition to scrub-shrub wetland occurred in the first three to six years. Small fractions became agricultural land, aquatic bed wetland, cultivated wetland, unconsolidated bottom wetland, and urban development.

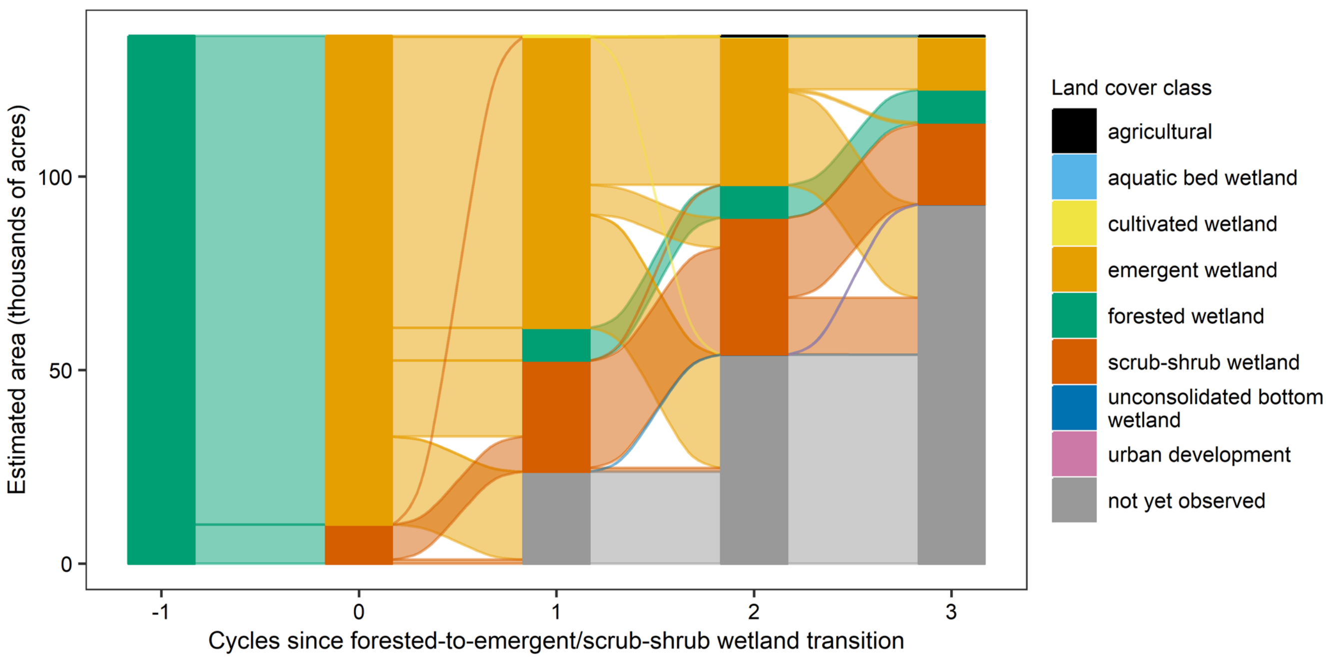

Figure 7: Wetland area that underwent a transition from forested wetland to emergent or scrub-shrub wetland. Bars represent estimated statewide area in the cycles during and after the transitions, where all area considered started as forested wetland (cycle -1), then became emergent or scrub-shrub wetland (cycle 0), and then remained in those classes or became other land cover classes (cycles 1-3). Ribbons represent the area that shifted from a given class in one cycle to the same or a different class in the next cycle. Ribbons are partially transparent and colored by the preceding land cover class. When area is categorized as “not yet observed”, the forested wetland transition occurred more recently, so we do not yet have data on the first, second, or third cycle past this transition. Values are in Table S10.

Drivers of wetland change

More wetland and deepwater changes were due to direct than indirect drivers (Fig. 8, Table S11). The largest changes in area due to direct or indirect drivers were consistently in emergent and unconsolidated bottom wetlands. The role of direct and indirect drivers in the other wetland classes shifted over time. For example, relatively large gains in cultivated wetlands occurred due to direct drivers in the second and fourth consecutive monitoring cycles (cycles 2-3 and 4-5), but due to indirect drivers between the first and second cycles. Between the fourth and fifth cycles, the gains in scrub-shrub wetland were due to direct drivers more than indirect, while the gains in forest wetland were due to indirect drivers more than direct. Direct drivers 17explained 69%, 67%, 39%, and 82% of wetland gains in the first, second, third, and fourth consecutive cycles, respectively. Indirect drivers explained 31%, 33%, 61%, and 18% of wetland gains in the first, second, third, and fourth consecutive cycles, respectively. Direct drivers explained 97%, 88%, 96%, and 100% of wetland losses in the first, second, third, and fourth consecutive cycles, respectively. Indirect drivers explained 3%, 12%, 4%, and 0% of wetland losses in the first, second, third, and fourth consecutive cycles, respectively.

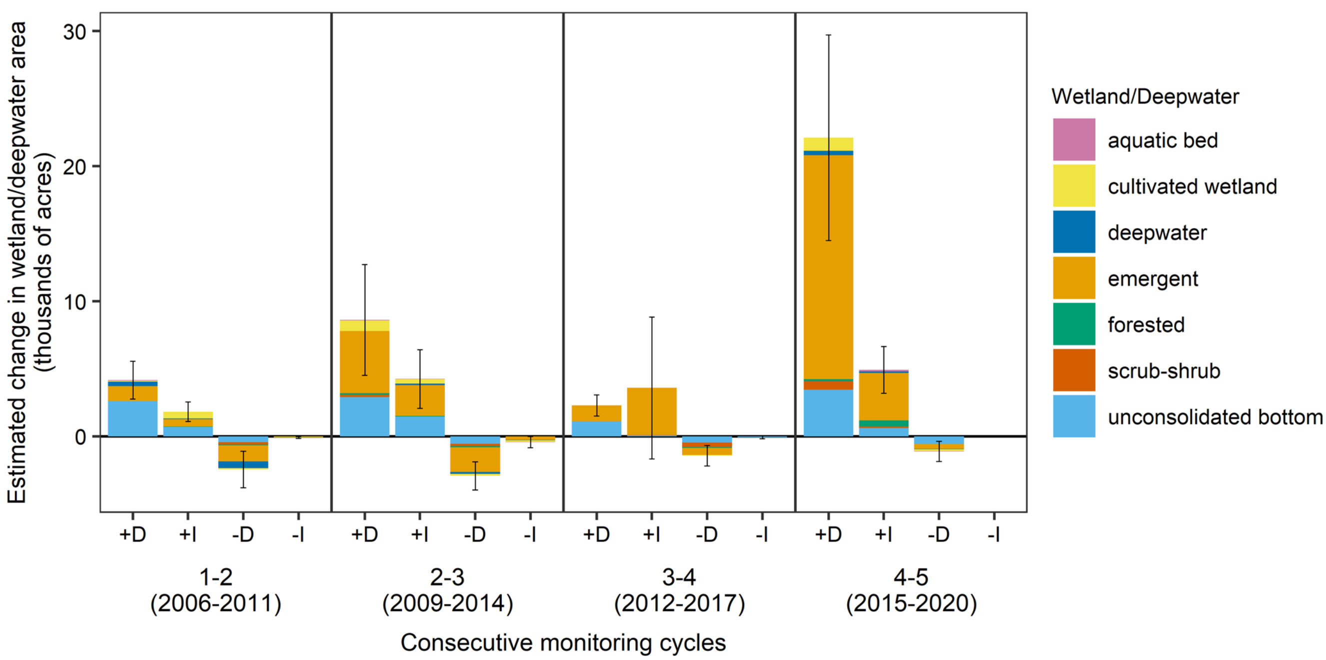

Figure 8: Gains (+) and losses (-) in wetland and deepwater area between consecutive monitoring cycles attributed to direct (D) and indirect (I) drivers, estimated for the entire state of Minnesota and color-coded by wetland class/deepwater. Values are in Table S11.

Precipitation

The probability of wetland/deepwater gaining area from direct drivers increased from 13% to 48% across the range of cumulative precipitation (Fig. 9, Table S12). However, the probability of gain from indirect drivers only increased from 9% to 12%. The probability of wetland/deepwater losing area was not significantly related to precipitation (Table S13). The probability of loss increased from 28% to 30% due to direct drivers and 2% to 5% due to indirect drivers across the precipitation gradient (Fig. 9).

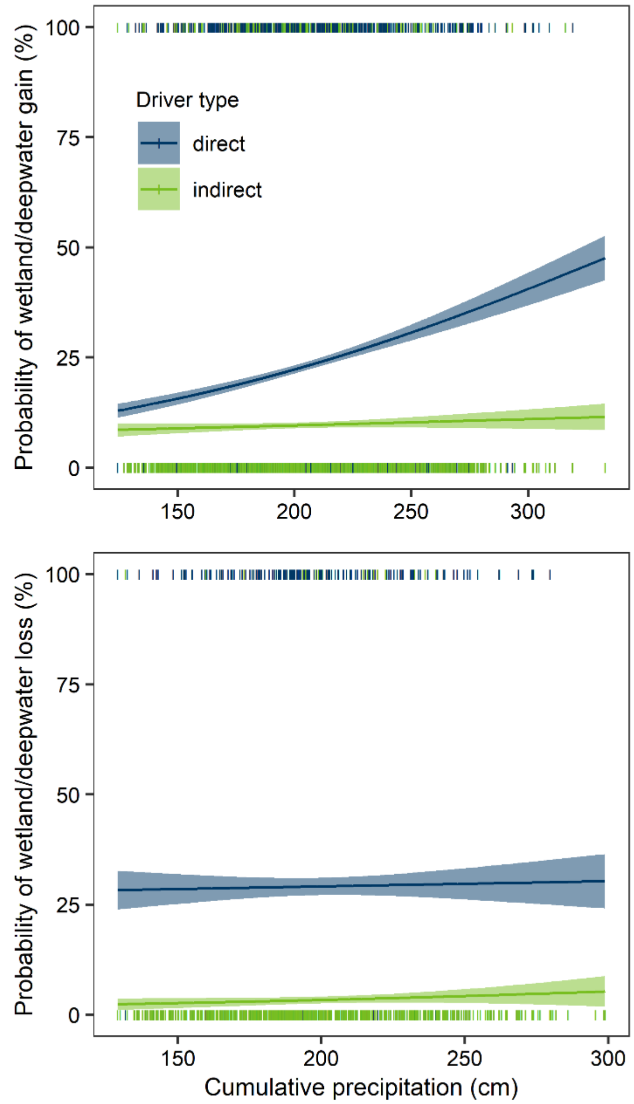

Figure 9: The probability of wetland/deepwater gain (top panel) and loss (bottom panel) across a gradient of cumulative precipitation (since the previous monitoring cycle). Lines and shading indicate mean ± SE from binomial mixed effects models with plot as a random intercept (Tables S12-S13). Vertical lines at zero and one indicate observed wetland/deepwater gains or losses.

Discussion

Wetlands in Minnesota and across the globe are vital habitats for biodiversity and ecosystem functions (Keddy et al. 2009). Through a long-term monitoring program, we have estimated the wetland area in Minnesota and the change in wetland and deepwater area over time. Despite many pressures on wetlands, Minnesota has had a decline in wetland losses and a net gain in wetland area over the past 15 years. Gains were observed across all four ecological provinces and primarily occurred between the most recent monitoring cycles due to direct drivers. Precipitation increased wetland gains, especially those associated with direct drivers.

Most of the gains in Minnesota's wetland area were in emergent and unconsolidated bottom wetlands. In other wetland categorization schemes (Shaw and Fredine 1956, MN DNR 2003, Eggers and Reed 2015), multiple wetland types fall into our definition of emergent wetland, including deep marshes, shallow marshes, seasonally flooded basins, wet meadows, wet prairies, rich and poor fens, calcareous fens, and some open bogs. This diverse group of wetlands can serve as critical habitat for threatened and endangered species (MN DNR 2022a), support a disproportionately high percentage of waterfowl (Batt et al. 1989), and store substantial carbon pools (Weishampel et al. 2009, Chaudhary et al. 2020). Unconsolidated bottom wetlands may include "Type 5 – inland open fresh water" wetlands (Shaw and Fredine 1956) or may not be considered wetlands due to low vegetation cover (Eggers and Reed 2015). Most wetland gains in these categories came from agricultural land, suggesting active restoration or passive wetland creation through abandonment. For further discussion of gains in unconsolidated bottom wetlands, see Kloiber and Norris (2017).

There were ~4.2 million acres of forested wetland in Minnesota during the first monitoring cycle, and ~127,500 acres, or 3%, transitioned to emergent or scrub-shrub wetland by the final monitoring cycle. For forested wetland area that transitioned between the first and second monitoring cycles, 19% returned to forested wetland by the final monitoring cycle. Loss of forested wetland is not isolated to Minnesota. Approximately 8% of forested wetlands were lost from North America's Coastal Plain over ten years and from the Great Lakes basin over four decades, with large transitions to emergent and scrub-shrub wetlands (White et al. 2022, Amani et al. 2022). These transitions are likely associated with resource extraction, flooding, development, and forest pests (Johnston 1989, van Asselen et al. 2013, MN DNR 2022b). Tree loss from wetlands can impact hydroperiod, canopy cover, and litter quantity and quality, with consequences for plants and animals (Youngquist et al. 2017, Grinde et al. 2022). Because WSTMP data are collected during spring leaf-off, it is difficult to identify newly standing dead trees. Therefore, loss of forested wetlands in our analysis either represent tree removal or long-term standing dead trees. Wetland quality in Minnesota is primarily driven by spatially-variable factors, with higher quality in the LMF province relative to the rest of the state (Bourdaghs et al. 2019). Most of the forested wetlands are in the LMF and the most common wetland type in the LMF is forested wetlands. Therefore, continued loss of forested wetlands could impact LMF wetland quality.

Wetland/deepwater gains in three of four monitoring cycles were primarily caused by direct, observable drivers. Further, cumulative precipitation between monitoring cycles helped explain wetland/deepwater gains associated with direct drivers. It is possible that increased precipitation led to adaptive changes in infrastructure and land management practices that in turn increased wetland/deepwater area. Interestingly, wetland losses due to direct drivers did not show an opposite relationship, although the sample size for wetland losses was smaller than that for gains. Wetland gains and losses associated with indirect drivers were not strongly related to cumulative precipitation. This may be because precipitation affects transitions among wetland/deepwater classes (e.g., emergent, aquatic bed, unconsolidated bottom, and deepwater), rather than between wetland and non-wetland, without direct drivers.

Our results may be influenced by imagery substitutions made due to the Covid-19 pandemic restrictions on flying in spring 2020. Imagery acquired from external sources was used to quantify 5,889 acres gained and 364 acres lost statewide. Imagery we acquired in the fall was used to quantify 384 acres gained and 13.6 acres lost statewide. Wetland water levels generally peak during seasons with high precipitation or snow melt and decline during seasons with drought (van der Valk 2005). Therefore, changes detected in imagery collected from different times of the year may reflect within-year seasonal fluctuations. Because WSTMP is ongoing, we will be able to assess whether changes detected with alternative imagery persist when the same plots are monitored again in 2023.

In 2019, the Minnesota Department of Natural Resources completed an update of the state's National Wetland Inventory (NWI) (Kloiber et al. 2019). This effort mapped all wetland and deepwater within the state that were larger than ½ acre or, for long, narrow features, wider than 15 ft. Based on the NWI, the estimated statewide wetland area is 12.2 million acres and the statewide deepwater area is 2 million acres. The NWI wetland estimate is ~1.6 million acres greater than the WSTMP estimate (and ~1.3 million acres greater than the upper 95% CI) and the deepwater estimate is ~400,000 acres less than the WSTMP estimate (and ~250,000 acres less than the lower 95% CI). A few factors may explain these discrepancies. First, the NWI was produced by a different group of technical experts using different source data than the WSTMP. Second, the NWI had more inclusive criteria for wetlands than WSTMP. For example, a 2 ft deeper threshold was required in NWI for a waterbody to be deepwater rather than wetland, there was a smaller minimum surface area threshold for delineating wetlands, and uncertainty about depth within lakes, where littoral zones were categorized as wetland and limnetic as deepwater, was addressed by assuming more littoral area. Ongoing work by the MN DNR aims to refine the delineation of wetland and lake features. Although WSTMP is a random sample of the state, and may therefore omit small, isolated wetlands, the estimated statewide wetland area using NWI within WSTMP plots is 12.2 million acres, suggesting that WSTMP plots are not omitting wetlands. Because of methodological differences between NWI and WSTMP, we encourage users to consider which set of assumptions best meets their purposes, with the understanding that NWI's estimate for statewide wetland area may be an overestimate and WSTMP's estimate may be an underestimate.

Minnesota had a net gain in wetland area between 2006 and 2020 and for every pair of consecutive monitoring cycles of this program, with the greatest gains in the most recent consecutive cycles (2015-2020). Further, the most recent consecutive cycles had the smallest wetland losses observed so far. Therefore, Minnesota is meeting the WCA goal of no net loss of wetland quantity over this time period. Wetland quality and biodiversity are central to the functions and values of wetlands as well as to WCA goals. The Minnesota Pollution Control Agency's wetland quality monitoring programs have detected relatively stable wetland quality over 2-3 monitoring cycles (Bourdaghs et al. 2019, Genet et al. 2019), which may be supporting wetland functions in areas of the state with higher quality wetlands. Yet, as wetlands transition between different classes, which is not reflected in overall quantities of wetland losses or gains, functions may be lost. Integrating functional indices, such as those being developed with the Wisconsin-Minnesota Wetland Functional Assessment Initiative (BWSR 2022), with the quantitative data presented here, may help characterize nuances in Minnesota's progress towards the goal of no net loss of wetland quantity, quality, and biological diversity.

Vegetation in a fen (an emergent wetland) at Lake Maria State Park. Photograph by A. Kendig.

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Appendix

Table S1: Number of sample plots per province and monitoring panel.

Scale	Panel 1	Panel 2	Panel 3	Total
Prairie Parkland	369	366	381	1116
Tallgrass Aspen Parklands	69	64	66	199
Eastern Broadleaf Forest	274	282	272	828
Laurentian Mixed Forest	538	538	531	1607
statewide	1250	1250	1250	3750

Table S2: Estimated area (and 95% CI) statewide and for each province in thousands of acres for each wetland/deepwater class during the most recent monitoring cycle (2018-2020). Values rounded to the nearest 1,000 acres. See Fig. 2 for visualization.

Wetland/ deepwater class	Statewide	PP	TAP	EBF	LMF
aquatic bed	276 (247–305)	50 (33–67)	6 (-1–12)	101 (85–116)	120 (104–136)
cultivated wetland	167 (139–195)	83 (73–93)	23 (8–38)	32 (26–38)	29 (8–50)
deepwater	2,453 (2,288–2,618)	205 (161–248)	8 (5–11)	376 (307–444)	1,864 (1,721–2,008)
emergent	3,299 (3,179–3,418)	546 (505–587)	304 (252–357)	752 (702–803)	1,696 (1,610–1,782)
forested	4,090 (3,939–4,242)	64 (53–75)	89 (63–114)	224 (198–251)	3,713 (3,567–3,860)
scrub-shrub	2,340 (2,247–2,433)	64 (52–75)	189 (156–222)	218 (197–240)	1,869 (1,785–1,952)
unconsolidated bottom	481 (434–528)	114 (95–133)	29 (7–51)	157 (131–183)	182 (155–209)

Table S3: Estimated change in area (and 95% CI) in thousands of acres for each wetland/deepwater class from the first (2006-2008) to the most recent monitoring cycle (2018-2020). Values rounded to the nearest 1,000 acres. Losses are multiplied by -1 for figure. See Fig. 4 for visualization.

Class	Change	Statewide	PP	TAP	EBF	LMF
total	gain	50.7 (39–62.5)	21.1 (14.9–27.3)	6.7 (-1–14.4)	10.7 (8.2–13.2)	12.3 (6.4–18.2)
total	loss	7.3 (5.1–9.6)	1.9 (1–2.8)	0.5 (0–1)	1.9 (1–2.7)	3.1 (1.3–4.9)
total	net	43.4 (31.4–55.3)	19.2 (12.9–25.4)	6.2 (-1.5–14)	8.8 (6.2–11.4)	9.2 (3.1–15.3)
aquatic bed	gain	0.3 (0.1–0.5)	0 (0–0.1)	0 (0–0)	0.2 (0–0.3)	0.1 (0–0.2)
aquatic bed	loss	0 (0–0.1)	0 (0–0)	0 (0–0)	0 (0–0.1)	0 (0–0)
aquatic bed	net	0.3 (0.1–0.5)	0 (0–0.1)	0 (0–0)	0.1 (0–0.3)	0.1 (0–0.2)
cultivated wetland	gain	3 (1.2–4.9)	1.6 (0–3.3)	0.5 (0–1)	0.9 (0.3–1.4)	0 (0–0.1)
cultivated wetland	loss	0.5 (0.2–0.8)	0.4 (0.1–0.7)	0 (0–0)	0.1 (0–0.2)	0 (0–0.1)
cultivated wetland	net	2.6 (0.7–4.4)	1.3 (-0.4–3)	0.5 (0–1)	0.8 (0.2–1.4)	0 (0–0.1)
deepwater	gain	0.7 (0.1–1.4)	0 (0–0.1)	0 (0–0)	0.2 (0–0.4)	0.5 (-0.1–1)
deepwater	loss	0.4 (-0.1–0.9)	0 (0–0.1)	0 (0–0)	0 (0–0)	0.4 (-0.1–0.9)
deepwater	net	0.3 (0–0.7)	0 (-0.1–0.1)	0 (0–0)	0.2 (0–0.4)	0.1 (-0.1–0.3)
emergent	gain	33.5 (22.2–44.8)	15.5 (9.8–21.2)	5 (-2.7–12.6)	5.3 (3.1–7.5)	7.7 (2–13.4)
emergent	loss	4.2 (2.8–5.7)	1.4 (0.6–2.1)	0.4 (0–0.9)	1.3 (0.5–2)	1.2 (0.3–2.1)
emergent	net	29.3 (17.9–40.7)	14.2 (8.4–19.9)	4.5 (-3.2–12.3)	4 (1.8–6.3)	6.5 (0.8–12.3)
forested	gain	0.8 (0–1.6)	0.1 (-0.1–0.2)	0 (0–0)	0 (0–0)	0.7 (-0.1–1.5)
forested	loss	0.3 (0.1–0.4)	0 (0–0.1)	0 (0–0)	0.1 (0–0.2)	0.1 (0–0.2)
forested	net	0.5 (-0.3–1.3)	0 (-0.1–0.2)	0 (0–0)	-0.1 (-0.2–0)	0.6 (-0.2–1.3)
scrub-shrub	gain	0.9 (0.2–1.7)	0.4 (0–0.8)	0 (0–0)	0.4 (-0.3–1.1)	0.2 (0–0.3)
scrub-shrub	loss	0.7 (0.3–1.1)	0.1 (0–0.1)	0 (0–0)	0.3 (0–0.6)	0.3 (0.1–0.6)
scrub-shrub	net	0.3 (-0.6–1.1)	0.3 (-0.1–0.7)	0 (0–0)	0.1 (-0.6–0.8)	-0.2 (-0.4–0.1)
unconsolidated bottom	gain	11.4 (9.1–13.6)	3.4 (2.3–4.5)	1.2 (0–2.4)	3.7 (2.8–4.6)	3.1 (1.9–4.3)
unconsolidated bottom	loss	1.2 (-0.2–2.6)	0 (0–0)	0 (0–0.1)	0.1 (0–0.2)	1 (-0.3–2.4)
unconsolidated bottom	net	10.2 (7.5–12.8)	3.4 (2.3–4.5)	1.2 (-0.1–2.4)	3.6 (2.7–4.5)	2 (0.2–3.8)

Table S4: Estimated change in wetland/deepwater area (and 95% CI) in thousands of acres from (gain) or to (loss) each non-wetland class from the first (2006-2008) to the most recent monitoring cycle (2018-2020). Values rounded to the nearest 1,000 acres. Losses are multiplied by -1 for figure. See Fig. 5 for visualization.

Class	Change	Statewide	PP	TAP	EBF	LMF
total	gain	50.7 (39–62.5)	21.1 (14.9–27.3)	6.7 (-1–14.4)	10.7 (8.2–13.2)	12.3 (6.4–18.2)
total	loss	7.3 (5.1–9.6)	1.9 (1–2.8)	0.5 (0–1)	1.9 (1–2.7)	3.1 (1.3–4.9)
total	net	43.4 (31.4–55.3)	19.2 (12.9–25.4)	6.2 (-1.5–14)	8.8 (6.2–11.4)	9.2 (3.1–15.3)
agricultural	gain	28.3 (18.6–38)	15.4 (9.7–21.1)	5.9 (-1.8–13.6)	6.4 (4.7–8.1)	0.6 (0.2–1)
agricultural	loss	3.6 (2.3–5)	1.7 (0.8–2.5)	0.1 (0–0.3)	0.8 (0.2–1.3)	1 (0.2–1.9)
agricultural	net	24.7 (14.9–34.5)	13.7 (7.9–19.5)	5.8 (-1.9–13.5)	5.6 (3.8–7.4)	-0.4 (-1.4–0.5)
artificially flooded	gain	3.5 (-1.7–8.8)	0 (0–0)	0.1 (-0.1–0.3)	0.2 (-0.1–0.4)	3.2 (-2–8.5)
artificially flooded	loss	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)
artificially flooded	net	3.5 (-1.7–8.8)	0 (0–0)	0.1 (-0.1–0.3)	0.2 (-0.1–0.4)	3.2 (-2–8.5)
natural upland	gain	12.8 (9.5–16.1)	4.6 (2.3–6.8)	0.6 (0.1–1)	2.4 (0.6–4.3)	5.2 (3.9–6.4)
natural upland	loss	0.4 (0–0.8)	0 (0–0.1)	0.2 (-0.1–0.6)	0.1 (0–0.2)	0 (0–0.1)
natural upland	net	12.4 (9.1–15.7)	4.5 (2.3–6.8)	0.4 (-0.2–0.9)	2.4 (0.5–4.2)	5.1 (3.9–6.4)
other upland	gain	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)
other upland	loss	0.2 (-0.2–0.7)	0 (0–0)	0 (0–0)	0.2 (-0.2–0.7)	0 (0–0)
other upland	net	-0.2 (-0.7–0.2)	0 (0–0)	0 (0–0)	-0.2 (-0.7–0.2)	0 (0–0)
rural development	gain	5.6 (3–8.2)	1.1 (0.4–1.8)	0.1 (0–0.2)	1.2 (0.4–2)	3.2 (0.8–5.5)
rural development	loss	2.8 (1.2–4.5)	0.1 (0–0.2)	0.1 (0–0.3)	0.6 (0.2–1)	2 (0.4–3.5)
rural development	net	2.8 (0–5.6)	1 (0.3–1.6)	-0.1 (-0.1–0)	0.6 (0–1.3)	1.2 (-1.4–3.9)
silviculture	gain	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)
silviculture	loss	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)
silviculture	net	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0)
urban development	gain	0.5 (0.2–0.7)	0 (0–0.1)	0 (0–0)	0.4 (0.2–0.6)	0 (0–0)
urban development	loss	0.2 (0.1–0.4)	0.1 (0–0.2)	0 (0–0)	0.2 (0.1–0.3)	0 (0–0.1)
urban development	net	0.2 (0–0.5)	0 (-0.1–0)	0 (0–0)	0.3 (0–0.5)	0 (0–0)

Table S5: Estimated change in area (and 95% CI) statewide for each pair of consecutive monitoring cycles in thousands of acres for each wetland/deepwater class. Values rounded to the nearest 1,000 acres. Losses are multiplied by -1 for figure. See Fig. 6 for visualization.

Class	Change	1-2 (2006-2011)	2-3 (2009-2014)	3-4 (2012-2017)	4-5 (2015-2020)
total	gain	6 (4.4–7.6)	12.9 (8.5–17.2)	5.9 (0.6–11.2)	27 (19.2–34.8)
total	loss	2.5 (1.2–3.9)	3.3 (2.2–4.5)	1.5 (0.7–2.3)	1.1 (0.4–1.9)
total	net	3.5 (1.6–5.4)	9.6 (5–14.1)	4.4 (-1–9.8)	25.9 (18.1–33.8)
aquatic bed	gain	0.1 (0–0.1)	0.1 (0–0.1)	0 (0–0)	0.1 (0–0.2)
aquatic bed	loss	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0.1)
aquatic bed	net	0.1 (0–0.1)	0 (0–0.1)	0 (0–0)	0.1 (0–0.2)
cultivated wetland	gain	0.6 (0.2–1)	1.1 (0.5–1.7)	0 (0–0)	1 (-0.7–2.6)
cultivated wetland	loss	0.1 (0–0.2)	0.3 (0–0.5)	0 (0–0.1)	0.1 (0–0.3)
cultivated wetland	net	0.5 (0–0.9)	0.9 (0.2–1.5)	0 (-0.1–0)	0.8 (-0.8–2.5)
deepwater	gain	0.4 (-0.2–0.9)	0.1 (0–0.2)	0 (0–0)	0.5 (0–0.9)
deepwater	loss	0.5 (-0.1–1.1)	0.2 (0–0.3)	0 (0–0)	0 (0–0)
deepwater	net	-0.1 (-0.5–0.2)	0 (-0.2–0.2)	0 (0–0)	0.5 (0–0.9)
emergent	gain	1.7 (1–2.4)	6.9 (2.9–10.9)	4.7 (-0.6–10)	20 (12.7–27.4)
emergent	loss	1.2 (0.3–2.1)	2.1 (1.1–3)	0.5 (0.1–0.9)	0.3 (0.1–0.6)
emergent	net	0.5 (-0.7–1.6)	4.8 (0.7–8.9)	4.2 (-1.1–9.5)	19.7 (12.3–27.1)
forested	gain	0 (0–0)	0.2 (0–0.3)	0 (0–0)	0.6 (-0.2–1.4)
forested	loss	0.1 (0–0.1)	0.1 (0–0.2)	0.1 (0–0.1)	0 (0–0)
forested	net	-0.1 (-0.1–0)	0.1 (-0.1–0.2)	-0.1 (-0.1–0)	0.6 (-0.2–1.4)
scrub-shrub	gain	0 (0–0)	0.2 (0–0.3)	0 (0–0.1)	0.7 (0–1.5)
scrub-shrub	loss	0.2 (0–0.4)	0.2 (0–0.3)	0.3 (0–0.7)	0 (0–0)
scrub-shrub	net	-0.2 (-0.3–0)	0 (-0.2–0.2)	-0.3 (-0.6–0)	0.7 (0–1.5)
unconsolidated bottom	gain	3.3 (2.1–4.5)	4.4 (2.7–6.1)	1.2 (0.7–1.7)	4.1 (3–5.1)
unconsolidated bottom	loss	0.4 (0–0.9)	0.6 (0–1.1)	0.5 (-0.1–1.1)	0.6 (-0.1–1.2)
unconsolidated bottom	net	2.9 (1.7–4.1)	3.8 (2.1–5.6)	0.7 (-0.1–1.4)	3.5 (2.3–4.8)

Table S6: Change in estimated statewide area (acres) of each wetland and non-wetland class from the first monitoring cycle (2006-2008) to the second monitoring cycle (2009-2011). See Table 1 for abbreviation meanings. Boxes are shaded by transition magnitude, with larger areas represented by more blue and less yellow colors. Horizontal and vertical lines separate wetland from non-wetland classes. Area that transitioned from one non-wetland class to another (bottom right) is omitted. Total area in thousands of acres for the first and second monitoring cycles are in the right column and bottom row, respectively.

2009-2011 Cover → 2006-2008 Cover ↓	AB	CW	DW	EM	FO	SS	UB	A	AF	N	O	R	S	U	total (x 1000)
AB	239,600	0	4,377	2,189	0	3	3,833	0	0	0	0	7	0	0	250
CW	0	151,863	0	1,776	0	121	2,895	56	0	0	0	63	0	1	157
DW	3,365	0	2,464,446	240	0	15	0	0	0	0	0	497	0	0	2,469
EM	127	7,952	457	3,172,956	22	20,273	9,411	819	0	31	230	118	0	23	3,212
FO	0	31	35	42,578	4,127,061	926	46	9	0	0	16	41	0	4	4,171
SS	0	217	26	3,049	8,969	232,2076	97	112	0	20	0	37	0	0	2,335
UB	8,608	87	87	9,674	0	61	450,576	5	0	43	0	373	0	0	470
A	40	530	0	1,047	0	0	1,515								
AF	0	0	0	20	0	0	0								
N	11	42	35	526	13	12	725								
O	0	0	0	0	0	0	0								
R	9	0	330	84	0	0	943								
S	0	0	0	0	0	0	0								
U	0	0	0	9	0	0	120								
total (x 1000)	252	161	2,470	3,234	4,136	2,343	470								

↑ wetland/deepwater gains

← wetland/deepwater gains

Table S7: Change in estimated statewide area (acres) of each wetland and non-wetland class from the second monitoring cycle (2009-2011) to the third monitoring cycle (2012-2014). See Table 1 for abbreviation meanings. Boxes are shaded by transition magnitude, with larger areas represented by more blue and less yellow colors. Horizontal and vertical lines separate wetland from non-wetland classes. Area that transitioned from one non-wetland class to another (bottom right) is omitted. Total area in thousands of acres for the second and third monitoring cycles are in the right column and bottom row, respectively.

2012-2014 Cover → 2009-2011 Cover ↓	AB	CW	DW	EM	FO	SS	UB	A	AF	N	O	R	S	U	total (x 1000)
AB	239,048	8	2,891	2,205	0	6	7,592	0	0	6	0	5	0	0	252
CW	0	152,332	0	6,559	0	1,281	288	264	0	0	0	0	0	0	161
DW	6,068	0	2,462,826	572	0	0	149	0	0	26	0	152	0	0	2,470
EM	2,503	9,128	210	3,181,115	8,607	21,482	9,046	1,257	0	210	0	488	0	102	3,234
FO	0	177	14	31,586	4,096,622	7,263	308	72	0	0	0	16	0	7	4,136
SS	76	593	3	2,733	13,392	2,326,019	504	142	0	0	0	22	0	4	2,343
UB	12,847	526	0	8,245	0	22	447,966	346	0	2	0	187	0	20	470
A	43	909	10	4,540	0	50	2,651	↑ wetland/deepwater gains							
AF	0	0	0	0	0	0	7								
N	15	205	99	937	152	119	777								
O	0	0	0	0	0	0	0	← wetland/deepwater gains							
R	0	0	36	1,331	0	0	866								
S	0	0	0	11	0	0	0								
U	0	0	0	45	0	0	82								
total (x 1000)	261	164	2,466	3,240	4,119	2,356	470								

Table S8: Change in estimated statewide area (acres) of each wetland and non-wetland class from the third monitoring cycle (2012-2014) to the fourth monitoring cycle (2015-2017). See Table 1 for abbreviation meanings. Boxes are shaded by transition magnitude, with larger areas represented by more blue and less yellow colors. Horizontal and vertical lines separate wetland from non-wetland classes. Area that transitioned from one non-wetland class to another (bottom right) is omitted. Total area in thousands of acres for the third and fourth monitoring cycles are in the right column and bottom row, respectively.

2015-2017 Cover → 2012-2014 Cover ↓	AB	CW	DW	EM	FO	SS	UB	A	AF	N	O	R	S	U	total (x 1000)
AB	260,255	0	0	97	0	0	243	0	0	5	0	0	0	0	261
CW	0	162,975	0	659	0	0	202	0	0	0	0	29	0	11	164
DW	1,330	0	2,464,450	310	0	0	0	0	0	0	0	0	0	0	2,466
EM	3,141	6,953	207	3,213,765	0	14,381	903	325	0	0	0	166	0	39	3,240
FO	0	164	0	29,396	4,088,279	867	0	32	0	0	0	37	0	0	4,119
SS	0	209	0	1,773	22,042	2,331,870	20	263	0	0	0	42	0	23	2,356
UB	375	24	0	939	0	0	468,383	68	0	2	0	390	0	53	470
A	0	0	0	290	0	0	501	↑ wetland/deepwater gains							
AF	0	0	0	3,240	0	0	0								
N	0	0	0	1,125	0	30	238								
O	0	0	0	0	0	0	0	← wetland/deepwater gains							
R	0	0	0	32	0	0	389								
S	0	0	0	0	0	0	0								
U	0	0	0	0	0	0	45								
total (x 1000)	265	170	2,465	3,252	4,110	2,347	471								

Table S9: Change in estimated statewide area (acres) of each wetland and non-wetland class from the fourth monitoring cycle (2015-2017) to the fifth monitoring cycle (2018-2020). See Table 1 for abbreviation meanings. Boxes are shaded by transition magnitude, with larger areas represented by more blue and less yellow colors. Horizontal and vertical lines separate wetland from non-wetland classes. Area that transitioned from one non-wetland class to another (bottom right) is omitted. Total area in thousands of acres for the fourth and fifth monitoring cycles are in the right column and bottom row, respectively.

2018-2020 Cover → 2015-2017 Cover ↓	AB	CW	DW	EM	FO	SS	UB	A	AF	N	O	R	S	U	total (x 1000)
AB	263,657	0	388	119	0	0	915	1	0	22	0	0	0	0	265
CW	0	161,864	0	8,289	0	6	19	0	0	0	0	118	0	30	170
DW	7,528	0	2,450,866	6,198	0	51	0	0	0	0	0	13	0	0	2,465
EM	1,112	2,995	814	3,233,936	22	2,821	9,579	193	0	27	0	124	0	4	3,252
FO	552	0	188	22,685	4,083,965	1,025	1,902	5	0	0	0	0	0	0	4,110
SS	50	1,041	49	4,349	5,765	2,335,191	688	0	0	0	0	14	0	0	2,347
UB	3,400	2	0	3,088	0	0	463,874	32	0	8	0	512	0	7	471
A	0	14	0	14,373	84	731	987	↑ wetland/deepwater gains							
AF	0	0	0	251	0	0	0								
N	103	954	133	4,458	543	0	1,489								
O	0	0	0	4	0	0	0	← wetland/deepwater gains							
R	0	0	344	840	0	0	1,471								
S	0	0	0	0	0	0	0								
U	0	0	0	117	0	0	133								
total (x 1000)	276	167	2,453	3,299	4,090	2,340	481								

Table S10: Estimated statewide area (acres) that transition from forested wetland to emergent or scrub-shrub wetland. We do no present 95% CIs, but instead note the number of sampling plots contributing to these estimates (N). See Fig. 7 for visualization.

Transition classes	Acres	N
FO-EM-CW-CW-CW	181	1
FO-EM-CW-NY-NY	10	1
FO-EM-EM-A-A	30	1
FO-EM-EM-AB-AB	84	1
FO-EM-EM-CW-CW	4	1
FO-EM-EM-EM-EM	13,480	55
FO-EM-EM-EM-NY	24,146	89
FO-EM-EM-EM-SS	513	1
FO-EM-EM-NY-NY	29,260	112
FO-EM-EM-SS-NY	943	3
FO-EM-EM-SS-SS	6,745	22
FO-EM-EM-U-U	9	1
FO-EM-FO-FO-FO	8,460	1
FO-EM-NY-NY-NY	22,685	57
FO-EM-SS-NY-NY	126	1
FO-EM-SS-SS-NY	6,496	18
FO-EM-SS-SS-SS	13,018	28
FO-EM-UB-UB-NY	1	1
FO-EM-UB-UB-UB	54	2
FO-SS-CW-NY-NY	5	1
FO-SS-NY-NY-NY	1,025	4
FO-SS-SS-EM-EM	46	1
FO-SS-SS-NY-NY	862	8
FO-SS-SS-SS-NY	7,263	17
FO-SS-SS-SS-SS	880	5

Class abbreviations: A = agricultural, AB = aquatic bottom wetland, CW = cultivated wetland, EM = emergent wetland, FO = forested wetland, SS = scrub-shrub wetland, UB = unconsolidated bottom wetland, U = urban development, NY = not yet observed

Table S11: Estimated gain (+) and loss (-) of area (and 95% CI) due to direct (D) and indirect (I) drivers statewide for each pair of consecutive monitoring cycles in thousands of acres for each wetland/deepwater class. Values rounded to the nearest 1,000 acres. Losses are multiplied by -1 for figure. See Fig. 8 for visualization.

Class	Change	1-2 (2006-2011)	2-3 (2009-2014)	3-4 (2012-2017)	4-5 (2015-2020)
total	+D	4.2 (2.8–5.6)	8.6 (4.5–12.7)	2.3 (1.5–3.1)	22.1 (14.5–29.7)
total	+I	1.8 (1.1–2.5)	4.3 (2.1–6.4)	3.6 (-1.7–8.8)	4.9 (3.2–6.7)
total	-D	2.4 (1.1–3.8)	2.9 (1.9–4)	1.4 (0.7–2.2)	1.1 (0.4–1.9)
total	-I	0.1 (0–0.1)	0.4 (0–0.8)	0.1 (0–0.2)	0 (NA–NA)
aquatic bed	+D	0.1 (0–0.1)	0 (0–0.1)	0 (0–0)	
aquatic bed	+I	0 (0–0)	0 (0–0)	0 (0–0)	0.1 (0–0.2)
aquatic bed	-D	0 (0–0)	0 (0–0)	0 (0–0)	0 (0–0.1)
aquatic bed	-I	0 (0–0)	0 (0–0)	0 (0–0)	
cultivated wetland	+D	0.1 (0–0.1)	0.8 (0.2–1.3)	0 (0–0)	1 (-0.7–2.6)
cultivated wetland	+I	0.5 (0.1–0.9)	0.3 (0–0.6)	0 (0–0)	0 (0–0)
cultivated wetland	-D	0.1 (0–0.2)	0.1 (0–0.3)	0 (0–0.1)	0.1 (0–0.3)
cultivated wetland	-I	0 (0–0.1)	0.1 (-0.1–0.4)	0 (0–0)	
deepwater	+D	0.3 (-0.2–0.9)	0 (0–0)	0 (0–0)	0.3 (-0.1–0.8)
deepwater	+I	0 (0–0.1)	0.1 (0–0.2)	0 (0–0)	0.1 (0–0.3)
deepwater	-D	0.5 (-0.1–1.1)	0.2 (0–0.3)	0 (0–0)	0 (0–0)
deepwater	-I	0 (0–0)	0 (0–0.1)	0 (0–0)	
emergent	+D	1.1 (0.5–1.8)	4.6 (0.8–8.4)	1.2 (0.6–1.7)	16.6 (9.3–23.8)
emergent	+I	0.6 (0.3–0.8)	2.3 (0.9–3.7)	3.5 (-1.8–8.8)	3.5 (2–4.9)
emergent	-D	1.2 (0.3–2.1)	1.8 (1–2.7)	0.5 (0.1–0.9)	0.3 (0.1–0.6)
emergent	-I	0 (0–0.1)	0.2 (-0.1–0.6)	0 (0–0)	
forested	+D	0 (0–0)	0.1 (0–0.2)	0 (0–0)	0.2 (0–0.4)
forested	+I	0 (0–0)	0 (0–0.1)	0 (0–0)	0.5 (-0.3–1.2)
forested	-D	0.1 (0–0.1)	0.1 (0–0.2)	0.1 (0–0.1)	0 (0–0)
scrub-shrub	+D	0 (0–0)	0.2 (0–0.3)	0 (0–0)	0.6 (-0.1–1.4)
scrub-shrub	+I	0 (0–0)	0 (0–0)	0 (0–0.1)	0.1 (-0.1–0.3)
scrub-shrub	-D	0.2 (0–0.4)	0.2 (0–0.3)	0.3 (0–0.7)	0 (0–0)
unconsolidated bottom	+D	2.6 (1.5–3.7)	2.9 (2–3.8)	1.1 (0.6–1.6)	3.5 (2.5–4.4)
unconsolidated bottom	+I	0.7 (0.2–1.2)	1.5 (-0.1–3)	0.1 (0–0.2)	0.6 (0.3–0.9)
unconsolidated bottom	-D	0.4 (0–0.9)	0.5 (0–1.1)	0.4 (-0.1–1)	0.6 (-0.1–1.2)
unconsolidated bottom	-I	0 (0–0)	0 (0–0)	0.1 (0–0.2)	0 (0–0)

Table S12: Generalized linear mixed-effect model summary for the probability of wetland/deepwater gain in response to precipitation and the type of driver (logit-link, N = 4128).

Term	Estimate	Std. Error	Z value	Pr(>|z|)
Intercept (average precipitation, direct driver)	-1.24	0.05	-23.15	1.46×10^{-118}
Scaled precipitation	0.29	0.05	5.62	1.91×10^{-8}
Indirect driver	-1.01	0.09	-10.98	4.95×10^{-28}
Scaled precipitation × indirect driver	-0.24	0.09	-2.64	0.01
Random intercept SD: plot (N = 514)	3.72×10^{-5}			

Table S13: Generalized linear mixed-effect model summary for the probability of wetland/deepwater loss in response to precipitation and the type of driver (logit-link, N = 1072).

Term	Estimate	Std. Error	Z value	Pr(>|z|)
Intercept (average precipitation, direct driver)	-0.89	0.10	-9.36	7.74×10^{-21}
Scaled precipitation	0.02	0.09	0.21	0.83
Indirect driver	-2.48	0.26	-9.52	1.73×10^{-21}
Scaled precipitation × indirect driver	0.15	0.25	0.59	0.55
Random intercept SD: plot (N = 134)	3.41×10^{-5}			