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Research Article

Vegetation Response to Mechanically and Chemically Treating Willows (*Salix caroliniana*) Invading Marshes in the Corkscrew Watershed, Southwest Florida

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ABSTRACT

Florida freshwater herbaceous marshes are inundated approximately 6–10 mo/y, have predominantly organic soils, and are maintained by fire, which restricts invasion by woody plants. Marshes are becoming dominated by willow (*Salix caroliniana* Michx.) throughout Florida. Corkscrew Swamp Sanctuary and Corkscrew Regional Ecosystem Watershed Management Area treated willows in marshes from 2008 to 2016 with helicopter herbicide treatments and mechanical shredding. Our objective was to determine if treatments were shifting vegetation closer to a desirable marsh community with burnable fuels. Untreated areas were compared with (1) all herbicide and all mechanical treatments, (2) imazapyr/glyphosate mixes and other herbicides, primarily glyphosate, and (3) three imazapyr/glyphosate combination mixing rates. Mechanical treatment areas had more desirable vegetation and grasses/sedges than herbicided areas. Herbicided areas had more cattails (*Typha* spp., a nuisance species), and less sawgrass (*Cladium jamaicense* Crantz) and grasses/sedges than untreated areas. Imazapyr/glyphosate and other herbicides (mostly glyphosate) had less cover of sawgrass and grasses/sedges than untreated areas, and other herbicides also had less desirable species cover than untreated areas. Sample size was small, but the strongest imazapyr/glyphosate mix had more cattails and the weakest mix had less willow than untreated areas, while both had less grasses/sedges than untreated areas. Although more expensive and difficult, mechanical treatments better retained and/or restored desirable marsh vegetation, which was our primary objective. Sawgrass and other grasses and sedges are excellent fuels for burning. Mechanical treatments also have significantly more cover of grasses and sedges than herbicide treatments, increasing the ability to burn hot and frequently.

Index terms: fire exclusion; Florida; herbaceous wetland restoration; marsh restoration; willow invasion

INTRODUCTION

Florida freshwater marshes are wetlands dominated by herbaceous vegetation in basins with predominantly organic soils (FNAI 1990, 2010). These marshes are inundated on average 6–10 mo/year (Duever and Roberts 2013). Fire maintains an open herbaceous community by restricting invasion by woody plants (Frost 1995). The normal interval between fires is 1–10 y (FNAI 1990; Duever and Roberts 2013) with strictly herbaceous marshes burning about every 1–3 y (FNAI 1990). Duever and Roberts (2013) compiled successional and transitional models describing the effects of fire on marsh communities in South Florida based on information provided by natural area land managers; without moderate intensity growing season fire for more than roughly 18 y, marshes generally succeed to shrub wetlands, and without growing season fire for roughly longer than 40 more years, shrub wetlands will succeed to cypress (*Taxodium distichum* (L.) Rich) or mixed cypress-hardwood forests if seed sources are available. Woody encroachment into herbaceous communities is primarily determined by frequency and intensity of fire (Wade et al. 1980; Lugo 1995). Quintana-Ascencio and Fauth (2011) determined that willow (*Salix caroliniana* Michx.) greater than 1.2 m tall will not be killed by fire.

Throughout Florida, marshes have been succeeding from herbaceous vegetation communities to shrub communities dominated by willow and to a lesser extent by other woody shrubs and trees (Hall et al. 2017). An example of this is Corkscrew Swamp Sanctuary's (CSS) Central Marsh seen from the boardwalk observation platform. Historical photos from the 1950s show an herbaceous marsh, which was still present as late as the early 1980s (Figure 1). Since then, willows have formed a dense canopy with scattered maple (*Acer rubrum* L.) and cypress (Figure 2). Near the northern boundary of CSS in 1974 the North Marsh was also dominated by herbaceous vegetation (Figure 3), but currently supports a rapidly expanding willow community dominated by large willow, as well as Peruvian primrosewillow (*Ludwigia peruviana* (L.) H. Hara) and cattail (*Typha* spp.) (Figure 4). The development of this willow community is at least partially due to an almost continuous water flow from a canal to the north that has seriously limited the ability to prescribe burn this area. Aerial treatments using a variety of herbicides and ground treatment to remove willow have been conducted throughout Florida (Hall et al. 2017). St. Johns River Water Management District (SJRWMD) has been a

Figure 1.—Corkscrew Swamp Sanctuary's Central Marsh seen from the vicinity of the current observation platform along the boardwalk in May 1955 when the marsh was composed of herbaceous vegetation. Photo by Alexander Sprunt IV, with permission to use given to Michael Duever.

Figure 2.—Corkscrew Swamp Sanctuary's Central Marsh seen from about 7.5 m above ground on the current boardwalk observation platform in March 2015 showing a thick canopy of willow with scattered maple and cypress.

Figure 3.—Corkscrew Swamp Sanctuary's North Marsh in December 1974 showing predominantly herbaceous marsh vegetation beyond the open water of the ditch along Washout Road at Seven Culverts. Note tree line in this and following photo. This photo was taken about 0.16 km south of Figure 4.

Figure 4.—Corkscrew Swamp Sanctuary's North Marsh in June 2006 taken from about 7.5 m above ground on an observation platform overlooking the area shown in Figure 4. The marsh is now occupied by large willow, Peruvian primrosewillow, and cattail, which is at least partially due to additional flow from a canal to the north that has seriously affected the ability to burn. This is the area aerially treated with herbicide in 2008 and 2014. The photo inset was taken at ground level in the same area in 1992.

leader in conducting and evaluating willow treatment and marsh restoration and has been a mentor to others, with many publications on their own work (Miller et al. 1998; Ponzio et al. 2006, 2015; Hutchinson and Langeland 2010; Quintana-Ascencio and Fauth 2011; Quintana-Ascencio et al. 2013; Rohr 2017) and a compendium of knowledge on willow control across the state (Hall et al. 2017). But information on vegetation response after treatments and progress toward restoration of marsh vegetation outside the SJRWMD is not well documented.

Willow treatments were conducted in a freshwater marsh in southwest Florida since 2008 including single and multiple herbicide treatments with different herbicides and application rates as well as mechanical treatments. These willow treatments, conducted on CSS and Corkscrew Regional Ecosystem Watershed Management Area and Wildlife and Environmental Area (CREW), provided a unique opportunity to evaluate vegetation response to herbicide and mechanical treatments in South Florida.

Our objectives were to determine if treatments were shifting vegetation closer to a desirable marsh community and to compare the success of several treatment methods. Plots were also compared based on time since treatment to determine long-term progress toward a natural marsh community. Since fire is the primary mechanism land managers have to maintain these marshes in the future, another objective was to determine if post-treatment vegetation provided sufficient fuel to burn with enough frequency and intensity to keep woody species from returning and dominating the community.

METHODS

Study Sites and Treatments

CSS (managed by National Audubon Society) and CREW (jointly managed by the South Florida Water Management District [SFWMD] and Florida Fish and Wildlife Conservation Commission [FWC]) share a marsh system in southwest Florida's Collier and Lee counties (Figure 5). All of the study areas in this marsh developed under similar long-term environmental conditions, including hydrologic and fire regimes, plant community complexes, substrates, and surrounding land uses. All willow treatment areas within this marsh are connected hydrologically and are inundated most of the year.

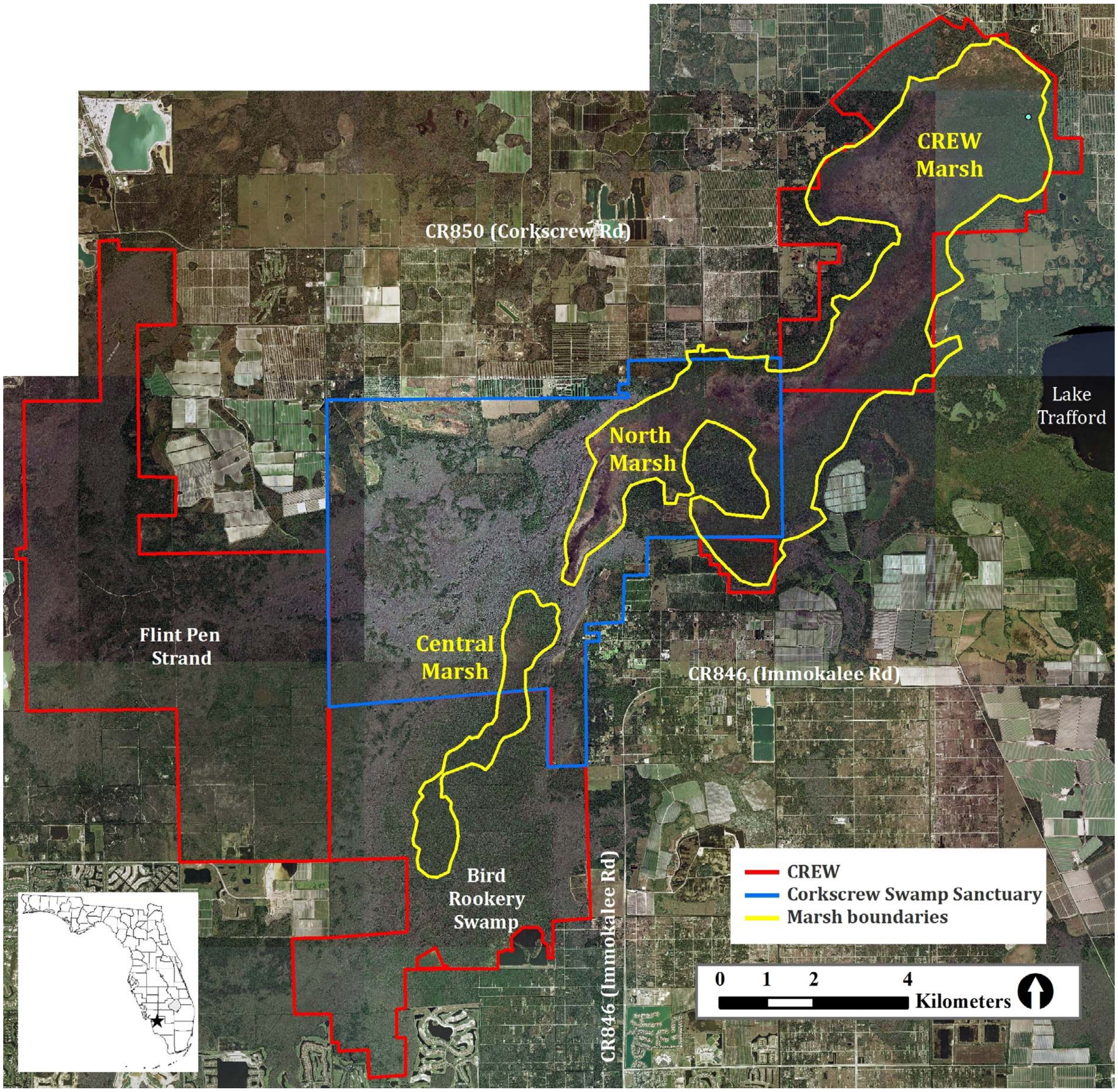

Figure 5.—Corkscrew Swamp Sanctuary (CSS) and Corkscrew Regional Ecosystem Watershed Management Area and Wildlife and Environmental Area (CREW) share a marsh system that extends from the CREW Marsh on CREW property south through CSS and into CREW's Bird Rookery Swamp in Collier and Lee counties, Florida. Treatment areas on CREW are located in the CREW Marsh. Treatment areas on CSS are located in the North Marsh.

U.S. Fish and Wildlife Service Wetland Inventory (2021) classifies this marsh as freshwater emergent wetland and freshwater forested/shrub wetland. The marsh, including all treatment areas, is classified as basin marsh using Florida Natural Areas Inventory's natural community classifications (FNAI 2010).

Soils for all treatment areas are listed as "Winder, Riviera, limestone substratum, and Chobee soils, frequently ponded, 0 to 1 percent slopes" (U.S. Department of Agriculture, Natural Resources Conservation Service 2019). Organic soil depths were taken at both ends of the sample transects by pushing a 2 cm diameter metal rod into the substrate until mineral soil was reached or we could go no deeper with the probe rod. All treated areas had organic soil at both the beginning and end of the transect. Mechanical treatment areas had shallower organic soils; mechanical treatment areas' organic soil depths ranged from 0.2 m to >0.9 m (i.e., deeper than the probe could reach), while in herbicided treatment areas organic soil depths ranged from 0.6 m to >1.6 m (i.e., deeper than the probe could reach) and untreated areas ranged from 0.6 m to >1.6 m (i.e., deeper than the probe could reach).

Treatment names begin with the year of initial treatment. The following herbicides, their concentrations, and timing of treatments were selected because they were thought to be the most potentially effective means for controlling willows and restoring marsh vegetation at that time. All aerial treatments on CREW and CSS used helicopters.

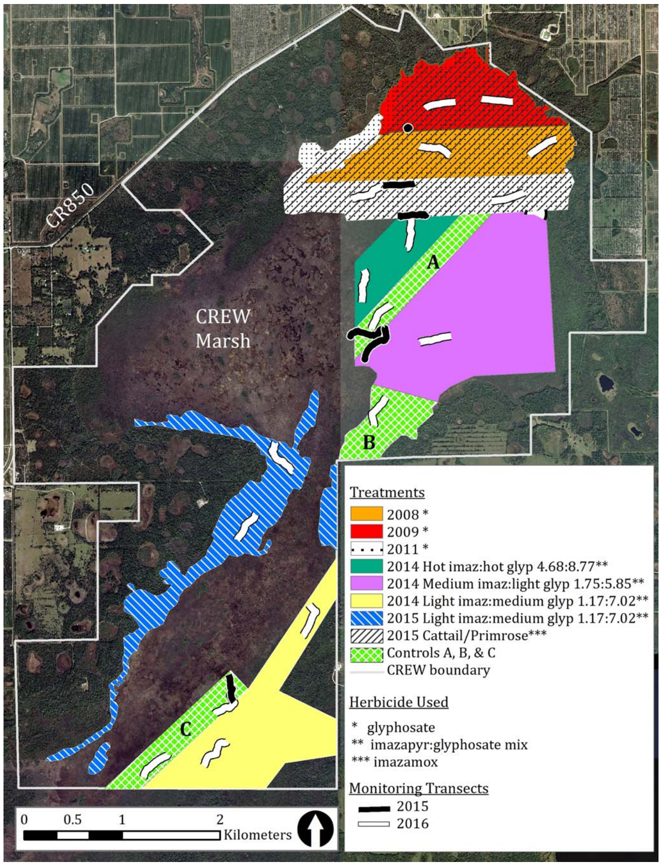

Figure 6.—Corkscrew Regional Ecosystem Watershed Management Area's CREW Marsh treatment areas and sampling transects. The 2014–2015 treatment names include the proportions of imazapyr:glyphosate applied in liters per hectare.

On CREW in 2008 and 2009, the SFWMD aerially treated willow with glyphosate in the northern portion of the CREW Marsh (Figure 6, Table 1). Then in 2011, the 2008 and 2009 areas were retreated and an adjacent area received an initial treatment with glyphosate. In 2014–2015, FWC and the SFWMD continued aerial herbicide applications to treat four areas in the central and southern CREW Marsh. Three different mixes of imazapyr and glyphosate were used to treat the four areas; the three mixes included herbicide in the following proportions of imazapyr to glyphosate liters applied per hectare: "hot imazapyr:hot glyphosate" was 4.68:8.77 L/ha, "medium imazapyr:light glyphosate" was 1.75:5.85 L/ha, and "light imazapyr:medium glyphosate" was 1.17:7.02 L/ha. The aggressive imazapyr concentration was applied to the most mature willow, the moderate imazapyr concentration was applied to the middle-aged willow, and the most conservative imazapyr concentration was applied to the youngest willow. Three control plots were established adjacent to the 2014 treatments for comparison post-treatment. In fall 2015, the areas that had been treated in 2008–2011 were sprayed with imazamox by FWC and the SFWMD to reduce cattails, which became abundant in these previously sprayed areas (Rodgers and Black 2012; Center for Aquatic and Invasive Plants 2020). All CREW treatments were conducted in the wet season (August and September) except the 2011 (June)

Table 1.—Corkscrew Regional Ecosystem Watershed Management Area's (CREW) CREW Marsh herbicide treatment summary. See Figure 6 for treatment and sampling locations.

Sampling area name	Treatment year	Treatment month	Treatment type	Application equipment	Herbicide	Rate (liters/hectare)	Target species	Target species density	Year sampled	Hectares
2008	2008	15 September	Aerial	Helicopter	Glyphosate	8.77	*Salix caroliniana*	High	2016	132
2009	2009	August	Aerial	Helicopter	Glyphosate	8.77	*Salix caroliniana*	Medium	2015, 2016	100
2008	2011	6 March	Aerial	Helicopter	Glyphosate	8.77	*Salix caroliniana*	Medium	2016	132
2011	2011	16 June	Aerial	Helicopter	Glyphosate	8.77	*Salix caroliniana*	Medium	2015, 2016	131
2009	2011	17 June	Aerial	Helicopter	Glyphosate	8.77	*Salix caroliniana*	Medium	2015, 2016	100
2014 "hot imazapyr: hot glyphosate" 4.68:8.77	2014	September	Aerial	Helicopter	Imazapyr: glyphosate	4.68:8.77	*Salix caroliniana*	High	2015, 2016	51
2014 "medium imazapyr: light glyphosate" 1.75:5.85	2014	August	Aerial	Helicopter	Imazapyr: glyphosate	1.75:5.85	*Salix caroliniana*	High	2015, 2016	294
2014 "light imazapyr: medium glyphosate" 1.17:7.02	2014	August	Aerial	Helicopter	Imazapyr: glyphosate	1.17:7.02	*Salix caroliniana*	High	2016	153
2015 "light imazapyr: medium glyphosate" 1.17:7.02	2015	May	Aerial	Helicopter	Imazapyr: glyphosate	1.17:7.02	*Salix caroliniana*	Medium	2016	118
2008, 2009, & 2011	2015	September	Aerial	Helicopter	Imazamox: MSO	2.34:1.17	*Typha* & *Ludwigia* spp.	Medium /Low	2015, 2016	290
Control A	–	–	Untreated	–	–	–	–	–	2015, 2016	41
Control B	–	–	Untreated	–	–	–	–	–	2016	40
Control C	–	–	Untreated	–	–	–	–	–	2015, 2016	40

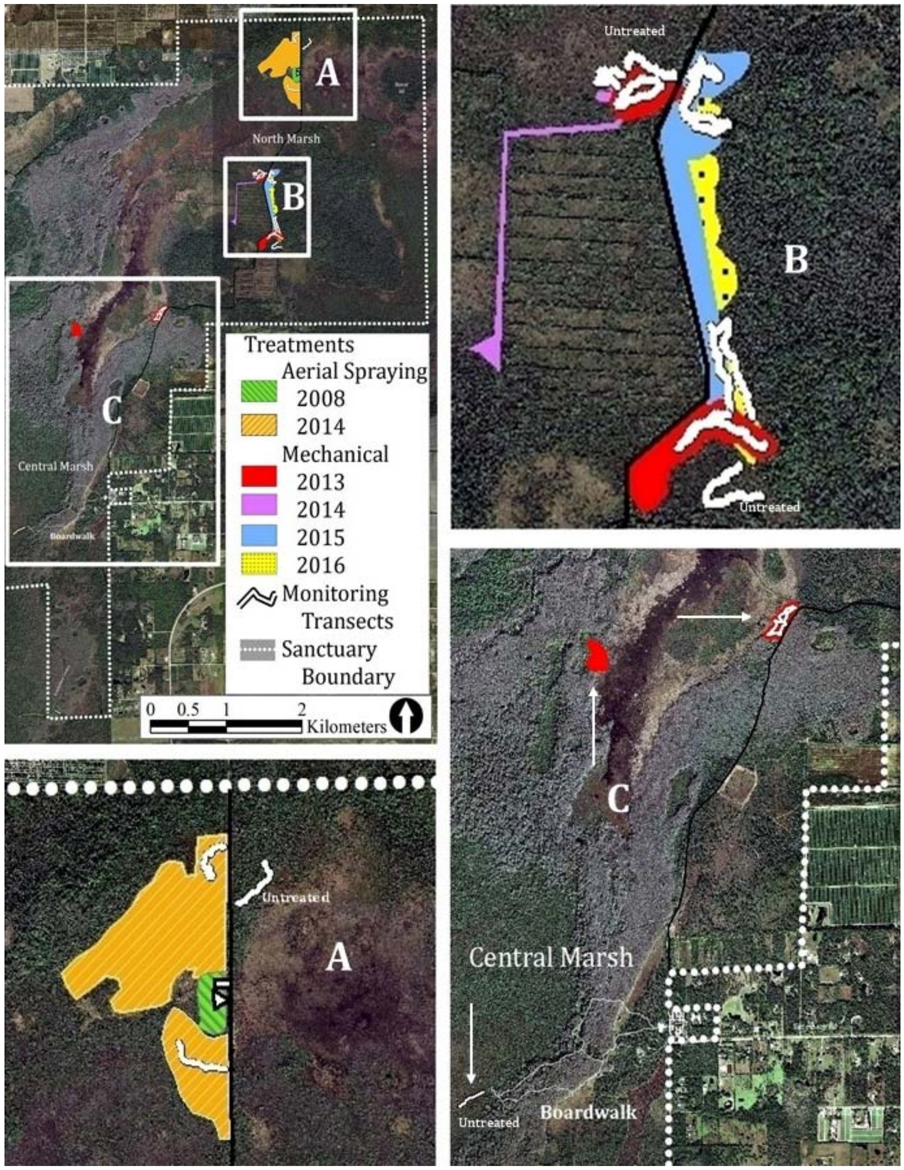

Figure 7.—Corkscrew Swamp Sanctuary's North Marsh willow treatment areas and North Marsh and Central Marsh sampling transects. (A) The aerial spraying treatments and transects and one untreated area transect. (B) Multiple mechanical treatment areas (some not sampled) and transects and two transects in untreated areas. (C) Arrows point to two 2013 mechanical treatment areas, one unsampled and one sampled with transect, plus one untreated transect.

glyphosate and 2015 "light imazapyr:medium glyphosate" (May) treatments, which were conducted at the end of the dry season; the May 2015 treatment was conducted when water levels were below ground (Table 1).

On CSS, at the end of the rainy season when water levels are usually high (October 2008), CSS managers conducted an aerial treatment using glyphosate and diquat in the North Marsh to target willow (Figures 4 and 7, Table 2). In June 2014 additional areas of dense willow adjacent to the 2008 treatment were aerially treated using the same "hot imazapyr:hot glyphosate" mix (4.68:8.77 L/ha) used on CREW later that same year. Although treatment was conducted at the end of the dry season when water levels would normally be below ground, this area receives water from a canal to the north where pumping for agriculture can create unnaturally wet conditions; no record exists on water levels at time of treatment (Figures 4 and 7, Table 2). Also, in the North Marsh, CSS conducted mechanical treatment of willow at different sites from 2013 through 2016. Willow and other vegetation were shredded using a rubber track skid steer with a gyro track mulching head that was light enough to access the areas with minimal rutting (J. Jones, 2016, pers. comm.; Figure 8). All treatments on CSS were conducted near the end of the dry season (May–June) except the 2008 aerial treatment, which was done in the late wet season.

Sampling Methods

Monitoring of vegetation response to willow treatments was conducted almost exclusively during the months of October–December in 2015 and 2016. This gave the 2016 spring

Table 2.—Corkscrew Swamp Sanctuary's herbicide and mechanical treatment summary. See Figure 7 for treatment and sampling locations.

Sampling area name	Treatment year	Treatment month	Treatment type	Application equipment	Herbicide	Rate (liters/ hectare)	Years sampled	Hectares treated
2008 Aerial Glyphosate	2008	October	Aerial herbicide application	Helicopter	Glyphosate: diquat	unknown	2015, 2016	1.7
2014 CSS N "hot imazapyr: hot glyphosate"	2014	June	Aerial herbicide application	Helicopter	Imazapyr: glyphosate	4.68:8.77	2016	15.8
2014 CSS S "hot imazapyr: hot glyphosate"	2014	June	Aerial herbicide application	Helicopter	Imazapyr: glyphosate	4.68:8.77	2016	5.6
2013 Eagle Island Curve	2013	May	Mechanical (mulching)	Gyrotrack	–	–	2016	1.2
2013 N of Fishfarm	2013	May	Mechanical (mulching)	Gyrotrack	–	–	2016	1.2
2013 W of Washout Rd	2013	May	Mechanical (mulching)	Gyrotrack	–	–	2016	0.5
2014 W of Washout Rd	2014	May	Mechanical (mulching)	Gyrotrack	–	–	2016	0.4
2015 E of Washout Rd	2015	May	Mechanical (mulching)	Gyrotrack	–	–	2016	2.2
2016 S-Central Area E of Washout Rd	2016	May	Mechanical (mulching)	Gyrotrack	–	–	2016	1.2
Control E of Washout Rd	–	–	Untreated	–	–	–	2016	–
Control W of Washout Rd	–	–	Untreated	–	–	–	2016	–
Control N of Fishfarm	–	–	Untreated	–	–	–	2016	–
Control Central Marsh	–	–	Untreated	–	–	–	2016	–

Figure 8.—Rubber track skid steer with a gyro trac mulching head mulching willow at Corkscrew Swamp Sanctuary.

mechanical treatment a full growing season to recover and the fall 2015 herbicide treatment time to be effective, while at the same time allowing access to the treatment sites with an airboat or Marsh Master (tracked terrestrial and aquatic vehicle) when water was still present and while vegetation was still green.

Sampling generally followed the relevé method with modifications (Mueller-Dombois and Ellenberg 1974; Minnesota Department of Natural Resources 2013). Monitoring aerially sprayed willow growing in organic soils with standing water most of the year is a logistical challenge. The three aerially sprayed areas on CSS required walking in water and unconsolidated organic substrate sometimes over our waists, which made climbing over downed tree trunks and crowns very demanding. On CREW, areas could only be accessed when water was deep enough to travel by airboat. Moving the airboat through downed tree trunks and crowns was arduous, requiring hacking our way free at times. Differences in treatments and times since treatments meant quite variable conditions between and within a treatment area; this led us to use transects that would incorporate the heterogeneity within each treatment area. Vegetation coverage categories were reduced to four since the whole sample could not be viewed from one point, decisions had to be mentally retained until the end of the transect, and traveling along the transect could be distracting.

The majority of the samples were collected along an approximately 0.32 km transect. Since vegetation within the treatments was very heterogeneous, an increased sample area beyond the recommended 100–400 m^2 was appropriate. Assuming at least 1.5 m were included in the sample on each side, 322 m transects included 981 m^2; therefore, minimum sample area is more than adequate to include most species regularly distributed through the treatment area (Peet et al. 1998; Chytry and Otypkova 2003).

The CREW samples were collected from an airboat or Marsh Master moving slowly along the transect with at least two observers, surveying opposite sides of the vehicle/vessel, noting all species of vascular plants. The vehicle/vessel was stopped as necessary to confirm the identity of plants. Some plants were collected to verify identifications. At CSS, all transects were sampled on foot using the same methods.

Each new plant species was recorded as it was seen, and it was pointed out to the other observers so all were aware of its presence and appearance. Observers noted abundance of each species while traveling along the transect. Abundance categories were labeled as "Abundant," "Common," "Occasional," and "Rare." No time limit was imposed since stops were necessary and travel often difficult through dead and live trees. At the end of the transect, observers reported their observations of abundance for each species. If abundance categories were different between observers, the observers discussed the species and came to a consensus on abundance.

On CREW, seven areas that received different treatments were sampled; three untreated control areas were also sampled (Figure 6, Table 3). On CSS, nine different treated areas were sampled; four untreated control areas were also sampled (Figure 7, Table 3). Within these 16 treated and seven untreated areas, data were collected along transects within the areas (Figures 6 and 7). Survey transects were nonrandom in herbicided and untreated areas due to the abundance of downed and living willows obstructing access and in smaller mechanically treated areas where transects were positioned to avoid edges and still achieve the desired length.

A total of 38 samples were collected, seven in 2015 and 31 in 2016, 24 on CREW and 14 on CSS (Table 3). Twenty-two of the samples were taken in areas aerially treated with herbicide; eighteen of these were from CREW and four were from CSS. Six samples were taken in areas treated mechanically; all were on CSS. There are 10 samples taken from untreated areas, six from CREW and four from CSS. The number of transects sampled were not equal between treatments (Tables 3 and 4A).

Plants names follow Wunderlin et al. as listed on 1 November 2017 (Wunderlin et al. 2017). Additional detail on coordinates, transect lengths, monitoring time, water depths, and organic soil depths at each transect, and species found on each transect including their classification, can be found in the initial report to CSS and CREW (McCollom et al. 2017).

Analysis

Sample areas are not homogeneous. Areas were intentionally chosen that represent treatments over a broad range of conditions including the ability to access and maneuver within sites, gradients from large to small willows within treatments, a variety of herbicides and application rates, differences in time since treatment, and the number of treatments per area.

Three target species important in defining the health of the marsh were analyzed individually: willow, cattail, and sawgrass (*Cladium jamaicense* Crantz). Native grasses and sedges were pooled for analysis since they are important in supporting fire in marshes (Anderson 1982). Plants were also characterized as either "desirable" or "undesirable" marsh species. Undesirable species included all nonnative plants, nuisance natives, and species that are not normally a significant component of a fire-maintained marsh, including shrubs, trees, and vines. Desirable species included all other herbaceous marsh plants, including ferns, floating and submerged plants, grasses, sedges, and forbs.

Since qualitative categories were not assigned numeric values before data collection, at the end of field sampling, observers discussed, gained consensus, and assigned conversion values as follows: Abundant was roughly three times more cover than Common, Occasional was roughly three times less cover than Common, and Rare was approximately 1–2% cover. Therefore, the relative cover data for individual species (Abundant, Common, Occasional, Rare) along each transect were quantified using the conversion values called Coverage Scores to emphasize that the numbers are not percent cover (Abundant = 100, Common = 31, Occasional = 10, and Rare = 2).

When individual species comparisons were analyzed, the Coverage Score values for a species were averaged for all the transects represented in each treatment involved in the comparison.

$$\text{Coverage Index} = \frac{\text{Sum (Coverage Score for the species)}}{\text{Number of transects}}$$

The Coverage Score values for the individual species comparisons can range from 0 to 100.

When treatments (e.g., Herbicide, Mechanical, Untreated) involving a group of species (i.e., desirable species, undesirable species, grasses and sedges) were compared, the Coverage Score values for all species within the group were summed for each transect. Then the summed transect values were averaged for all transects in each treatment involved in the comparison.

$$\text{Coverage Index} = \frac{\text{Sum (Coverage Score for all species in the group for all transects in the treatment)}}{\text{Number of transects in the treatment}}$$

Because each species could have a Coverage Score from 0 to 100, and multiple species are summed, some Coverage Index values may be greater than 100. The Coverage Index is dependent on the number of species in the group and their abundance; the more species and/or the greater abundance, the higher the Coverage Index value.

Treatment comparisons included:

- All Herbicide vs. All Mechanical treatments vs. Untreated
- Imazapyr/Glyphosate Mixes vs. Other Herbicides (primarily glyphosate) vs. Untreated
- Three Imazapyr/Glyphosate combination mixing rates vs. Untreated

Analyses were conducted in the statistical program R 4.0.2 (R Core Team 2020). Nonparametric comparison tests were used to identify differences in Coverage Index depending on treatment for each cover type/category (desirable, undesirable, willow, cattail, sawgrass, grasses and sedges). First, a Kruskal-Wallis rank sum test (Kruskal and Wallis 1952) was performed to determine if there were statistically significant differences between the treatment types/levels, and if so, then Wilcoxon-Mann-Whitney tests were performed (Wilcoxon 1945; Mann and Whitney 1947) to detect which pairs of treatment types/levels were statistically different (Table 4A). The *P*-values used to determine statistically significant differences between samples were adjusted to account for multiple tests performed on the same dataset using a Bonferroni correction (Bonferroni 1935, 1936) and are listed as "adjusted *P*" (Table 4B).

Table 3.—Summary information for sampling transects. The first three columns indicate which sampling transects were used for comparisons of vegetation cover between (1) all herbicide treatments (H), all mechanical treatments (M), and untreated areas (U); (2) imazapyr/glyphosate herbicide (I), other herbicides, primarily glyphosate only, older treatments (O), and untreated areas (U); and (3) three different mixing rates of imazapyr and glyphosate including a "hot imazapyr:hot glyphosate" mix (H:H) of 4.68 L imazapyr and 8.77 L glyphosate per hectare, "medium imazapyr:light glyphosate" mix (M:L) of 1.75 L imazapyr and 5.85 L glyphosate per hectare, and "light imazapyr:medium glyphosate" mix (L:M) of 1.17 L imazapyr and 7.02 L glyphosate per hectare. The right six columns show the Coverage Index, a measure of plant cover, for each sampling transect for (1) desirable plant species, (2) undesirable plant species, (3) willow, (4) cattail, (5) sawgrass, and (6) grasses and sedges. For individual species, Coverage Indices range from 0 to 100. Where multiple species are included in the category, the Coverage Index can exceed 100.

Comparisons						Coverage Index for each sample					
Herbicide **M**echanical **U**ntreated	**I**mazapyr/ glyphosate mix **O**ther herbicides **U**ntreated	**Imazapyr/ glyphosate mixes:** **H**ot **M**edium **L**ight **U**ntreated	**Sampling year**	**Area**	**Sampling transect**	**Desirable marsh species**	**Undesirable marsh species**	**Willow**	**Cattail**	**Sawgrass**	**Grass/sedge**
H	O		2016	CREW	2008	140	187	31	10	0	28
H	O		2016	CREW	2008 #2	94	324	100	10	0	2
H	O		2015	CREW	2009 from edge	0	100	0	100	0	0
H	O		2016	CREW	2009	186	59	2	31	0	33
H	O		2016	CREW	2009 #2	91	329	2	10	0	26
H	O		2015	CREW	2011	66	271	100	31	0	8
H	O		2016	CREW	2011	232	92	31	2	31	68
H	O		2016	CREW	2011 #2	85	198	10	31	0	6
H	I	H:H	2015	CREW	2014 "hot imazapyr:hot glyphosate" 4.68:8.77 along edge only	0	161	10	100	0	0
H	I	H:H	2016	CREW	2014 "hot imazapyr:hot glyphosate" 4.68:8.77	357	67	31	10	0	31
H	I	H:H	2016	CREW	2014 "hot imazapyr:hot glyphosate" 4.68:8.77 #2	71	332	100	100	0	6
H	I	M:L	2015	CREW	2014 "medium imazapyr:light glyphosate" 1.75:5.85	426	137	100	0	0	114
H	I	M:L	2016	CREW	2014 "medium imazapyr:light glyphosate" 1.75:5.85	97	346	100	100	0	14
H	I	M:L	2016	CREW	2014 "medium imazapyr:light glyphosate" 1.75:5.85 #2 Very Short	26	143	2	100	0	4
H	I	L:M	2016	CREW	2014 "light imazapyr:medium glyphosate" 1.17:7.02	179	113	31	10	0	6
H	I	L:M	2016	CREW	2014 "light imazapyr:medium glyphosate" 1.17:7.02 #2	293	138	10	10	0	35
H	I	L:M	2016	CREW	2015 "light imazapyr:medium glyphosate" 1.17:7.02	366	6	2	2	0	20
H	I	L:M	2016	CREW	2015 "light imazapyr:medium glyphosate" 1.17:7.02 #2	389	6	0	0	0	16
U	U	U	2015	CREW	Control A	257	116	100	0	100	104
U	U	U	2016	CREW	Control A	178	141	100	31	100	104

Table 3.—Continued.

Comparisons						Coverage Index for each sample					
Herbicide **M**echanical **U**ntreated	**I**mazapyr/ glyphosate mix **O**ther herbicides **U**ntreated	**Imazapyr/ glyphosate mixes:** **H**ot **M**edium **L**ight **U**ntreated	**Sampling year**	**Area**	**Sampling transect**	**Desirable marsh species**	**Undesirable marsh species**	**Willow**	**Cattail**	**Sawgrass**	**Grass/sedge**
U	U	U	2016	CREW	Control B	155	288	100	10	100	104
U	U	U	2015	CREW	Control C	218	53	31	2	31	53
U	U	U	2016	CREW	Control C	190	136	100	0	31	41
U	U	U	2016	CREW	Control C #2	393	53	31	0	31	43
H	O		2015	CSS	2008 Aerial Glyphosate	0	214	100	0	0	0
H	O		2016	CSS	2008 Aerial Glyphosate	0	232	100	100	0	0
M			2016	CSS	2013 Eagle Island Curve	292	111	10	10	0	165
M			2016	CSS	2013 N of Fishfarm	319	112	10	31	10	238
M			2016	CSS	2013 W of Washout Rd	203	200	31	31	31	74
H	I	H:H	2016	CSS	2014 CSS N "hot imazapyr:hot glyphosate" 4.68:8.77	89	357	0	100	0	16
H	I	H:H	2016	CSS	2014 CSS S "hot imazapyr:hot glyphosate" 4.68:8.77	229	371	10	100	0	28
M			2016	CSS	2014 W of Washout Rd	429	55	10	10	31	111
M			2016	CSS	2015 E of Washout Rd	438	89	0	10	31	155
M			2016	CSS	2016 S-Central Area	544	42	2	2	10	116
U	U	U	2016	CSS	Control Central Marsh	286	135	100	0	100	102
U	U	U	2016	CSS	Control E of Washout Rd	268	386	100	2	0	136
U	U	U	2016	CSS	Control N of Fishfarm	271	324	100	10	31	180
U	U	U	2016	CSS	Control W of Washout Rd	95	134	100	2	31	43

Table 4.—(A) Results of the Kruskal-Wallis rank sum test (shaded rows) identify statistically significant differences between comparisons of treatment type, herbicide type, and imazapyr/glyphosate mixes, and the results of the Wilcoxon-Mann-Whitney test (non-shaded rows) show which pairs of treatment types/mixes were statistically different. (B) Bonferroni correction values were used to adjust *P*-values to determine statistically significant differences since multiple tests were performed on the same dataset; these corrections are distinguished in the text as "adjusted *P*" and are expressed in the Significance Codes in this table.

A Kruskal-Wallis Rank Sum Test and Wilcoxon-Mann-Whitney Rank Sum Test

			Desirable Species		Undesirable Species		Willow		Cattail		Sawgrass		Grasses & Sedges	
N	Treatments	Compare	*P*-value	Significance Code	*P*-value	Significance Code	*P*-value	Significance Code	*P*-value	Significance Code	*P*-value	Significance Code	*P*-value	Significance Code
	TREATMENT TYPE		0.006	**	0.164		0.002	**	0.024	*	0.000	***	0.000	***
22	**H=Herbicided (Aerial)**	**H-M**	0.007	*	0.085		0.340		0.567		0.000	***	0.000	**
6	**M=Mechanical**	**H-U**	0.087		0.612		0.004	*	0.012	*	0.000	***	0.000	***
10	**U=Untreated**	**M-U**	0.016	*	0.116		0.001	**	0.044		0.053		0.057	
	HERBICIDE TYPE		0.033	*	0.860		0.013	*	0.036	*	0.000	***	0.000	***
12	**I=Imazapyr:Glyphosate**	**I-O**	0.126		0.915		0.689		0.485		0.290		0.618	
10	**O=Glyphosate only (older)**	**I-U**	0.771		0.717		0.005	*	0.025		0.000	***	0.001	**
10	**U=Untreated**	**O-U**	0.004	*	0.624		0.025		0.040		0.001	**	0.001	**
	IMAZAPYR/GLYPHOSATE MIX		0.244		0.082	.	0.014	*	0.024	*	0.001	***	0.007	**
5	**H:H="hot imazapyr: hot glyphosate"**	**H:H-M:L**	0.786		0.571		0.539		0.696		1.000		1.000	
3	**M:L="medium imazapyr: light glyphosate"**	**H:H-L:M**	0.111		0.065		0.530		0.027		1.000		0.711	
4	**L:M="light imazapyr: medium glyphosate"**	**H:H-U**	0.206		0.198		0.015		0.005	*	0.004	*	0.003	*
10	**U=Untreated**	**M:L-L:M**	0.629		0.108		0.280		0.467		1.000		0.857	
		M:L-U	0.573		0.271		0.567		0.254		0.020		0.269	
		L:M-U	0.188		0.103		0.004	*	0.657		0.009		0.006	*

B Bonferroni Correction

	For 3 comparisons:		For 4 comparisons:	
Significance Code	If *P* ≤	then adjusted *P* ≤	If *P* ≤	then adjusted *P* ≤
***	0.00033	0.001	0.00025	0.001
**	0.00333	0.01	0.0025	0.01
*	0.01667	0.05	0.0125	0.05

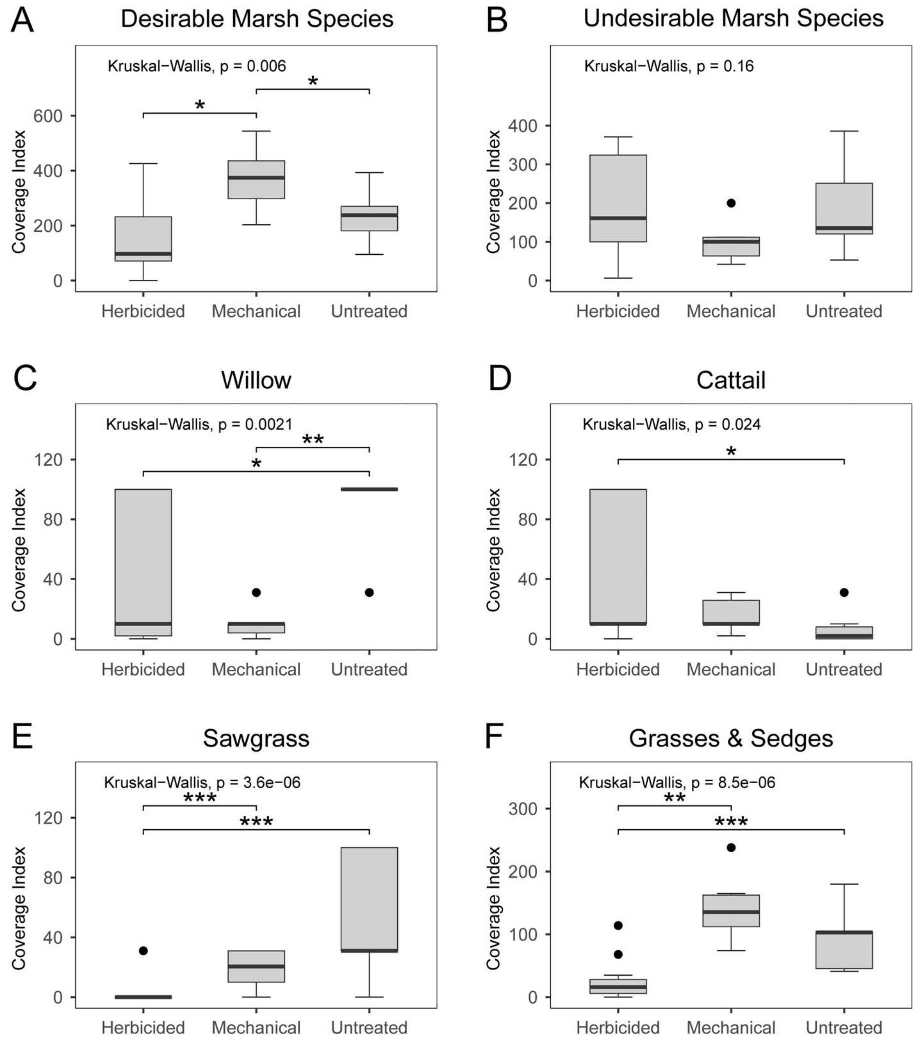

Figure 9.—Comparison of Coverage Indices for aerial herbicide treatments, mechanical treatments, and untreated areas for (A) desirable species, (B) undesirable species, (C) willow, (D) cattail, (E) sawgrass, and (F) grasses and sedges. In graphs for individual species, Coverage Indices range from 0 to 100. Where multiple species are included in the category, the Coverage Index can exceed 100. In the box plots, the horizontal line in each box is the median, the boxes define the hinge (25–75% quartile), the whiskers extend from the hinge to the largest/smallest value no further than 1.5 times the inter-quartile range of the hinge, and any data points outside the whiskers are considered outliers and are represented as dots (Table 5). Comparisons between groups are based on results of Kruskal-Wallis rank sum tests and Wilcoxon-Mann-Whitney tests (Table 4A). Significant differences are shown by a horizontal line above the plots connecting two treatments; one, two, and three asterisks above this line indicate that the two treatments are significantly different after Bonferroni adjustment at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively (Table 4B).

Box-and-whisker plots were created in R for each comparison. In graphs for individual species, the y-axis range was between 0 and 100. When multiple species were included in the category, the Coverage Index could exceed 100. In both cases, the greater the Coverage Index, the more area was covered by this species or group of species; where multiple species are included, larger Coverage Indices also could represent greater diversity.

RESULTS AND DISCUSSION

Mechanical Treatment vs. Aerial Spraying of Herbicides

Untreated areas still retained a fair amount of desirable marsh vegetation such as pickerelweed (*Pontederia cordata* L.) and sawgrass (Figure 9A, Tables 3, 4, and 5). This is encouraging; if these areas are treated in the future, there is still desirable seed and root stock present to repopulate the areas.

Median cover of desirable plant species in mechanical treatments was 3.85 times higher than the median for herbicided areas and approximately 1.5 times higher than the untreated areas (Figure 9A, Tables 3, 4, and 5). Undesirable species cover was not significantly different between treatments or untreated areas (Figure 9B), so no significant progress has been made at eliminating undesirable species.

Willow cover was abundant in the untreated areas (Figure 9C). It was much lower in both aerially sprayed (adjusted $P \leq 0.05$) and mechanically treated (adjusted $P \leq 0.01$) areas.

Cattail is not a component of undisturbed South Florida marsh communities, so it was considered a nuisance native and therefore an undesirable species. Cattail thrives in areas with high sun exposure and was not common in the untreated areas, partially due to shading from the willow canopy and lack of disturbance (Figure 9D). Both treatments showed more cattail

Table 5.—Median (1st quartile, 3rd quartile) Coverage Index, a measure of plant cover, for comparisons between (1) all herbicide treatments (H), all mechanical treatments (M), and untreated areas (U); (2) imazapyr/glyphosate herbicide (I), other herbicides, primarily glyphosate only, older treatments (O), and untreated areas (U); and (3) different mixing rates of imazapyr and glyphosate including a "hot imazapyr:hot glyphosate" mix (H:H) of 4.68 L imazapyr and 8.77 L glyphosate per hectare, "medium imazapyr:light glyphosate" mix (M:L) of 1.75 L imazapyr and 5.85 L glyphosate per hectare, and "light imazapyr:medium glyphosate" mix (L:M) of 1.17 L imazapyr and 7.02 L glyphosate per hectare. Individual and groups of plants are (1) desirable plant species, (2) undesirable plant species, (3) willow, (4) cattail, (5) sawgrass, and (6) grasses and sedges. For individual species, Coverage Indices range from 0 to 100. Where multiple species are included in the category, the Coverage Index can exceed 100.

	Comparisons					
	Herbicided (H) Mechanical (M) Untreated (U)		**Imazapyr/glyphosate (I) Other herbicides, primarily glyphosate only [older] (O) Untreated (U)**		**Imazapyr/glyphosate mixes: Hot imaz:hot glyp (H:H) Medium imaz:light glyp (M:L) Light imaz:medium glyp (L:M) Untreated (U)**	
Desirable	H	97 (71, 232)	I	204 (85, 359)	H:H	89 (71, 229)
	M	374 (299, 436)	O	91 (66, 140)	M:L	97 (62, 262)
	U	237.5 (181, 270)	U	237.5 (181, 270)	L:M	329.5 (265, 372)
					U	237.5 (181, 270)
Undesirable	H	161 (100, 324)	I	140.5 (102, 336)	H:H	332 (161, 357)
	M	100 (64, 112)	O	198 (100, 271)	M:L	143 (140, 245)
	U	135.5 (121, 251)	U	135.5 (121, 251)	L:M	59.5 (6, 119)
					U	135.5 (121, 251)
Willow	H	10 (2, 100)	I	10 (2, 48)	H:H	10 (10, 31)
	M	10 (4, 10)	O	31 (2, 100)	M:L	100 (51, 100)
	U	100 (100, 100)	U	100 (100, 100)	L:M	6 (2, 15)
					U	100 (100, 100)
Cattail	H	10 (10, 100)	I	55 (8, 100)	H:H	100 (100, 100)
	M	10 (10, 26)	O	10 (10, 31)	M:L	100 (50, 100)
	U	2 (0, 8)	U	2 (0, 8)	L:M	6 (2, 10)
					U	2 (0, 8)
Sawgrass	H	0 (0, 0)	I	0 (0, 0)	H:H	0 (0, 0)
	M	20.5 (10, 31)	O	0 (0, 0)	M:L	0 (0, 0)
	U	31 (31, 100)	U	31 (31, 100)	L:M	0 (0, 0)
					U	31 (31, 100)
Grasses & Sedges	H	16 (6, 28)	I	16 (6, 29)	H:H	16 (6, 28)
	M	135.5 (112, 163)	O	8 (2, 28)	M:L	14 (9, 64)
	U	103 (46, 104)	U	103 (46, 104)	L:M	18 (14, 24)
					U	103 (46, 104)

cover, but only the herbicided areas had significantly more cattail than the untreated areas (adjusted $P \leq 0.05$). In some herbicided areas, cattail formed a thick, often impenetrable cover that created monocultures of cattail. Treatment areas where cattails were abundant had significantly less desirable species cover than untreated areas where willow was abundant (Wilcoxon-Mann-Whitney, $U = 59$, $n_1 = n_2 = 8$, $P = 0.005$). Untreated willow areas had vertically stratified vegetation with some desirable species and were accessible to wildlife for movement and foraging on the ground and through gaps in the willow canopy.

Grasses and sedges are excellent fuels that will carry fire through the marsh (Wade et al. 1980; Lee et al. 2005). Although other herbaceous plants like arrowhead (*Sagittaria* spp.) and pickerelweed will burn, they require drier conditions even later in the dry season when Florida Forest Service is more likely to prohibit burning. There is also a higher risk of burning organic soils later in the dry season, causing undesirable muck fires. Without the grass and sedge component, it is much more difficult to reach a balance between being dry enough to burn, yet not so dry that the organic substrate will burn. The best way to control willow once an area is restored is with fire, so fuels are critical to the long-term success of restoring marshes. If they cannot be burned, natural succession without fire will return them to woody plants or dense cattails.

The biggest problem with herbicide treatments is that the herbicides used (glyphosate and/or glyphosate and imazapyr) eliminated most of the already patchy grasses and sedges (Figures 9E and 9F). Sawgrass is a common species in South Florida marshes and an excellent fuel for burning. Herbicide treatment areas had significantly less sawgrass than either the mechanical or untreated areas (adjusted $P \leq 0.001$, Figure 9E). Sawgrass was present in 90% of untreated, 100% of mechanical, but only 5% of herbicided transects. Sawgrass cover in mechanically treated areas was not significantly lower than the untreated areas. Grass and sedge cover in herbicided areas was significantly lower than in the mechanical (adjusted $P \leq 0.01$) or untreated (adjusted $P \leq 0.001$) areas (Figure 9F). Median cover of grasses and sedges in mechanical treatment areas were more than eight times higher than in the herbicided areas (adjusted $P \leq 0.01$), but not significantly different from the untreated areas. Median grass and sedge cover in herbicided areas was more than six times less than in the untreated areas, suggesting that

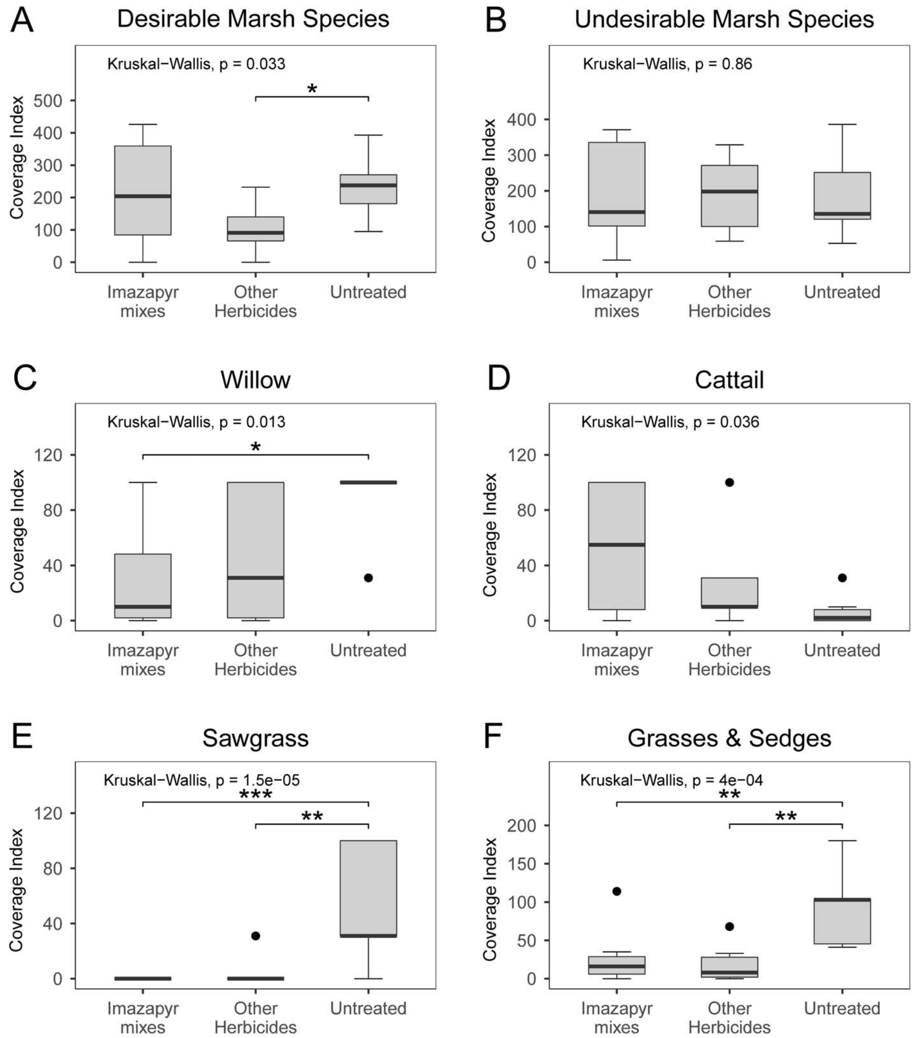

Figure 10.—Comparison of Coverage Indices for aerial herbicide treatments with imazapyr/glyphosate mixes, other herbicides (primarily glyphosate), and untreated areas for (A) desirable species, (B) undesirable species, (C) willow, (D) cattail, (E) sawgrass, and (F) grasses and sedges. In graphs for individual species, Coverage Indices range from 0 to 100. Where multiple species are included in the category, the Coverage Index can exceed 100. In the box plots, the horizontal line in each box is the median, the boxes define the hinge (25–75% quartile), the whiskers extend from the hinge to the largest/smallest value no further than 1.5 times the inter-quartile range of the hinge, and any data points outside the whiskers are considered outliers and are represented as dots (Table 5). Comparisons between groups are based on results of Kruskal-Wallis rank sum tests and Wilcoxon-Mann-Whitney tests (Table 4A). Significant differences are shown by a horizontal line above the plots connecting two treatments; one, two, and three asterisks above this line indicate that the two treatments are significantly different after Bonferroni adjustment at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively (Table 4B).

herbicide treatments are significantly removing grasses and sedges (adjusted $P \leq 0.001$).

The mechanical treatments used at CSS involved shredding woody vegetation with a gyro track mulching head that grinds vegetation to ground level, causing minimal soil and root disturbance. This technique is more expensive and more time-consuming than aerial herbicide treatments. This method is also dependent on dry ground so equipment will not sink or rut organic soils that usually do not dry down until late in the dry season and, in some years, do not dry down at all. It is also critical that wet season water levels rise soon enough after the mechanical treatment and remain high long enough to drown resprouting from the willow bases (Ponzio et al. 2006). With these restrictions at both ends of the treatment, there is a short window of time to get the work done. Therefore, the amount of area that can be treated is dependent on the number and size of machines available to do the work. Compared to mechanical treatment, helicopter aerial herbicide treatment is cheaper, quicker, can be conducted during most times of the year, and can cover large areas easily. A challenge with aerial herbicide treatments is that when mature willows are treated, large willow stumps, trunks, and crowns remain, and for years these prevent managers from both accessing the area for retreatment or for post-treatment evaluation. Access is much improved and immediate with mechanical treatment.

Organic soils were present on all transects but organic soil depth on mechanical transects (0.2 to >0.9 m) were generally not as deep as on herbicide transects (0.6 to >1.6 m). This difference in depth could have an effect on vegetation response. Since this study was conducted, CSS has continued mechanical treatments in areas with deeper organic soils; they are using larger equipment, treating larger areas, and are comfortable with the results, although no data are currently available on vegetation response.

Although more expensive and difficult, mechanical treatments better retained and/or restored desirable marsh vegetation, which is our primary goal. Mechanical treatments also have significantly more cover of grasses and sedges, increasing the ability to burn hot enough and often enough to control new or resprouting willow. The median cover of sawgrass was zero following aerial herbicide treatments; only one herbicide transect contained any sawgrass. Cover of grasses and sedges in the herbicide areas was significantly lower than in the mechanical or untreated areas. This reduction could seriously hamper marsh restoration both spatially and temporally, since grasses and sedges are integral parts of the marsh system.

Other Herbicides vs. Imazapyr/Glyphosate Mixes and Recovery Over Time

The older treatments from 2008–2011 (glyphosate, but also 2015 imazamox) on CREW and 2008 (glyphosate/diquat) on CSS (Other Herbicides) had significantly less cover of desirable species than the untreated areas (adjusted $P \leq 0.05$; Figure 10A, Tables 3, 4, and 5). Glyphosate treatments may have initially eliminated desirable species and/or the undesirable species may be outcompeting the desirable species over time. Also, multiple treatments on CREW, including retreatment of two areas in 2011 (glyphosate) and retreatment of all glyphosate-treated areas in 2015 (imazamox), may have further reduced the cover of desirable species. Desirable species cover in the imazapyr/glyphosate treatments were not significantly different from either the other herbicide treatments or the untreated areas. The cover of undesirable species in all aerially treated areas was not significantly different than the untreated areas, so no progress has been made at eliminating undesirable species with either imazapyr/glyphosate or any other chemical treatment (Figure 10B).

Less willow cover was present in recently sprayed imazapyr/glyphosate areas than in untreated areas (adjusted $P \leq 0.05$), but willow cover in the older other herbicide treated areas was not significantly different than the untreated areas (Figure 10C). This result could be a function of time, with willow resprouting or reseeding in the older plots, or it could be the effect of multiple treatments or the types of herbicide that were used. In the more recently treated plots, most of the large willow appeared to have been killed, but there were small willows present, either root sprouts off the old trees or new plants.

Although there was more cattail cover in the recently sprayed areas treated with the imazapyr/glyphosate mixes, it was not significantly higher that the untreated areas or other herbicide group (Figure 10D). Since cattails are now well established in the surrounding areas on both CSS and CREW, proximity of a seed source could have contributed to the increased dominance in the more recently treated plots. The 2015 imazamox treatment on CREW could also have eliminated cattail in the older other herbicide plots because imazamox is a selective herbicide used for cattail (Rodgers and Black 2012; Center for Aquatic and Invasive Plants 2020).

Significantly less sawgrass cover was observed in the imazapyr/glyphosate areas (adjusted $P \leq 0.001$) and older other herbicide areas (adjusted $P \leq 0.01$) than in untreated areas (Figure 10E). Sawgrass was absent in all the imazapyr/glyphosate treatment areas and present in only one of the ten other herbicide treatment areas, which is a serious problem for the long-term maintenance of these areas with fire, even if willow and cattail are controlled. Rohr (2017) also found that imazapyr eliminated sawgrass from all plots in treatments at SJRWMD. Hutchison and Langeland (2010) also found that sawgrass densities decreased when treated with imazapyr. Grass and sedge cover was also much lower in both types of aerial herbicide treatment (adjusted $P \leq 0.01$), regardless of time since treatment, compared to the untreated areas (Figure 10F).

Desirable herbaceous vegetation cover in areas recently treated with imazapyr/glyphosate is not significantly less than the desirable vegetation cover in the untreated areas. In these areas recently treated with imazapyr/glyphosate, the dominant cover was pickerelweed, arrowhead, and string lily (*Crinum americanum* L.). Unfortunately, grass and sedge cover were very low, with no sawgrass present. Other herbicide areas treated longer ago primarily with glyphosate, and some areas also treated recently with imazamox, do not appear to be recovering to marsh vegetation; they had significantly lower cover of desirable species (adjusted $P \leq 0.05$), sawgrass (adjusted $P \leq 0.01$), and grasses and sedges (adjusted $P \leq 0.01$) than the untreated areas.

Imazapyr/Glyphosate Combination Mixing Rates

Sample size was small and not equal for comparisons of mixing rates (Table 4A). No significant differences in desirable and undesirable species cover were found (Figures 11A and 11B, Tables 3, 4, and 5). Willow cover was significantly lower only with the "light imazapyr:medium glyphosate" mix (adjusted $P \leq 0.05$; Figure 11C). Cattail cover was higher (adjusted $P \leq 0.05$) and sawgrass cover was lower (adjusted $P \leq 0.05$) than in untreated areas with the "hot imazapyr:hot glyphosate" mix (Figures 11D and 11E). Cover of grasses and sedges were also lower with the "hot imazapyr:hot glyphosate" mix (adjusted $P \leq 0.05$) as well as the "light imazapyr:medium glyphosate" mix (adjusted $P \leq 0.05$) compared with the untreated areas (Figure 11F).

The "hot imazapyr:hot glyphosate" mix, which was applied to the largest trees, achieved the least desirable results based on the increased cover of cattails and the reduction of sawgrass as well as grasses and sedges. The "light imazapyr:medium glyphosate" mix, which was applied to the youngest trees, had significantly less willow, but it also had less grasses and sedges than the untreated areas. More rigorous sampling is necessary to draw definitive conclusions.

Prescribed Burning in Treated Areas

The ultimate goal of the treatments is to achieve willow reduction and allow herbaceous vegetation to repatriate the marsh. Annual maintenance and long-term reduction of woody vegetation could then be achieved through routine prescribed burning.

At CREW, limited herbaceous, burnable vegetation has returned from the 2014–2015 herbicide treatments, while willow

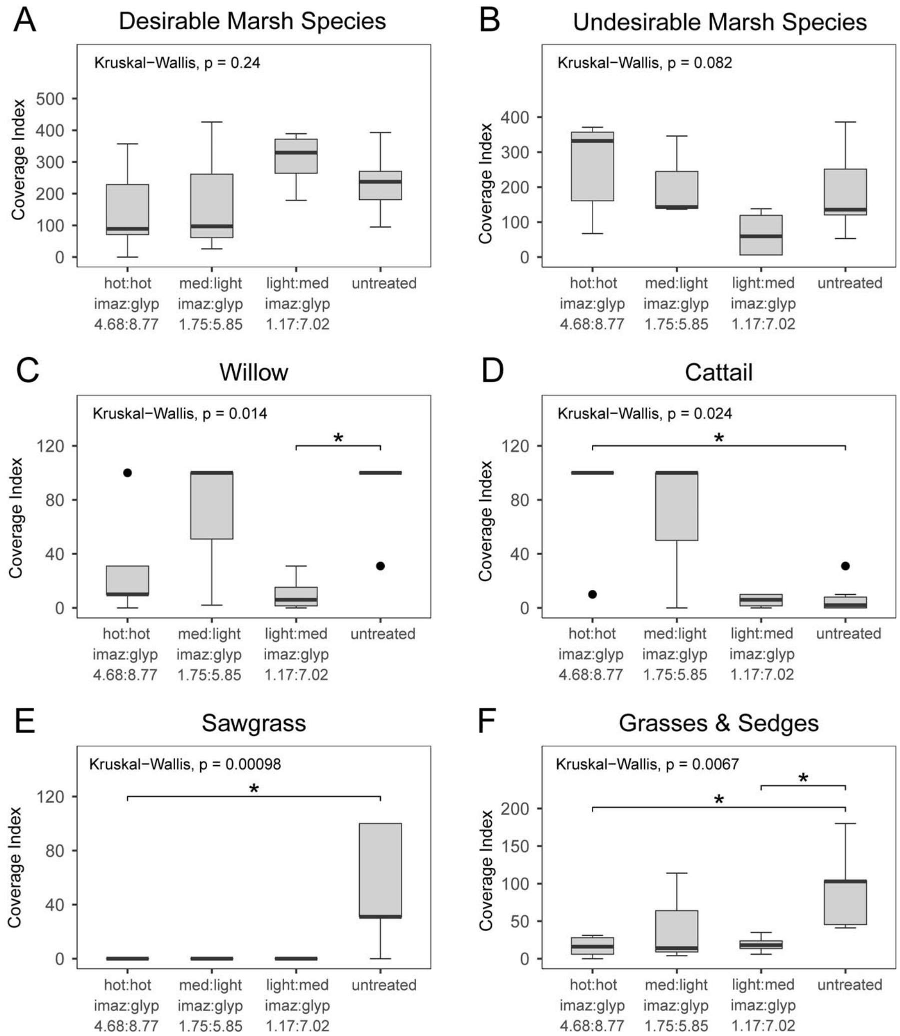

Figure 11.—Comparison of Coverage Indices for aerial herbicide treatments with different mixes of imazapyr and glyphosate and untreated areas for (A) desirable species, (B) undesirable species, (C) willow, (D) cattail, (E) sawgrass, and (F) grasses and sedges. Mix liters per hectare of imazapyr and glyphosate respectively are "hot imazapyr:hot glyphosate" 4.68:8.77, "medium imazapyr:light glyphosate" 1.75:5.85, and "light imazapyr:medium glyphosate" 1.17:7.02. In graphs for individual species, Coverage Indices range from 0 to 100. Where multiple species are included in the category, the Coverage Index can exceed 100. In the box plots, the horizontal line in each box is the median, the boxes define the hinge (25–75% quartile), the whiskers extend from the hinge to the largest/smallest value no further than 1.5 times the inter-quartile range of the hinge, and any data points outside the whiskers are considered outliers and are represented as dots (Table 5). Comparisons between groups are based on results of Kruskal-Wallis rank sum tests and Wilcoxon-Mann-Whitney tests (Table 4A). Significant differences are shown by a horizontal line above the plots connecting two treatments; one, two, and three asterisks above this line indicate that the two treatments are significantly different after Bonferroni adjustment at $P \leq 0.05$, $P \leq 0.01$, and $P \leq 0.001$, respectively (Table 4B).

is readily recolonizing. In addition, the presence of large willow stumps from these treatments limits access for ground ignition in the treated areas. While some herbaceous vegetation has returned to areas treated between 2008 and 2011, enough willow has also returned to limit accessibility by airboat. None of the marsh burns since 2014 have included treated areas. CREW's manager said it was unlikely that the treated areas would carry fire (J. Bozzo, 2021, pers. comm.).

On CSS, the northern 2014 herbicide area does not have enough fuel to burn and the 2008 herbicide area is dominated by willow with Peruvian primrosewillow and cattails; neither is likely to burn. The southern 2014 herbicide area has recently been retreated mechanically. Two burns were attempted that included mechanical treatment areas. The burn manager stated that fuel moisture was higher than anticipated on both burns so they did not burn well; she also stated that the problem was not lack of fuel, both areas had sufficient fuel to burn (A. Webb, 2021, pers. comm.).

Helicopter ignition may be an option to effectively burn herbicided areas that have enough vegetation to carry a fire, but still contain stumps and large woody debris. Airboat burns require enough water to safely manipulate the airboat, but aerial burns could be done later in the dry season with less standing water. On CSS mechanical treatment areas are burned with swamp buggies and ATVs. Advanced coordination with Florida Forest Service (FFS) to review site locations, fire lines, and burn prescriptions could allow burning in the marsh when general FFS restrictions are in place for upland areas, but soil moisture is high enough to safely burn the marsh.

CONCLUSIONS

Currently, mechanical treatment is the environmentally better treatment method because it came closest to returning willow-infested areas to a marsh community dominated by desirable herbaceous vegetation. In addition, mechanical treatment had more grass and sedge cover, which may allow managers to control willow long-term with prescribed fire. Despite the high cost and difficult logistics, mechanical treatment was effective. Since this study was conducted, CSS has continued mechanical treatments, treating 33 ha in 2017 and more than 40 ha/y for the last 3 y by increasing the number of machines working each spring and developing techniques for using larger equipment with minimal adverse environmental effects.

Herbicide treatments with mixes of imazapyr and glyphosate had much lower cover of grasses and sedges, low enough that, at least after two growing seasons, they were unlikely to support fire. Areas treated with other herbicide combinations, but primarily glyphosate, required additional treatments and still had lower cover of desirable species, sawgrass, and grasses and sedges than the untreated areas.

Aerial treatment with a mix of 1.17 L imazapyr and 7.02 L glyphosate per hectare (the "light imazapyr:medium glyphosate" mix) lowered willow cover, while areas treated with a mix of 4.68 L imazapyr and 8.77 L glyphosate per hectare (the "hot imazapyr:hot glyphosate" mix) had more cattail, but both these mixes, at least two growing seasons after treatment, did not have enough grass and sedge cover to support prescribed fire.

Fire is the most effective land management tool for retaining desirable native freshwater marsh vegetation and suppressing willow encroachment. Marshes currently in good condition or partially covered with willow should be burned regularly to maintain the herbaceous plant cover and kill smaller willow. In areas where woody encroachment has already occurred, managers may be able to use a combination of mechanical treatment and prescribed fire to return the marsh to a more desirable condition.

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Kathleen Smith received her MS in Wildlife Ecology from Oklahoma State University in 2005 and her BS in Zoology from Colorado State University in 2001. She worked for the Florida Fish and Wildlife Commission for over 13 years as the Fish and Wildlife Biologist III at the CREW Wildlife and Environmental Area, Big Cypress Wildlife Management Area, and Picayune Strand Wildlife Management Area. In February 2021, Kathleen became the Wildlife Biologist for the Willamette Valley Project at the U.S. Army Corps of Engineers near Eugene, Oregon.

Michael Duever received his PhD in Forest Resources from the University of Georgia in 1973. His professional interests since graduating have focused largely on wetland ecology and natural area restoration and management. He worked for the National Audubon Society for 20 years, working with Audubon's Science and Sanctuary Departments on numerous sites in South Florida and around the United States, as well as long-term ecological studies in the Okefenokee Swamp, coastal Louisiana marshes, a hurricane-impacted old-growth floodplain forest in South Carolina, and the Platte River in Nebraska and Wyoming. He subsequently worked for seven years for The Nature Conservancy on a large wetland mitigation project in central Florida. During the past 21 years he has been the ecological lead on South Florida Water Management District's Picayune Strand Restoration Project and the Southwest Florida Comprehensive Watershed Plan.

Florent Bled earned his PhD from University Paul Sabatier in France. His research interests are at the interface between statistics and ecology, aiming at explicitly integrating ecological processes in a meaningful statistical framework to provide realistic and efficient tools and solutions for population management and conservation. Florent has had the chance to work on projects as diverse as large carnivore ecology (Mississippi State University), predator–prey dynamics and conservation (University of Georgia), bird species trends and distribution in the USA (Patuxent Wildlife Research Center, USGS) and in South Africa (University of Cape Town). He is also the author of Prelude in R*, an introduction to the statistical program R. Florent is currently providing statistical support to the researchers and managers of the Florida Fish and Wildlife*

Conservation Commission as a biostatistician with the Center for Biostatistics and Modeling and Fish and Wildlife Research Institute.

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