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ECOLOGY AND MANAGEMENT OF CAROLINA WILLOW (*SALIX CAROLINIANA*): A COMPENDIUM OF KNOWLEDGE

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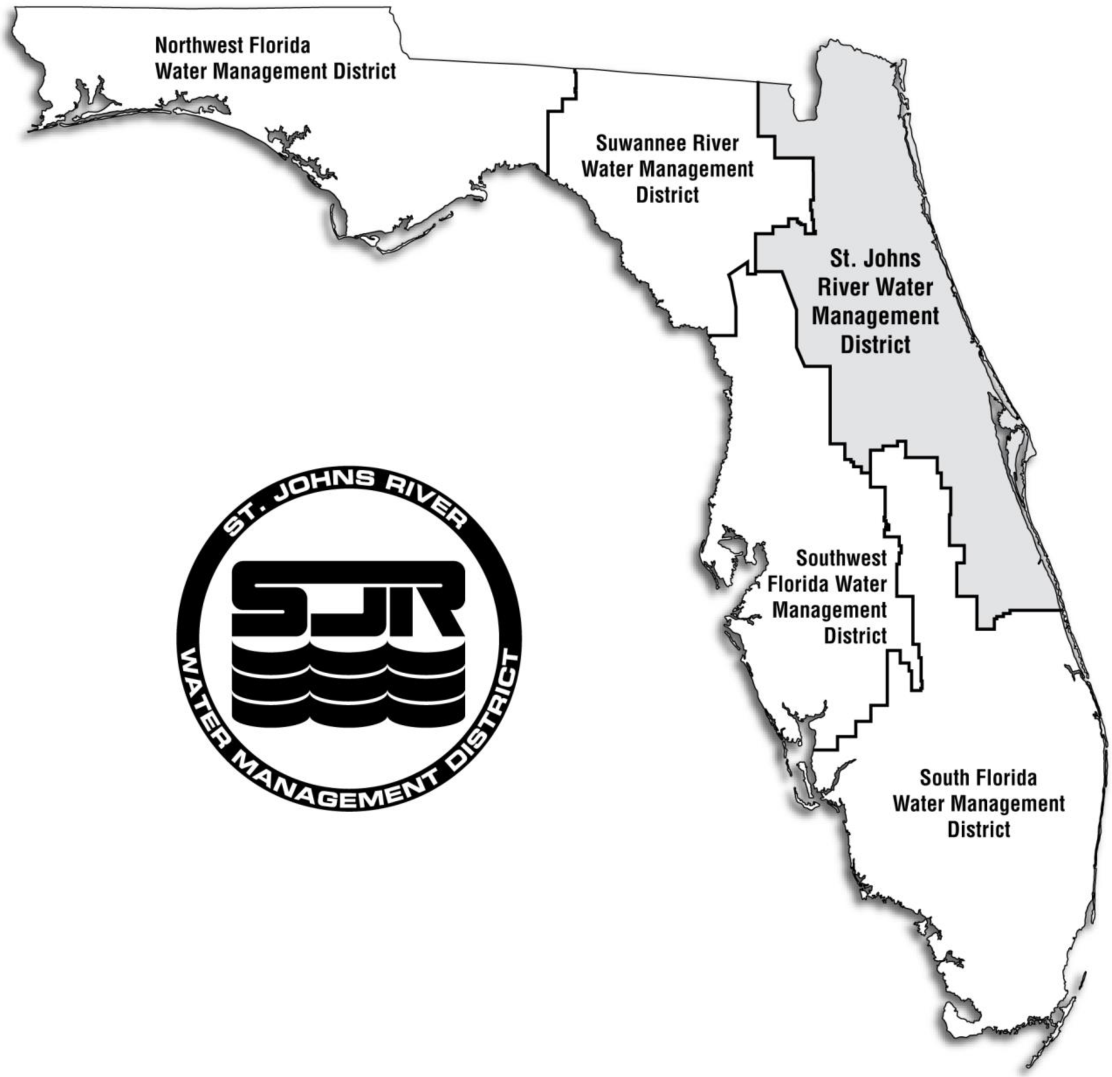

The St. Johns River Water Management District was created in 1972 by passage of the Florida Water Resources Act, which created five regional water management districts. The St. Johns District includes all or part of 18 counties in northeast and east-central Florida. Its mission is to preserve and manage the region's water resources, focusing on core missions of water supply, flood protection, water quality and natural systems protection and improvement. In its daily operations, the District conducts research, collects data, manages land, restores and protects water above and below the ground, and preserves natural areas.

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EXECUTIVE SUMMARY

Expansion of Carolina willow communities, with large-scale replacement of herbaceous wetland communities, has become a major management concern for the St. Johns River Water Management District (District, SJRWMD) on the public lands the agency owns within its 18-county jurisdiction of northeastern and east-central Florida. Initial efforts to control this wetland shrub shed light on how little scientists understood about the biology and ecology of Carolina willow. Early studies at the District focused on the response of mature Carolina willow communities to fire. However, control with fire was limited to areas that were not already inhabited by dense, fire-tolerant stands of mature willow. Subsequently, mechanical removal of willow was evaluated and found to be successful when followed by deep inundation. But this management technique was limited by accessibility on organic soils where willow grows. Subsequent use of chemical management prompted targeted investigations to elucidate the critical aspects of willow biology and ecology that promoted willow expansion on District lands. While some of the information generated from these studies has been formally shared in the scientific literature, much of it was not catalogued, nor documented, in any formal way. District staff anticipated that other management organizations in Florida may have similar unpublished data and realized that compiling and organizing this information would allow each entity to make more informed willow management decisions. Moreover, staff have included published information on the biology and ecology of other willow species that might be relevant to management decisions in instances where that information is unknown for Carolina willow. Altogether, the objectives of compiling this compendium of knowledge was to increase understanding of the environmental conditions that are most favorable to the establishment and persistence of Carolina willow and to provide a useful reference for managing Carolina willow with effective techniques to prevent and control its invasion into herbaceous marsh communities while minimizing undesirable off-target effects. A brief synopsis of findings follows.

Carolina willow is a quintessential pioneer species, quickly responding to conditions that promote its establishment, growth and proliferation. Like many willow species, the most important conditions for young Carolina willow, the age when they are most susceptible to mortality, are hydrology and light availability. Moist soil conditions in areas with plenty of sunlight promote seed germination and growth, allowing seedlings and saplings to quickly out-grow gradually rising water levels and competing vegetation. In addition, nutrient-rich organic soils and symbiotic nitrogen-fixing organisms can support rapid growth. However, drought conditions, especially on non-organic soils with limited capacity to retain water, can quickly lead to the mortality of willow seedlings and saplings. Fast-rising water levels that cause extended inundation and excessive shading by surrounding vegetation are also factors that will quickly kill seedlings and small individuals. Other major factors that may effect the survival and growth of young Carolina willow are fire and herbivory. Specifically, the absence of fire and cattle grazing, contribute to the persistence of small willows. Once mature, Carolina willow becomes less susceptible to the impacts of flooding, drought, competition, fire, and herbivory. Morphological traits, such as adventitious roots along the stem, enable adult willows to withstand extended periods of high water, while deep roots in the soil allow adult willows to tap groundwater during extended periods of drought. As

willows become taller, their canopies extend beyond the reach of most vertebrate herbivores, such as deer and cattle. Eventually, willows shade out plants in the understory reducing fuel loads that are necessary to carry fire. In addition, the high water-holding capacity of mature willows make them practically inflammable, and when subjected to fire, they are merely pruned and can show invigorated growth afterwards.

Mature willow communities harbor a diverse assemblage of flora and fauna that is comparable to, and in some cases, greater than that found in other plant communities occurring in the wetland. However, the propensity of willow to replace and eliminate other plant communities on a broad scale may result in the loss of rare fauna or flora that occur in those other communities and may reduce the overall mosaic of habitat diversity in the wetland landscape. When Carolina willow dominates the landscape, it changes the hydrologic balance by transpiring more water than the herbaceous plant communities that it replaces. This can result in a lower water table that promotes the proliferation of deeply rooted species and may facilitate the development of hardwood swamp communities. Consequently, willow management may be necessary to preserve herbaceous marsh communities.

Managers have a number of tools for controlling Carolina willow that have variable efficacy depending on site conditions. Fire can negatively impact Carolina willow, provided that it is applied when willows are at a young and vulnerable stage of development. Mechanical removal of Carolina willow can be successful when paired with hydrologic events that overtop or submerge chopped plants for extended periods. However, accessibility on organic soils is limited to dry conditions and the long-lasting impacts of heavy equipment on organic soils is of special concern. Some chemical treatments have proven to be successful in removing and reducing the cover of mature willow stands. The efficacy of a number of chemical treatments are currently being investigated. Where Carolina willow is removed by any of these treatments, managers need to address the reasons why the invasion initially occurred and change those conditions to prevent recolonization. A combination of these treatments can be used synergistically to control willow invasion. However, hydrologic manipulation, either to reduce germination on exposed soil or to flood mechanically and/or chemically treated willows, may prove to be one of the biggest challenges for managers that work on large-scale wetlands.

There is still much researchers don’t know about Carolina willow or the ramifications of different treatment options. To make informed management decisions, more investigations need to be conducted on the ecosystem services provided by willow and the attendant costs and benefits of removing willow, controlling its spread, or allowing succession to an alternate or climax community. If management actions include willow removal, managers should prioritize areas for treatment depending on: 1) the goals they wish to achieve, 2) known or suspected indirect impacts of removal, and 3) the probability of success based on the age of the willow and site conditions. Management techniques should be applied with an end goal in mind and with full knowledge of the site conditions that will best achieve that goal. Finally, managers should consider the necessity of using more than one technique, or repeated applications of those techniques, to reach the desired goal.

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ACRONYMS AND ABBREVIATIONS

Location or Organization Acronyms

BCMCA	Blue Cypress Marsh Conservation Area
CA	Conservation Area
CREW WEA	Corkscrew Regional Ecosystem Watershed Wildlife and Environmental Area
EMCA	Emeralda Marsh Conservation Area
District	St. Johns River Water Management District
FLEPPC	Florida Exotic Pest Plant Council
FDMCA	Fort Drum Marsh Conservation Area
RLCA	River Lakes Conservation Area
MCA	Marsh Conservation Area
MI	Moccasin Island Marsh Restoration Area
OPRA	Ocklawaha Prairie Restoration Area
SFWMD	South Florida Water Management District
SJRWMD	St. Johns River Water Management District
SOFIA	South Florida Information Access (USGS)
SRA	Sunnyhill Restoration Area
SW	Sweetwater
TFMCA	Three Forks Marsh Conservation Area
UCF	University of Central Florida
UORB	Upper Ocklawaha River Basin
USGS	United States Geological Survey
USJRB	Upper St. Johns River Basin

Technical Abbreviations

@	at
~	approximately
%	percent
2,4 D	2,4- Dichlorophenoxyacetic Acid
ac	acres
C	carbon
^{o} C	degrees Celsius
CH_4	methane
cm or cm^3	centimeters or cubic centimeters
CO_2	carbon dioxide
Cu	copper
d	day
eg	for example
ET	evapotranspiration
et al.	and others

Technical Abbreviations (continued)

etc.	etcetera
Fe	iron
Ft	feet
g	gram
G50	germination time of half of seeds sown
gal	gallon
ha	hectares
hr(s)	hour(s)
i.e.	in other words
in situ	in its original place or location
K	potassium
kg	kilograms
km	kilometers
m	meters
Mg	magnesium
mg	milligrams
min	minutes
mm	millimeters
mmol	millimoles
mo	month
mol	moles
mtons	metric tons
n	number of samples
N	nitrogen
NH_4-N	ammonium
NO_3-N	nitrate-N
oz	ounce
P	phosphorus
pers. obs.	personal observation
s	second
s^{-1}	per second
sq km	square kilometers
std error	standard error
SD	standard deviation
sp.	one species in the genus
spp.	More than one species in a genus
N/TP	Total Nitrogen/Total Phosphorus ratio
vs	versus
w/	with
w/o	without
wgt	weight
wk(s)	week(s)
yr(s)	year(s

INTRODUCTION

The following is an integrative review of literature pertaining to the biology, ecology, and management of willows, focused primarily on Carolina willow (*Salix caroliniana*), a dominant wetland shrub in the Upper St. Johns River Basin (USJRB) and on other District-owned lands. There are numerous studies that describe willows (*Salix* spp.) and their responses to environmental variables, however, relatively few sources are specific to Carolina willow. Most information on Carolina willow originates from investigations carried out by the St. Johns River Water Management District (District, SJRWMD).

The objectives for compiling this review are to:

- increase understanding of environmental conditions that are most favorable to the establishment and persistence of Carolina willow
- provide a useful reference for managing Carolina willow by identifying effective techniques for preventing/controlling Carolina willow invasion in herbaceous marsh communities
- ensure that land managers, invasive plant specialists, and environmental scientists are utilizing the most effective management techniques available and minimizing undesirable off-target effects

Each section of this compendium has been written so it can be read alone and still provide the reader with all of the information they are seeking in that section without having to refer back to other sections. As a result, scientific names and common names of willow species and acronyms and abbreviations are reintroduced in each new section. Occasionally, if information in a figure or table from a previous section would be useful to the reader, it is referred to in the text along with the page on which it can be found so the reader can quickly and easily refer to it. Standard scientific units for distances, elevations, and areas and metric units for concentrations and rates have been utilized to present units that are commonly used in District work and for ease of the laymen's understanding. Additionally, a list of the scientific and common names for willow species, referred to in this document, is included as reference for the reader in Appendix A. Finally, it was outside the scope of this review to incorporate current information concerning the use of willow as biofuel; however, numerous articles are available in scientific literature.

THE BIOLOGY OF CAROLINA WILLOW

DESCRIPTION


Figure 1. Mature growth form of Carolina willow.

Carolina willows (*Salix caroliniana*) are shrubs or small trees with broad open crowns that can achieve a height up to 10 m (Argus 1986; Figure 1) and can live from 13 to 40 years (Kinser et al. 1997, Quintana-Ascencio et al. 2011). Other willow species have similar life spans from 10–15 years for black willow (*S. nigra*) in southeastern Virginia (Spencer et al. 2001) and upwards of 22–45 years for Sitka willow (*S. sitchensis*) and Pacific willow (*S. lasiandra*) in Oregon, respectively (Cline and McAllister 2012). Young Carolina willows have smooth, grayish-brown bark that develops fissures and thick ridges as the plants age (Figure 2). *Salix* spp. tend to produce a single tap root that thickens with age (Karrenberg et al. 2002) and Carolina willow roots grow up to one-meter deep (McLaughlin 2009). Leaves are narrowly lanceolate, measuring from 7.5 to 15 cm long by 1.0 to 2.2 cm wide (Argus 1986). The simple, spirally-arranged, finely-serrated leaves are whitish beneath (Tomlinson 1980). Leaves of Carolina willow have stomates or pores for transpiration only on the bottom of the leaf (Argus 1986). Small, kidney-shaped stipules or leaf-like appendages occur at the leaf bases and persist on live shoots and sprouts throughout the growing season in 50% of individuals (Tomlinson 1980, Argus 1986).


Figure 2. Bark of Carolina willow stems: young and lacking furrows (left) and mature with grayish bark and deep furrows (right).

Carolina willow is deciduous, losing its leaves beginning in September in South Florida (historically, but now occurs later in October / November) and remaining leafless for about two months (Tomlinson 1980). Regrowth begins in December in South Florida (Tomlinson 1980) and as early as January (in recent years) in the upper St. Johns River basin (USJRB) (Figure 3; Quintana-Ascencio et al. 2013) when flowers, called catkins, are produced. Leaf production occurs quickly thereafter with full leaf-out by early March in the USJRB (Ponzio pers. obs.).

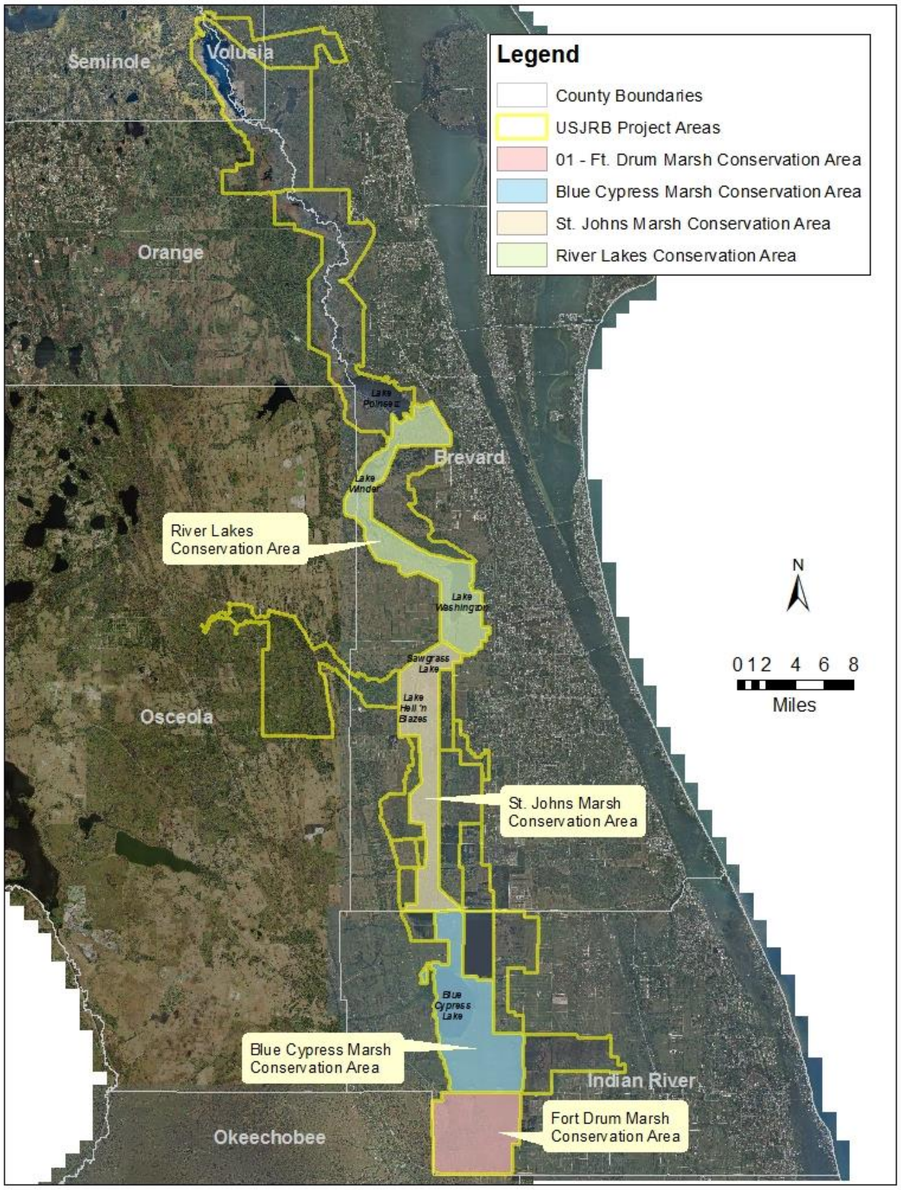

Figure 3. Location of the Upper St. Johns River Basin in East-Central Florida and selected project areas mentioned in the text.

The morphology of Carolina willow can be highly variable depending on the location within its natural distribution. In comparison with populations in the Ozarks, Carolina willow in the Southern Coastal Plain (including Florida) has tendencies toward shorter leaves with rounder bases, longer leaf stems (petioles), longer flower/fruit stems (stipes), and leaf-like appendages at the stem base (stipules) with no glands and more soft, downy hair on the branchlets (Argus 1986). Generally, these traits are exaggerated along a latitudinal gradient from north to south.

Native *Salix* spp. occurring in peninsular Florida can be distinguished by their leaf characteristics. Carolina willow and black willow can be differentiated by their morphological attributes where they co-occur in Florida (Table 1). The leaves of Carolina willow have small, yellowish glands on the leaf tips and in the serration notches, as compared to the reddish serrated tips of black willow. The leaves of Florida willow (*S. floridana*) have definite petioles and comparatively larger leaves with rounded bases; the serrated leaf margins have glands on veinlets (Godfrey 1988).

Table 1. Comparative morphologic charateristics of Carolina willow and black willow as recreated from Argus 1986.

Trait	Carolina willow	Black willow
Leaves	Spear-shaped to very narrowly so, whitish waxy coating beneath, pores (stoma) on lower leaf only, apex tapering to a point or sharply pointed	Narrowly spear-shaped to very narrowly so, no waxy coating beneath, 50% pores (stoma) on both leaf surfaces, apex tapering to a point
Branchlets	More or less brittle, hairless to coverage with short, dense hairs	Brittle, hairless to covered with long, soft hairs
Branches	Dark to light brown	Reddish to yellow-brown
Leaf stems (petioles)	4.5–14 mm; 8 mm average	3–10 mm; 6 mm average
Leaf-like appendages at stem base (stipules)	Usually prominent and persistent	Usually small and shedding early
Flower /fruit stems (stipes)	1.25–5.25 mm; 2 mm average, 6 times as long as the nectar-bearing gland (nectary)	0.5–1.5 mm; 3 times as long as the nectar-bearing gland (nectary)
Female flower part (styles)	0.3- 0.8 mm; 0.5 mm average	0.2- 0.4 mm; 0.3 mm average

Compared to other closely related genera in the family Salicaceae (*Populus* spp.), willow genomes have fewer replication sequences making them more primitive or closer to the Salicaceae ancestral genome (Liu et al. 2013, Xiaogang et al. 2014). Using molecular data on all American willows, Lauron-Moreau et al. (2015) characterized Carolina willow as phylogenetically closest to red willow (*S. laevigata*) found in the western temperate U.S., followed by Ball's willow (*S. ballii*), Goodding's willow (*S. gooddingii*), Humboldt's willow (*S. humboldtiana*), and peachleaf willow (*S. amygdaloides*) that range from South America to the eastern boreo-arctic. Interestingly, black willow, with which Carolina willow hybridizes (Argus 1986) and Florida willow, which may be errantly classified to the wrong subgenus (Lauron-Moreau et al. 2015), are more distantly related to Carolina willow. Although Carolina willow can hybridize with black willow, the zone of hybridization is very narrow, primarily in the Florida Panhandle. Argus (1986) reported that all known hybrid populations occur in man-made habitats. The phylogenetic associations of Carolina willow to other willow may be of particular interest given the paucity of ecological information on Carolina willow and the need to use information on closely related species.

DISTRIBUTION

Carolina willow is one of about 450 species of willow that occur worldwide and 103 species that occur in North America north of Mexico (Lauron-Moreau et al. 2015; Figure 4). In addition to Carolina willow, four other willow species are native to Florida, but generally occur in the panhandle or north-central Florida; black willow, Florida willow, prairie willow, and Missouri willow (*S. eriocephala*) (Godfrey and Wooten 1981, Argus 2007).

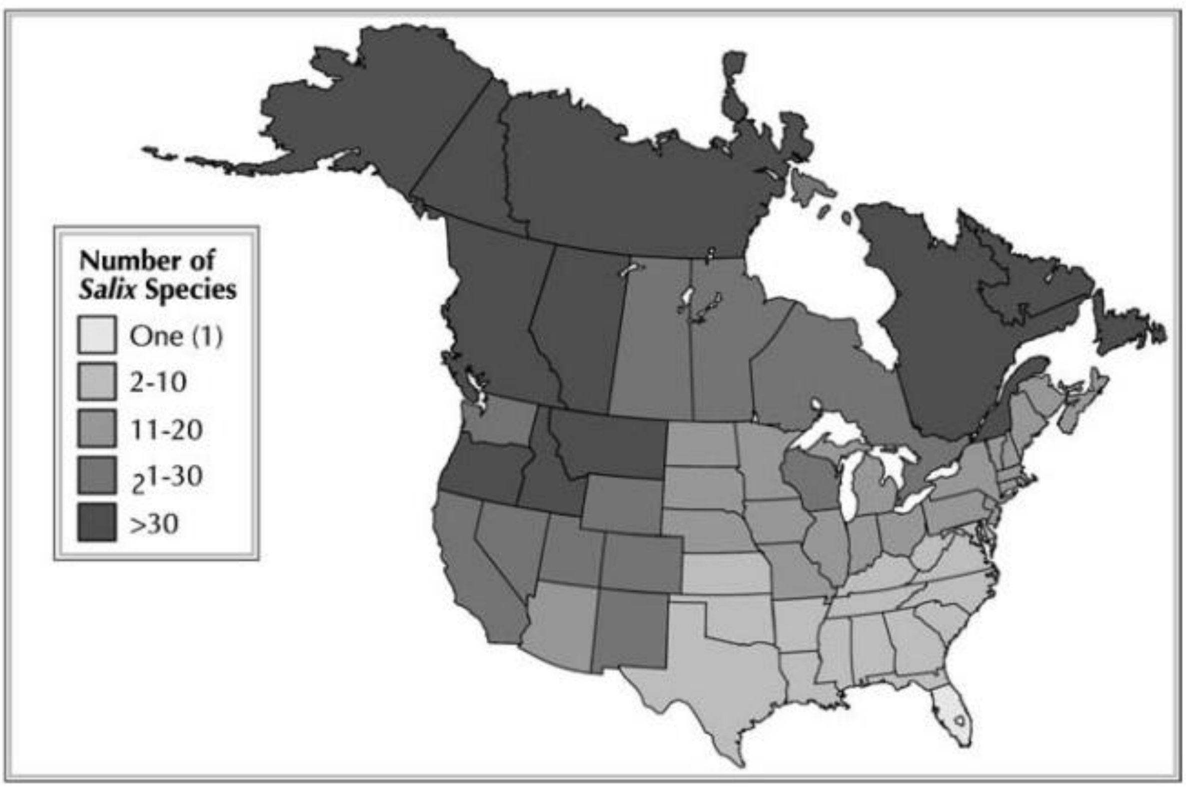

Figure 4. Willow species diversity in the U.S.A. and Canada based on regional floras – reprinted from Kuzovkina and Quigley (2005).

Carolina willow is distributed across the Atlantic Coastal Plain, Gulf Coastal Plain, the lower Midwest, and Texas and is the only species that occurs naturally in southern Florida (Figure 5; Kuzovkina and Quigley 2005). All willows are in the family Salicaceae, which includes the poplars (*Populus* spp.) and two recent additions based on gene sequencing, i.e., the *Flacourtia* and the *Xylosma*. Detailed morphological characteristics of willow can be found in taxonomic keys such as Argus et al. 2010 and Wunderlin and Hansen 2011.

Figure 5. Distribution (outlines) of Carolina willow in the United States and disjunct populations (circles) – reprinted from Argus 2007.

HYDROLOGY

Carolina willows are usually found in wetland habitats that experience periodic flooding which include lowlands, swamps, marshes, river banks and bars, interdunal and other natural swales, pond and lake shores, canal banks, and ditches (Godfrey 1988). Carolina willow in the St. Johns Marsh Conservation Area (SJMCA) in the USJRB (Figure 6) and in the marshes of the littoral zone of Lake Okeechobee (Pesnell and Brown 1977, Milleson 1987, David 1994, Richardson and Harris 1995, Richardson et al. 1995) usually occurs at higher elevations in the wetland, which are prone to shorter frequency of inundation (hydroperiod) than most other herbaceous wetland plant communities in those ecosystems. However, willow-dominated communities can experience a wide fluctuation in inundation frequencies and water depths (Table 2). The hydroperiod experienced by Carolina willow on Everglades tree islands and in surrounding marshes ranges from 97 to 361 days/yr and averages 281 days/yr (Espinar et al. 2011, J. Sah, unpublished data). At the drier end of the spectrum, the average inundation frequency of willow in the marshes surrounding Lake Washington in the USJRB is quite a bit shorter with an average hydroperiod of 49% (179 days) (SJRWMD, unpublished data). Generally, it is true that the distribution of wetland plant species is highly correlated to long-term hydrologic variables, like frequency of inundation and average annual depth, but some species also show good correlation to short-event variables (Duever 1982, Lowe 1986, David et al. 1996, Jimenez et al. 2003).

Table 2. Hydrologic data from various studies of Carolina willow in Florida. * This shrub swamp had Carolina ash (*Fraxinus caroliniana*) and Carolina willow as co-dominant taxa.

Days Inundated Per Year	**Average or Range of Hydroperiod**	**Average Annual Depth (ft)**	**Max Water Depth (ft)**	**Min Water Depth (ft)**	**Length of Study (yrs)**	**Location / Source**
308	84%	0.54	2.06	-3.36	1.5	*Sarasota County* CH2M Hill 1988 in SFWMD 1995*
281	27-99%				7	*Everglades Tree Islands* Espinar et al. 2011 and Sah (unpub data from 2004)
252	69%				9	*Everglades* McPherson 1973 in ESE 1991
274	75%				9	*Everglades* McPherson 1973 in ESE 1991
183	32–68%	0.15	0.7	-0.4	5	*Lake Okeechobee – Moore Haven 1972 transect* Milleson 1987
250	50–87%	0.85	1.6	0.1	5	*Lake Okeechobee – Moore Haven 1981 transect* Milleson 1987
335	92%	2.54			23	*Lake Okeechobee* Richardson et al. 1995
179	49%	0.09	4.21	-4.32	34	*Lake Washington Marshes* SJRWMD (unpub. data)
244	67%	0.46	3.61	-2.58	2	*St. Johns Marsh CA* SJRWMD (unpub. data)
259	**71%**	**0.77**	**3.29**	**-3.42**		**Average**

Deep flooding events may cause intolerant plant species to die back, creating openings in the marsh (Zaffke 1983, Gunderson 1989, Clough and Best 1991). Likewise, dry-downs, even of very short duration, may allow plants to germinate. Long duration dry-downs may cause the mortality of newly germinated seedlings whose roots have not developed deep enough in the soil profile to access water, especially in soils with higher bulk density or lower capillarity (Quintana-Ascencio et al. 2013).

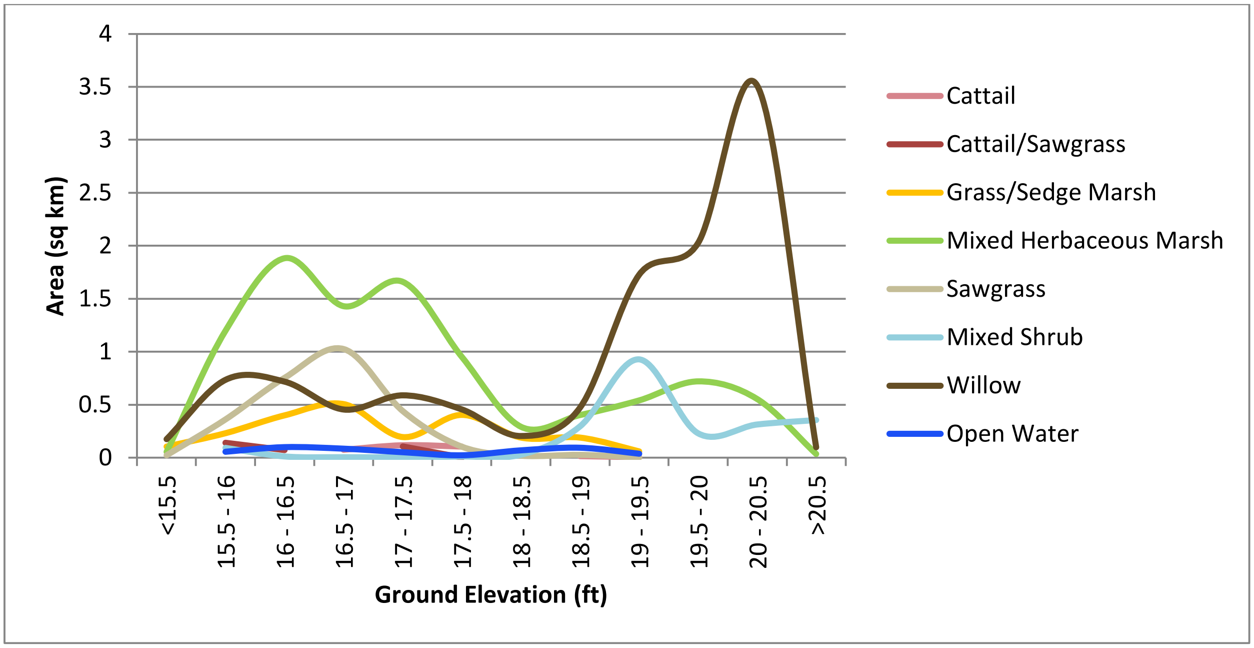

Figure 6. Plant community distribution along a topographic gradient in St. Johns Marsh Conservation Area in 2009 (SJRWMD unpublished data).

Figure 7 depicts hydrologic data from SJMCA for two years showing typical fluctuations that can promote or prevent successful establishment of Carolina willow seedlings. Typically water levels fall during the period of Carolina willow seed dispersal (Feb-Apr) allowing seedlings to germinate on saturated soils during the dry season. Seedlings can become vulnerable if water levels fall far enough below the soil surface that roots cannot reach moisture. However, Quintana-Ascencio et al. (2013) reported that peat soils in the USJRB provide better conditions for Carolina willow than sandy soils because of their ability to hold moisture, which enhances seedling survival. Subsequently, water levels begin to rise when the wet season begins, typically June, and water levels reach a level above the soil surface between June and August. If water levels rise too rapidly, seedlings are at risk of being drowned if covered by 0.5 ft for two weeks or longer (Figure 7; Quintana-Ascencio et al. 2011, 2013).

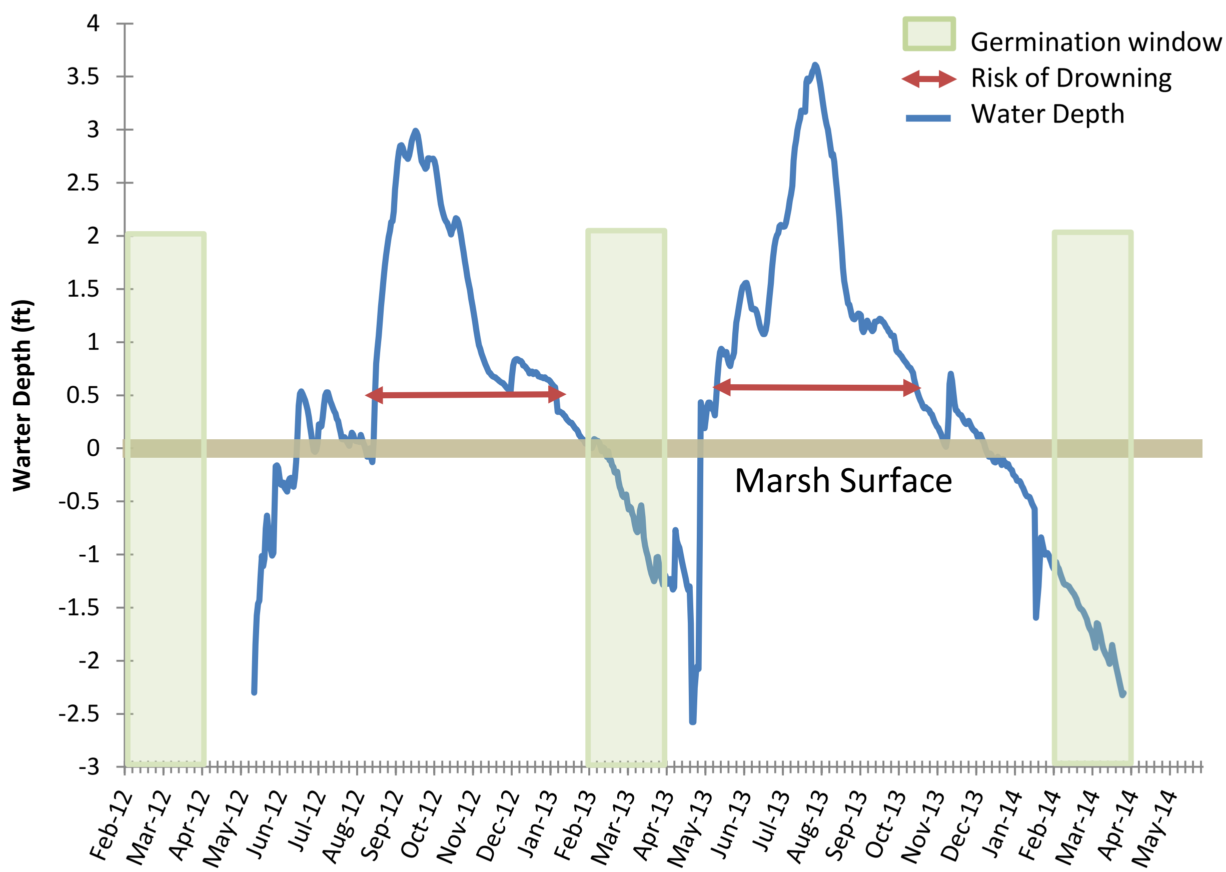

Figure 7. Water depth from May 2013 to April 2014 at a Carolina willow site in St. Johns Marsh Conservation Area showing the germination window from February to April and the vulnerability period of drowning.

SOILS

Carolina willows that occur in and around tree islands in the Everglades are found on soils that are nitrogen-limited with an approximate pH = 6.3, Total Nitrogen/Total Phosphorus (TN/TP) ratio = 40 and organic content = 75% (soil dry weight) (Espinar et al. 2011, Sah unpublished data). Richardson et al. (1995) found that soils where willows occur in the marshes surrounding Lake Okeechobee have low bulk density (<0.6g/cm^3) and high organic content (>34%). Some willows are particularly adapted to living in these type of N-limited environments due to the presence of microorganisms, which can fix atmospheric nitrogen into a more usable form such as ammonia, that grow in association with the stems (von Wuehlisch 2001) or roots of these species (Doty et al. 2009, Hrynkiewicz et al. 2009).

In comparison, willow dominated patches in the USJRB are found on soils that have a much higher TN/TP ratio (105) than those in the Everglades study (Bochnak et al., in prep). Based on limited sampling (n=1), soil underlying a Carolina willow community in the River Lakes

Conservation Area (RLCA) had lower bulk density and higher percent carbon (C) and nitrogen than soils collected from a nearby sand cordgrass (*Spartina bakeri*) marsh and bald cypress (*Taxodium distichum*) swamp (Table 3; Craft et al. 2015). Average soil phosphorus in the Carolina willow community (964 ± 79 mg/kg) was 50% and 138% higher than in the bald cypress and sand cordgrass communities, respectively (Craft et al. 2015). Pesnell and Brown (1977) saw a similar trend in Lake Okeechobee marshes with Carolina willow soils having significantly higher phosphorus (mg/kg) than soils found in sand cordgrass and Tracy's beaksedge (*Rhynchospora tracyi*) communities; phosphorus was approximately 0.130, 0.042 and 0.015 mg/kg, respectively. Osborne et al. (2014) collected more extensive data from Carolina willow and other plant communities 30 miles upstream in the SJMCA (see Table 3 and Figure 3) that corroborates the level of soil nutrients (C, N, P) observed in Craft's samples. However, while soils in a sawgrass (*Cladium jamiacense*) marsh had lower phosphorus than Carolina willow, southern cattail (*Typha domingensis*) communities had values that were 30–40% higher in phosphorus than those found in Carolina willow soils in both studies (Osborne et al. 2014).

Table 3. Comparative soil charateristics of Carolina willow and other USJRB plant communities in River Lakes or St. Johns Marsh Conservation Area in the USJRB. Data were averaged for the soil profile from 0-18 cm for both studies (mean ± std error) and is expressed in dry soil weight (dried at 70º C). Soil series for Osborne et al. (2014) sites was Everglades (for willow, sawgrass and southern cattail sites) and from Craft et al. (2015) sites were Tomoka (willow), Micco (bald cypress) and Floridana (sand cordgrass).

Plant Community	Source	Bulk Density (g/cm)	Total C (%)	Total N (%)	Total P (mg/kg)
Carolina Willow	Craft et al. 2015	0.14 ± 0.01	43.9 ± 0.6	3.64 ± 0.08	964 ± 79
Carolina Willow	Osborne et al. 2014	0.29 ± 0.01	48.3 ± 0.6	3.27 ± 0.05	813 ± 109
Bald cypress	Craft et al. 2015	0.37 ± 0.07	23.7 ± 4.1	1.87 ± 0.28	634 ± 97
Sand cordgrass	Craft et al. 2015	0.50 ± 0.08	12.0 ± 3.0	0.91 ± 0.21	335 ± 84
Southern cattail	Osborne et al. 2014	0.31 ± 0.02	43.8 ± 0.7	3.16 ± 0.03	1371 ±75
Sawgrass	Osborne et al. 2014	0.31 ± 0.02	47.8 ± 0.7	3.13 ± 0.04	764 ± 111

Reproduction

Willows can reproduce and expand either sexually through flowering and seed germination, or by clonal asexual reproduction from shoots, roots, and plant fragments (Karrenberg et al. 2002, Mosner et al. 2012). Sexual reproduction is favored when flowering and seeding coincide with wet substrate exposure, but when those conditions don't exist, asexual reproduction ensures willow survival and expansion when seed germination fails. Both reproductive processes depend on plant hormones that are activated by lengthening photoperiods (length of daylight).

Reproduction from Seed

Flowering / Fruiting

Willows are dioecious meaning that they bear female (pistillate) (Figures 8 and 9) or male (staminate) (Figure 10) flowers on separate trees — a condition that occurs in only about 4% of all flowering plants (Young 1992, Irish 1989). Willow flowers, called catkins, are extremely reduced in size and can be erect or spreading on the stem (Alvim et al. 1976, Godfrey and Wooten 1981). Although rare, bisexual flowering (male and female flowers on the same tree) also occurs in willows, including hybrid offspring, in Australia (Cremer 2003). However, this trait has not been reported for Carolina willow.

Figure 8. Fruiting female Carolina willow tree in St. Johns Marsh Conservation Area.

Figure 9. Female Carolina willow bearing fruit in the off-season (September 2004) after Hurricane Frances in the Upper St. Johns River Basin.

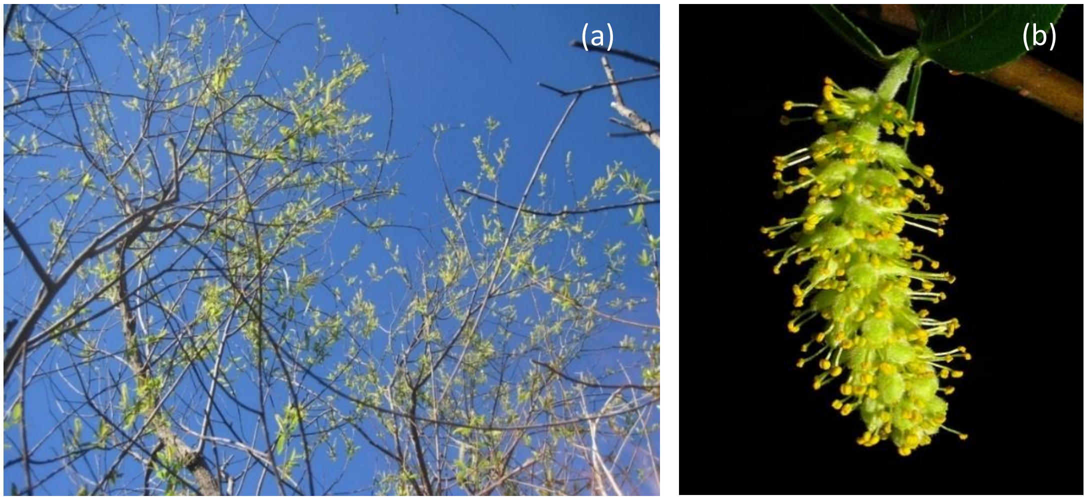

Figure 10. Male flowering Carolina willow tree (a) and male flower (b).

Willow flowers are generally pollinated by insects (entomemophilous), but can also be wind pollinated (anemophilous) (Argus 1986). Pollinators may include honey bees (*Apis* spp.) (Cremer 2003) and even stable flies (*Stomoxys calcitrans*) (Jarzen and Hogsette 2008). Willows in Alaska (Booth's willow [*S. novae-angliae*], diamondleaf willow [*S. planifolia*], feltleaf willow [*S. alaxensis*], Bebb willow [*S. bebbiana*], and Scouler's willow [*S. scouleriana*]) have dual pollination systems utilizing wind and insects (Fox 1992). Fox (1992) also found that in these Alaskan willows 1) seed development in willows is pollen-limited rather than resource-limited; 2) seed development in individual catkins is independent of other catkins on the same plant and; 3) there is little to no resource competition between catkins as close as 5–10 cm apart suggesting that willow catkins favor insect pollination. Consequently, the presence of nectar-bearing glands (nectaries), large pollen grains with higher nutritional value, and visual or aromatic characteristics on catkins, suggests that insect pollination is extremely valuable to willows. Like other willow species, flowering and seed set for Carolina willows in the USJRB occurs in the spring, usually from February to April (Castro-Morales et al. 2014). However, Carolina willow in the USJRB has been observed to produce flowers at other times, usually in response to stress. For example, Carolina willows produced flowers in late September 2004, following defoliation from a series of tropical storms and hurricanes impacting that area, including Hurricanes Frances and Jeanne (Figure 9). Similarly, weeping willow (*S. babylonica*) was observed re-flowering outside of its normal season due to defoliation of older leaves by rust disease (Cremer et al. 1999).

Seeding

For willows in Australia, trees become mature or bear fruit in 2–3 years (Cremer 2003). Conversely, Carolina willow cuttings matured earlier and were observed flowering in less than one year after being planted on an experimental island in an USJRB marsh (Quintana-Ascencio et al. 2011). However, plants were removed before seed maturation could occur. Cremer (2003) calculated the potential of seed production for white willow (*S. alba*) at several million seeds per tree; though, actual observed seed production was much lower at 500,000 assuming that 10% of the ovules were fertilized. For mature Carolina willow in the USJRB, the mean number of fruits per inflorescence was 32.5 (SD = 9.27) and mean number of viable seeds per fruit was 12.2 (SD = 2.36); approximately 165,000 viable seeds can be produced per mature tree per year (Quintana-Ascencio, pers comm.). Carolina willow seeds are quite small and lightweight with approximately 18,300 seeds weighing only one gram (Young 1992).

Carolina willow produces fruits that are cone-shaped capsules less than 0.64 cm long (Godfrey and Wooten 1981; Figures 11 and 12). Each capsule contains many seeds possessing fine, terminal hairs that allow for dispersal via wind (anemochory) and water (hydrochory) (Hupp 1992). However, wind dispersal may be a more important mechanism because it can result in colonization of a willow genotype for long distances measured in kilometers (Cremer 2003, Mosner et al. 2012). Seiwa et al. (2008) pointed out the important role cottony hairs play in Japanese fantail willow (*S. sachalinensis*) and dappled willow (*S. integra*) seeds as they encounter dry substrates and are repeatedly resuspended in the air until becoming trapped on wet microsites that are favorable for germination. After landing on wet substrates, the hairs are released and the seeds germinate (Cremer 2003, Quintana-Ascencio et al. 2013, Castro-Morales et al. 2014). However, species have variable release rates — Japanese fantail willow seeds released hairs within minutes, whereas the hairs of dappled willow seeds remained attached for over four days (Seiwa et al. 2008).

Figure 11. Female Carolina willow fruits with cottony hairs.

Figure 12. Carolina willow capsule showing two seed chambers.

Germination

Seed Viability

Willows produce extremely short-lived seeds. Viability is shorter than ten (10) days for many willow species, including Carolina willow seeds germinated under natural field conditions (Table 4). Castro-Morales et al. (2014) found that only green Carolina willow seeds were viable. However, some willow seeds stored in dry and/or extremely cold conditions in the laboratory have remained viable for up to three years (Young 1992, Maroder et al. 2000). While the ability of seeds to retain viability under subzero temperatures might confer an ecological advantage for species occurring in colder climes, there seems to be no advantage for temperate willow species occurring in warm, subtropical environments. Karrenberg et al. (2002) suggested that willow seed longevity is shortened by warm, humid conditions — a condition present nearly year-round in Florida. Castro-Morales et al. (2014) found that although Carolina willow seeds germinated after being held in cold temperatures for one month, none of the seedlings survived longer than a few days. For populations in the USJRB, seed viability peaked mid-way through the dispersal season and then tapered off (Castro-Morales et al. 2014).

Table 4. Germination characteristics of Carolina willow, black willow and other species found in the US and around the world.

Species	Location / Researcher	Viability under normal conditions (days)	Length of time seeds are viable if held in dry and/or cold storage (days or months)	Germination time of half of seeds sown (G50) (days)	Maximum germination of viable seeds (%)
Carolina willow	*Florida* Castro-Morales et al. 2014	10	>1 mo @ 4 ^{0}C	3-3.8	90–100
Black willow	*Tennessee* Hupp 1992	7			
Black willow	*Oklahoma* McLeod and McPherson 1973	56-70			79
Grayleaf willow	*Alaska* Zasada & Densmore in Young 1992		36 mo		89
White willow **Corkscrew willow**	*Argentina* Maroder et al. 2000	14	30 mo @ -70 ^{0}C		75–100
Hybrid Crack willow **Black willow** **Large gray willow**	*Australia* Cremer 2003 Cremer et al. 1999	21 27 43		12 20	90–100
S. rorida ***S. schwerinii*** ***S. miyabeana*** ***S. pierotii*** **Sachalin willow** **Weeping willow**	*Japan* Niiyama 1990		16-30 d	<2	80–97
White willow **Almond willow** **Basket willow**	*Netherlands* van Splunder et al. 1995	9		3.0 1.5 1.5	80–100

Most willows exhibit a lack of dormancy and, under natural conditions, seeds will usually germinate within 12–24 hours of reaching suitable habitat (Young 1992, Cremer et al. 1999, Maroder et al. 2000, Karrenberg et al. 2002, Castro-Morales et al. 2014). Despite short viability, willows have high germinability with maximum germination rates from 75–100% recorded (Table 4). Under laboratory conditions, between 90-100% germination was observed in Carolina willow growing in optimal conditions — moist, organic soil that was collected in native habitat (Figure 13; Castro-Morales et al. 2014). The presence of moisture is a key factor in the germination of willow and soils that have greater water-holding capacity represent optimal conditions (Figure 14; Gage and Cooper 2004, Azami et al. 2013, Castro-Morales et al. 2014). Carolina willow seeds sprout on moist inorganic and organic soils alike, but will not germinate on dry soil, regardless of soil type (Castro-Morales et al. 2014). Seed germination can also occur on or under water; seedlings can remain viable for up to a month while floating (Figure 15; Cremer 2003). Carolina willow has been observed to germinate under shaded conditions (Hall et al., pers. obs.), however, seedlings do not persist in shaded conditions (Craighead 1971, Conner et al. 2002, Quintana-Ascencio et al. 2011). Azami et al. (2013) concluded that bare substrates exposed by spring drawdowns were beneficial to seed germination of almond leaf willow (*S. subfragilis*) in Japan. Seed germination is followed by tap root development (Godfrey and Wooten 1981, Quintana-Ascencio et al. 2011).

Figure 13. Germination of Carolina willow seeds on saturated organic soil.

Figure 14. Carolina willow seedlings growing on organic soils kept moist through capillarity.

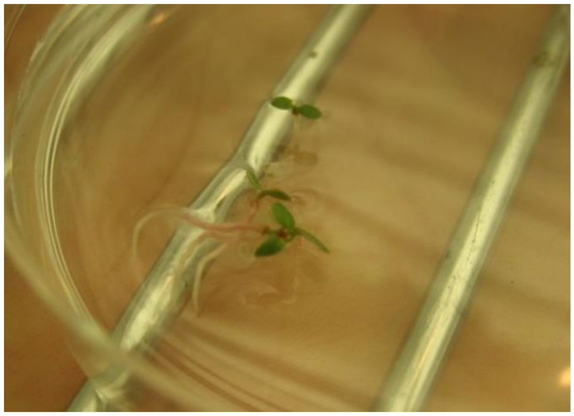

Figure 15. Germination of Carolina willow seeds while floating on water.

<u>Seed Banks</u>

Short seed viability prevents most willows from producing persistent seed banks (Niiyama 1990, Douglas 1995, Karrenberg et al. 2002, Quintana-Ascencio et al. 2011). Despite its presence in the extant vegetation, Carolina willow seeds (as assayed by seedling emergence) were notably absent from the soil seed bank of disturbed wetlands that were previously drained for agriculture and from undisturbed marshes in the USJRB (Lee 1994, Hanselman et al. 2005). Using a sieving technique to search for seeds in the soil from six plant communities in Blue Cypress Marsh Conservation Area (BCMCA), Hanselman et al. (2005) did not find Carolina willow seeds, but did find seeds from two other woody species (wax myrtle [*Myrica cerifera*] and buttonbush [*Cephalanthus occidentalis*]).

Vegetative Reproduction

Willow asexual reproduction and regeneration are often associated with cloning where multiple trunks, or ramets, originate from roots, shoots, rhizomes, or stem fragments of parent plants (Argus et al. 2010). As mentioned earlier, Carolina willow cuttings taken from mature willow stems and planted on artificial islands in the USJRB were able to produce flowers within a year of planting (Quintana-Ascencio et al. 2011). Ramets are genetically identical to the parent stock, and expand the basal area of individual willows (Figure 16). Narrowleaf willow (*S. exigua*) occurs in thickets of same-sex clones as large as 325 m^2 in diameter, especially in low-flow conditions (Douhovnikoff et al. 2005)**.**

A study by Budde et al. (2011) in Argentina exemplified a successful strategy for non-native willow persistence and expansion based on asexual reproduction. Using molecular markers, the researchers identified 13 genotypes in their area. They found that vegetative propagation, attributable to the brittle branches of crack willow, created extensive monoclonal stands. One dominant female genotype had female clones occurring at distances up to 790 km away. However, they warned that an increase in genotypes can be assumed if male individuals colonize the sites and make sexual reproduction possible to further facilitate the continued persistence and spread of this willow species.

Figure 16. Carolina willow trunk showing lateral bud production.

Several other studies documented the importance of asexual reproduction to willow expansion. Douhovnikoff et al. (2005) attributed the increase of narrowleaf willow in a riparian restoration area in California to cloning since *in situ* seedlings had low survival rates. In Japan, willow survival and recruitment was attributed to natural regrowth from a severed trunks or branches (coppicing) after parent plants were damaged by a flood disturbance (Asaeda et al. 2011). Mosner et al. (2012) attributed ramets and propagule dispersal to the spatially fragmented, but genetically similar, stands of basket willow in the Elbe River floodplain, Germany.

The development of adventitious roots (roots that develop in an unusual place, like along the upper stem) represents another form of vegetative reproduction in willow (Karrenberg et al. 2002). Originating from embryonic (meristematic) cells in locations other than the primary root system, adventitious roots allow willows to survive the waterlogged substrates that are typical in wetlands. Development of these roots appears to be related to seasonal levels of cytokinin, gibberellin, and auxin plant hormones (Michniewicz and Galoch 1972, Kriesel 1976, Blakesley et al. 1991, Karrenberg et al. 2002)**.**

Willow is so well-known for its successful regeneration from cuttings that it is commonly used for bank stabilization. Hunolt et al. (2013) found that black willow and silky willow (*S. sericea*) cuttings survived better when harvested during the non-growing season for streambank stabilization projects. Willow is also commonly used to generate material for scientific studies (Figure 17; Hussain et al. 2009, Quintana-Ascencio et al. 2011).

Figure 17. Cuttings of Carolina willow showing growth of roots from twigs.

GROWTH AND SURVIVAL

As with seed germination, willow seedling survival and growth is highly dependent on water availability. Willow seeds that germinate must be kept moist until seedlings are well established (Young 1992, Cremer et al. 1999, Maroder et al. 2000, Hough-Snee et al. 2013, Quintana-Ascencio et al. 2013, Castro-Morales et al. 2014). In Oklahoma, black willow seedlings appear to be dependent on a small ring of hairs at the junction of the root and the seedling stem for water absorption during at least the first week of growth (McLeod and McPherson 1973). These hairs do not appear to penetrate the soil, so free water at the soil surface must be available for them to persist. Seedlings perish within a couple of days of loss of standing surface water (McLeod and McPherson 1973, Quintana-Ascencio et al. 2011). The survivorship of Carolina willow seedlings and cuttings is best where hydrology prevents desiccation of the soil or prolonged submergence of the plants (i.e. about two weeks). Over a 10-month experiment in an USJRB marsh, 77% of planted Carolina willow cuttings (that are taller, more robust and resemble saplings) survived, whereas only 15% of shorter and more vulnerable seedlings survived (Figure 18; Quintana-Ascencio et al. 2013) following seasonal flooding. In Colorado, park willow (*Salix monticola*) seedling survival was greater in areas with a higher water table and on finer textured soils with greater water-holding capacity (Gage and Cooper 2004). After germination, Goodding's willow (*S. gooddingii*) seedlings in Mexico along the Colorado River must have access to moist soil or a high water table for two months during the first season (Mahoney and Rood as in Nagler et al. 2005) and a water table no deeper than 3–4m for continued growth thereafter (Horton et al. 2001). Competitive ability and survivability of park willow is particularly limited under drier environmental conditions (Peinetti et al. 2001).

Figure 18. Carolina willow cutting trying to out-grow rising water levels in 2009 in the Upper St. Johns River Basin.

Cremer (2003) indicated that the roots of willow (*Salix* spp.) seedlings grow quite slowly (<1mm/day). However, Quintana-Ascencio et al. (2011, 2013) found that small Carolina willow cuttings grew quickly and plants that were initially 10cm tall, grew another 90 cm in just six months (5mm/day). For the purposes of illustrating a seedling's ability or inability to out-grow rising water levels, we estimated the growth of Carolina willow seedlings using a slow-growth rate of 1mm/d and a fast-growth rate of 5mm/d and compared them to the water levels that actually occurred in SJMCA in 2012 and 2013 (Figure 7 on page 9). From that analysis, we estimated that both slow- and fast-growing willow seedlings, that germinated at any time between Feb. 1 and April 1 in 2012, could have easily outpaced rising water levels and survived (Table 5). However, if growth was slow, germinants most likely could not tolerate the flooding that occurred in 2013 and would experience mortality (Table 5).

Table 5. Estimated growth and survival of Carolina willow seedlings during 2012 and 2013 in response to hydrologic conditions in St. Johns Marsh Conservation Area. Estimates were based on assumed fast growth rates of 5mm/d (0.0164 ft/d) and slow growth rates of 1mm/d (0.0033 ft/d). Growth rates that were originally expressed in metric units (mm/d) were converted to standard units (ft/d) in order to calculate the height of plants in relation to the water level which is expressed in ft. It was assumed that plants would survive the flooding if they had approximately 0.5 ft of their length above the water surface.

Date of Germination	Growth Rate	Height of Plant (ft)	Height of Plant above 0.5 ft of water (ft)	Estimated Response
Feb. 1, 2012	Fast	3.41	2.91	survival
	Slow	0.68	0.18	survival
Mar. 1, 2012	Fast	2.95	2.45	survival
	Slow	0.59	0.09	survival
Apr. 1, 2012	Fast	2.44	1.94	survival
	Slow	0.49	-0.01	survival/mortality?
Feb. 1, 2013	Fast	1.83	1.33	survival
	Slow	0.37	-0.13	mortality
Mar. 1, 2013	Fast	1.38	0.88	survival
	Slow	0.28	-0.22	mortality
Apr. 1, 2013	Fast	0.87	0.37	survival
	Slow	0.17	-0.33	mortality

For mature Carolina willow, the diameter of the trees increased from 3.8-8.9 mm/yr as estimated from a tree ring analysis of trees occurring in the BCMCA (Kinser et al. 1997). Working on naturally growing willow stands that encircle prairie potholes in Saskatchewan, Canada, Schroeder et al. (2009) found that native willows (Missouri willow, meadow willow [*S. petiolaris*], Bebb willow [*S. bebbiana*], and pussy willow [*S. discolor*]) showed significant regrowth after harvesting for bioenergy production, although some differences in regrowth were noted based on harvest methodology. The authors suggest that these naturally growing willow stands could support biomass harvest on a 4–5 year return cycle. In Carolina willow, almost complete regrowth of willow canopy cover was seen within one year of management of willow via roller chopping (SJRWMD unpubl. data).

Methods for Estimating Growth and Age Structure

Growth, in the form of biomass production, and age structure of willow can be estimated using allometric methods or measurement of the relative growth of one part in relation to the entire plant. In peachleaf willow (a tree-form willow), basal diameter was a good predictor of growth and in Missouri willow (a shrub), height of the major stem and the number of stems greater or equal to 1.5 cm were the best estimators of growth (Aravanopoulos and Zsuffa 1993). Aravanopoulos and Zsuffa (1993) found that biomass production (growth) in peachleaf willow and Missouri willow was correlated with the height and basal diameter of the major stem, the number of stems ≥ 1.5 cm, and the number of stems < 1.5 cm. For peachleaf willow, basal diameter alone was a good predictor of growth. However, in Missouri willow, height of the major stem and the number of stems ≥ 1.5 cm were the best estimators of growth. For Carolina willow, Quintana-Ascencio et al. (2011) found that the plasticity of growth forms (from low and spreading to tall and erect) obscured the relationship between willow size (height or canopy diameter) and maximum trunk diameter – neither willow height nor canopy diameter explained more than 40% of the variation in maximum trunk diameter. However, willow age, estimated by the number of growth rings, was predictable from mean trunk diameter at ground level, especially for trunks ranging 1.6-8.0cm in size (Quintana-Ascencio et al. 2011). Employing a tree ring analysis (Figure 19), Quintana-Ascencio et al. (2011) found that willows in the USJRB were 14-37 years old. However, they suspected that the age of the older trees might have been underestimated due to difficulties in counting rings in the rotted centers that are often found in older Carolina willows. Tree ring analysis has proven useful to understand the relationship between tree growth and hydrology. Similarly, Conner et al. (2002) found that only Carolina willow and bald cypress (among 10 tree species inhabiting islands in the Everglades), had tree rings with enough definition and variation to provide a reliable means of determining a dating sequence.

Figure 19. Disk cut from a Carolina willow trunk for dendrochronology with one half stained to distinguish growth rings.

Nutrient Assimilation, Productivity and Decomposition

Many researchers have found that productivity of willows is enhanced by nutrient enrichment or fertilization (Table 6). Increased nitrogen supply resulted in a boost of productivity, specifically with greater leaf density and area, in grayleaf willow (*S. glauca*; Bowman and Conant 1994), an increase in leaf area in basket willow (*S. viminalis*; Merilo et al. 2005), and an increase in shoot biomass in myrsine-leaved willow (*S. myrsinifolia*; Hakulinen 1998). These species allocated resources to above-ground plant parts (shoots), rather than below-ground plant parts (roots), where there was a reduction in plant biomass in several cases. Adler et al. (2008) indicated that balanced enrichment of nitrogen : phosphorus : potassium : magnesium (N:P:K:Mg) at a ratio of 5:1:4:0.4 had the greatest effect on willow biomass as compared to high nitrogen wastewater and nutrient-poor water. In contrast, Balasus et al. (2012) observed no effect on several species of willow and poplar after two years of nitrogen dosing at two different concentrations. The response of Carolina willow to nutrient enrichment has been varied with seedlings showing a negative response in stem height and cuttings showing no differences from controls for stem height and diameter, with an increase in leaf density only for smaller individuals (Quintana-Ascencio et al. 2011). Ens et al. (2013) concluded that willows are nutrient-demanding and are quite resourceful at nutrient acquisition and efficient at nutrient recycling. However, these dynamics may change as a willow community ages.

The efficiency with which willow can assimilate nutrients has often been attributed, in part, to the presence of microbes and fungi living in the soil in close association with willow roots or within the roots themselves (Ipsilantis 2005, Doty et al. 2009, Hrynkiewicz et al. 2009, Johnston 2003, Marshall and Pattullo 1981). Ipsilantis (2005) observed that ergosterols (chemicals necessary to support fungal and protozoa survival), that are found in the soil and dead leaf litter, and fungi colonization in living roots were higher in Carolina willow communities than in most other marsh communities (e.g., sawgrass, cattail, maidencane, etc.) in BCMCA. Fungal colonization peaked during March and April when water levels were near their lowest and soil surfaces were exposed. However, there was no relationship between the abundances of fungi in the soil, leaf litter, or living willow roots and the amount of total phosphorus found in the soil or leaf litter.

Doty et al. (2009) and Hrynkiewicz et al. (2009) isolated *Sphingomonas*, a mycorrhizal-associated bacterial strain, that enhanced the ability of Sitka willow (*Salix stichensis*) and a *Salix* clone to grow in nitrogen-limited environments and improve nitrogen uptake. Johnston (2003) suggested that phosphorus uptake by willow may also be enhanced by soil mycorrhizae on slightly elevated sites. However, the presence and abundance of these microbes may be mediated by hydrologic conditions. Marshall and Patullo (1981) found that willow, at both an annually flooded site and a drier site (dry-down of 5cm below surface during mid-summer) in Michigan, had a symbiotic association with root fungus throughout the growing season. However, when testing the effect of added phosphorus, they documented a decline of mycorrhizae infection at wetter sites in the late summer. Chapin (1996) also noted that drier conditions in arctic willow (*Salix artica*) hummocks in Canada, caused nitrate-nitrogen (NO_3-N) produced in the soil to be greater than in sedge (*Carex* sp.) meadow sites owing to less anoxia which supported a higher abundance and activity of nitrifying bacteria.

Table 6. Summary of nutrient addition effects on willow growth and productivity. Arrow indicators – ↑ increase, ↓decrease, → no change or effect.

Species	Nutrient	Type of Study	Effects	Location / Source
Basket willow	N:P:K:Mg 5:1:4:0.4	Applied balanced fertilizer to cuttings	↑ Biomass (stems, branches, roots) ↑ Leaf density	*Sweden* Adler et al. 2008
Basket willow *S. dasyclados*	Nitrogen	Planted cuttings for short rotation crop	↑ Leaf area → Photosynthesis	*Estonia* Merilo et al. 2005
Black willow	Potassium Phosphorus	Field Study – Planted cuttings in 2 soils with different nutrients	↑ Growth	*Oklahama* McLeod and McPherson 1973
Carolina willow	Nitrogen, Phosphorus Micro-nutrients (K, Cu, Mg, Fe)	Greenhouse Study -Applied nutrients via water to seedlings and cuttings	*Seedlings* ↓ Stem Height → Leaf density → Stem diameter *Cuttings* → Stem Height ↑ Leaf density (small individuals) → Leaf density (large individuals) → Stem diameter	Upper St. Johns River Basin Quintana-Ascencio et al. 2011
Greyleaf willow	Nitrogen	Greenhouse Study - Applied amendments to natural populations	↑ Leaf area ↑ Leaf density	*Rocky Mountains* Bowman and Conant 1994
Greyleaf willow	Nitrogen Phosphorus Potassium	Natural Environment - Legacy effects of soil nutrients on natural populations	↑ Growth rate ↑ N content in twigs	*Canada* Melnychuk and Krebs 2005
Goodding's willow	Ammonium-N Nitrate-N Phosphate-P	Greenhouse Study - Applied nutrients via water to seedlings	↑ Leaf density ↑ Stem density ↑ Biomass ↑ Height	*Southwest U.S.* Marler et al. 2001

Table 6. continued

Species	Nutrient	Type of Study	Effects	Location / Source
Missouri River willow Pussy willow Sandbar willow Shining willow	Nitrate Phosphorus	Natural population distribution	↑ Productivity	*Netherlands* Johnston 2003
Myrsine-leaved willow	Nitrogen	Greenhouse Study - Applied fertilizer to cuttings	↑ Leaf area ↓ Root production	*Finland* Hakulinen 1998
Purple Osier willow White willow *S. dasyclados* *S. alba var. sanguinea* *S. rubens* *S. purpurea*	Ammonium nitrate, treble super-phosphate, muriate of potash	Planted cuttings for willow bioenergy production	↑ Growth rate → Maximum production	*New York* Kopp et al. 2001
Silky willow	1.25 g Peters® 20-20-20 NPK fertilizer/L	2-yr old plants	61% ↑ Growth rate	*New York* Orians et al. 2003
S. miyabeana	Ammonium (NH_4-N)	Short-rotation Crop – Applied polluted groundwater	↑ Growth rate ↑ Nutrient retention	*Canada* Nissim et al. 2014
***Salix* spp.**	Nitrogen (75 kg/ha/yr)	Planted cuttings	→ No effect on growth ↑ Leaching	*Germany* Balasus et al. 2012

Nutrients assimilated by willow can be removed from the ecosystem by harvesting the plants for biofuel or natural products (basket-making, furniture, etc.) or they may be recycled in the ecosystem. Lusby et al. (1998) suggested that nitrogen assimilated in plant tissues can be returned to the overlying water-sediment surface through litterfall and then may be subject to mineralization, nitrification, and denitrification, resulting in N loss as a gas. Plants like *Salix* can efficiently accumulate nitrogen and phosphorus by producing a large number of leaves, but leaf shedding during the fall causes a large portion of these nutrients to be returned to the soil (Adler et al. 2008). Bochnak et al. (2015) found that the *in situ* flux of total dissolved phosphorus in the Carolina willow (0.85 $g/m^2/yr$) community was higher than that found in sawgrass (0.18 $g/m^2/yr$) or cattail (0.50 $g/m^2/yr$) communities. Total Kjedahl nitrogen from soil in the Carolina willow (4.5 $g/m^2/yr$) community was higher than that found in sawgrass (2.9 $g/m^2/yr$) and lower than that found in southern cattail (5.4 $g/m^2/yr$) communities. Total organic carbon flux was intermediate for the Carolina willow (24.3 $g/m^2/yr$) community when compared to sawgrass (16.0 $g/m^2/yr$) and southern cattail (45.8 $g/m^2/yr$) communities. Duffy (2014) found that decomposition of both Carolina willow and sawgrass litter was relatively slow when compared to that of other marsh species such as southern cattail and knotweed (*Polygonum glabrum*). Slow litter decomposition in willow was partially due to its extremely high lignin content (54.7%) as compared to that found in sawgrass (13.5%), cattail (15.9%) and knotweed (18.9%). Lignin is recalcitrant and resists decomposition. Based on these characteristics, the contributions of Carolina willow litter to the soil profile could increase marsh elevation, thereby reducing the hydroperiod and water depths and increasing soil oxidation. This can lead to changes in soil properties and carbon cycling due to differential decay of Carolina willow leaf litter as opposed to herbaceous wetland plants.

The ability of willows to efficiently utilize nutrients for rapid growth enables its effective use around the world as a biofilter in water treatment systems and as biofuel. Willows commonly growing along streams and at the edges of swamps are considered essential elements in vegetation filters used for agricultural and urban runoff because they have been shown to substantially reduce the pollutant load (Elowson and Christersson 1994 in Kuzovkina and Quigley 2005). Willow clones of *Salix dasyclados*, grown in New York, increased nutrient removal from water under increased fertilization and irrigation rates (Adegbidi et al. 2001).

Willows grown specifically as vegetation filters in Sweden have been shown to effectively remove up to 100 kg/ha/yr of nitrogen if the stem biomass is removed and harvested (Elowson 1999). In a lake edge wetland in New Zealand, large gray willow (*Salix cinerea*) was found to dramatically reduce ammonium (NH_4-N) in groundwater that was within 5 meters of the trees, due to contact with the roots that extended beyond the above-ground canopy (Lusby et al. 1998). The entire littoral zone, including large gray willow and *Typha orientalis* zones, removed >95% of the NH_4-N entering the wetland via groundwater. While managers strategically plant willow to intercept runoff to reduce contaminants (Kuzovkina and Quigley 2005), perhaps the natural colonization of willow primarily along the borders of levees and roads can act as a buffer zone to “protect” interior marshes from polluted water.

In summary, willows are extremely efficient at accessing, assimilating and storing nutrients. Soils in willow communities typically have higher nutrient content than many other wetland plant communities. Consequently, nutrient flux or release may be higher in willow communities upon soil exposure and subsequent reflooding. In addition, if willows are not being harvested or the biomass is not being removed from the ecosystem (as in a biofilter or biofuel application), the shedding of leaves in the fall returns some of the stored nutrients to the water column and the soil.

EVAPOTRANSPIRATION AND CARBON EXCHANGE

Evapotranspiration rates are variable in willow depending on the species, its environment and geographic location. Some species of willow have stomata on both sides of the leaf (amphistomatous), while others, like Carolina willow, have stomata only on the lower side of the leaf (hypostomatous). Interestingly, black willow (the only other willow with which Carolina willow hybridizes in Florida) and Carolina willow have opposite stomatal arrangements (Argus 1986) that may confer differential advantages in regard to regulating water conductance in and out of the plant. Plants that are hypostomatous, like Carolina willow, were originally believed to be less commonly occurring in nature than their counterparts and occurred primarily in xeric habitats (Parkhurst 1978). However, when examining specimens of four plant families, Parkhurst (1978) found that willow species were distinct in that they exhibited a different stomatal distribution than the other three families; a majority of willow species had hypostomatous leaves occurring under all three habitat classes (xeric, mesic, hydric). The other families showed a trend of the greatest proportion of species having hypostomatous leaves least often in xeric habitats and then hydric habitats and most often in mesic habitats. Advantages of this stomatal arrangement were proposed to: 1) give the plant greater control over gas exchange (if bulk flow is important); 2) allow the pores on the lower leaf surface to exploit the microclimate (high humidity and low CO_2) to perform metabolic functions more efficiently; and 3) allow lower water loss on the cooler, underside of the leaf compared to the warmer upper surface (Parkhurst 1978). These phenomena would have an additive positive effect for Carolina willow and helps to explain why woody plants trap and utilize still air better than herbaceous plant communities. This may also help to explain greater transpiration rates in willow versus herbaceous wetland communities in the USJRB.

High transpiration/evapotranspiration rates (Grip et al. 1988, Kuzovkina and Quigley 2005, Bialowiec et al. 2007, Kocik et al. 2007) and high water consumption (Wikberg 2006, Doody and Benyon 2011, Budny and Benscoter 2016) have been documented in willow in comparison to a number of herbaceous species (Jablonska et al. 2014 and other references in Table 7). However, there was one exception with Munroe (1991) finding the opposite with broadleaf cattail (*Typha latifolia*) evapotranspiration rates (see note on Table 7) being higher than Carolina willow in SW Florida. Willow species also showed higher evapotranspiration rates than a few other woody species, including red maple (*Acer rubrum*), saltbush (*Baccharis halimifolia*, and cottonwood (*Populus deltoids*) (Nagler et al. 2005), but not Peruvian primrosewillow (*Ludwigia peruviana*). In a cross comparative analysis using data from the USJRB and the Everglades, Carolina willow was found to have ~15% higher evapotranspiration rates than sawgrass and open water during the times it has leaves in Feb-Nov (Mao 2002, unpublished data from SJRWMD, UCF, and USGS; Table 8 and Figure 20). This can result in upwards of 200 mm more water transpired per year from willow versus other herbaceous plant communities and open water (Table 8). Additionally, when willow was removed by treatment with herbicides and a floating aquatic community (*Spirodela polyrhiza*, *Lemna minor*, *Salvinia minima*) replaced it, the difference in evapotranspiration rates increased to an annual difference of greater than 500 mm/yr between treated and untreated sites (Tang 2016; Figure 21).

Table 7. Comparative water use for willow species, herbaceous species and other tree species in studies measuring parameters concurrently. Red highlight indicates higher water usage in each comparison. No highlight indicates no significant differences. ET = evapotranspiration. * Transpiration measured by Munroe (1991) has similar units, but two trials (Oct and Jan) differ by orders of magnitude and therefore may only be useful for with-in trial comparison.

Parameter (units)	Willow Species (value)	Herbaceous Species (value)	Tree Species (value)	Notes	Location / Source
Total seasonal transpiration (mm)	Peachleaf willow 522	Common reed 483	Cottonwood 431	2009 - Dry year	*Nebraska* Kabenge and Irmak 2012
Total seasonal transpiration (mm)	Peachleaf willow 655	Common reed 550	Cottonwood 496	2010 – Wet year	*Nebraska* Kabenge and Irmak 2012
ET (mm/d)	Weeping willow 16.35 ± 1.34	Broadleaf cattail 5.75 ± 0.94	Red maple 4.31 ± 0.66	All plants higher ET than bare soil and open water	*New York* Pauliukonis and Schneider 2001
Transpiration (mmol/m²/s)	Lemmon's willow 3–13 3–14	Nebraska sedge 2.5-12 7-17.5		(as interpreted from figure) 1988 – Dry Yr 1989 – Wet Yr	*California* Svejcar and Trent 1995
Maximum daily ET (mm/d)	Salix spp. 7.9	Common reed 5.9			*Germany* Frahm et al. 2010
ET (mm/yr)	Weeping willow (in creek) 2410, 1755, 1947 (on bank) 563		Red river gum 553	2005/06 Wet Yr 2006/07 Dry Yr 2007/08 Wet Yr (bank willow and Eucalyptus – 2005/06 only)	*Australia* Doody and Benyon 2011
Transpiration (g/hr/kg dry plant wgt)	Carolina willow 0.40 ± 0.06	Broadleaf cattail 1.13 ± 0.11	Groundsel tree 0.35 ±0.04 Mexican primrosewillow 0.59 ± 0.13	2-day measurements in Oct 1988	*Florida* * Munroe 1991
Transpiration (g/hr/kg dry plant wgt)	Carolina willow 311–463	Broadleaf cattail 980-1270		1-day measurement in Jan 1989	*Florida* * Munroe 1991
Stomatal conductance (mol $H_2O/m^2/s$)	Carolina willow 0.359	Sawgrass 0.240			*Florida* Budny and Benscoter 2016

Table 8. Comparison of annual evapotranspiration estimates (mm/yr) for Carolina willow, sawgrass, and open water in the USJRB and the Everglades.

Plant Community	Location	Annual ET (mm/yr)	Source / Location
Carolina willow	St. Johns MCA, USJRB	1484	UCF (unpublished data)
Sawgrass	Blue Cypress MCA, USJRB	1290	USGS, SJRWMD (unpublished data)
Open Water	Fort Drum MCA, USJRB Water Conservation Area 1, Everglades	1266	Mao 2002 for USJRB USGS (SOFIA Database) for Everglades

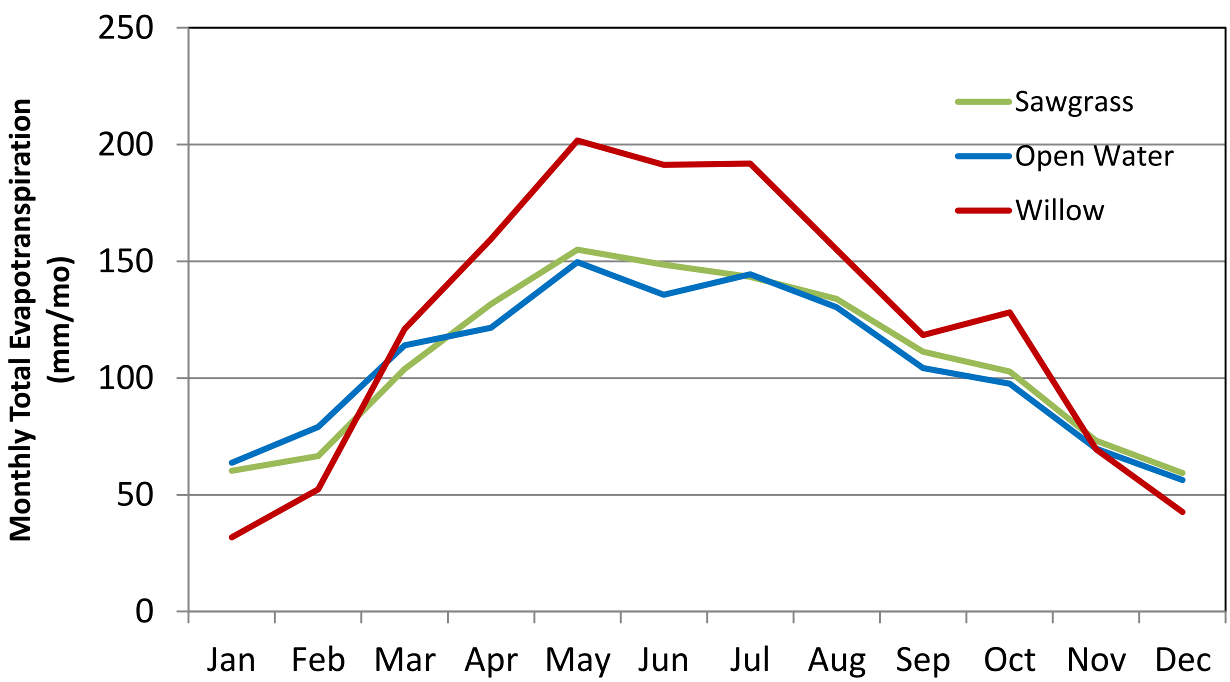

Figure 20. Comparison of monthly evapotranspiration among plant communities in the Upper St. Johns River Basin and Everglades. Data notes - Willow data from St. Johns Marsh and River Lakes Conservation Areas (4 sites) for Sept 2014 to Nov 2015 using Penman-Monteith method; sawgrass data from Blue Cypress Marsh Conservation Area averaged over 2010-2014 using Eddy Covariance method; open water data from Ft Drum Marsh Conservation Area averaged over 1996–1999 using lysimeter method and from Everglades Water Control Area 1 averaged over 1996–1997 using Eddy Covariance method.

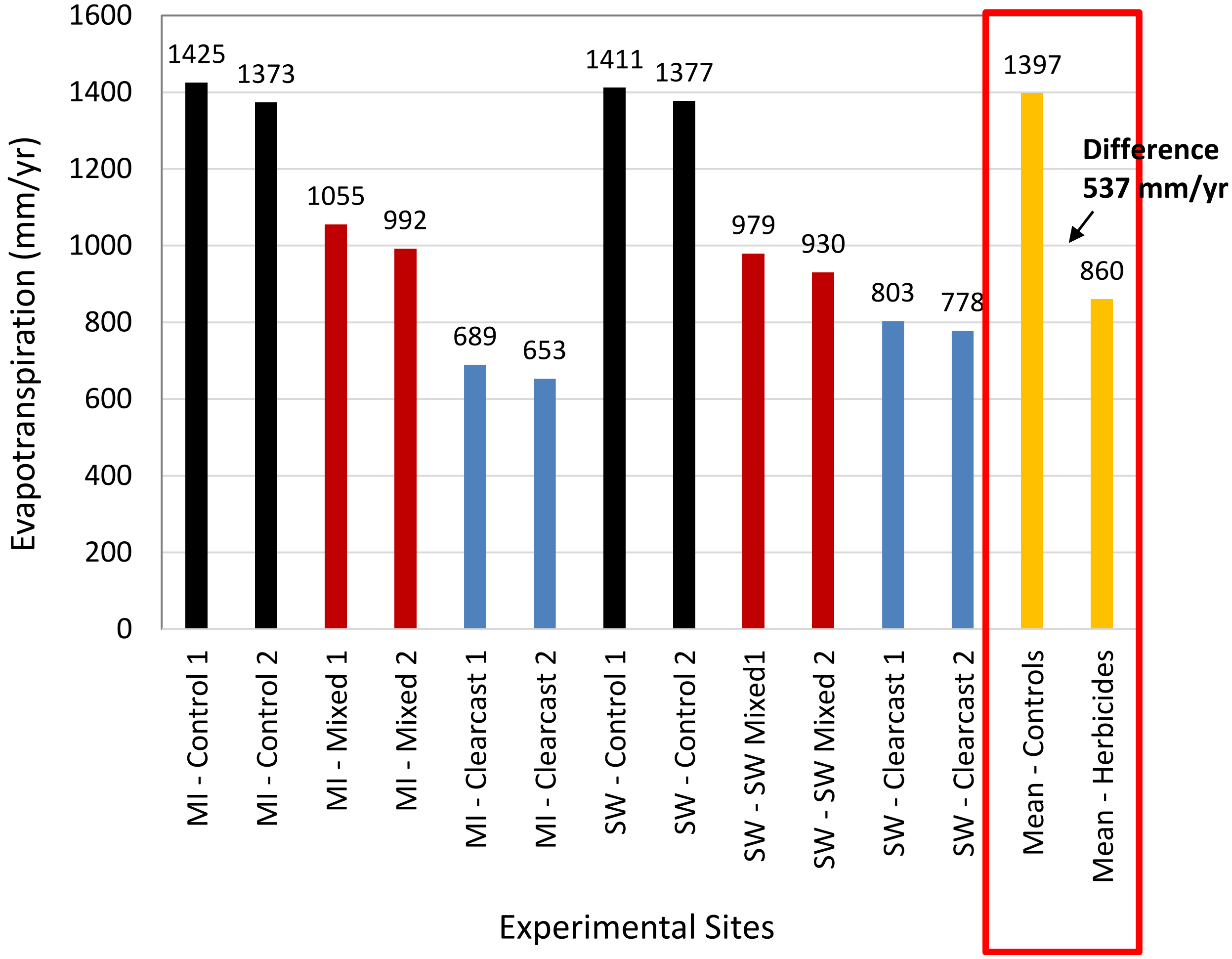

Figure 21. Annual evapotranspiration (7/1/14 to 5/1/16) from willow communities in Moccasin Island (MI) sites in River Lakes Conservation Area and Sweetwater (SW) sites in St. Johns Marsh Conservation Area. Plots were treated with herbicides in 2014 and 2015 as compared to untreated controls (Tang et al. 2016). Clearcast Treatment = treated with Clearcast in Aug 2014 and July 2015. Mixed Treatments = treated with Aquasweep in Aug 2014 and treated with Ecomazapyr in July 2015.

When plant communities were weighted for their areal extent in SJMCA, willow was shown to contribute a significantly greater amount of CO_2 to the atmosphere in comparison to herbaceous plant communities. On the other hand, methane (CH_4) loading to the atmosphere by willow is greater than that found with sawgrass and grass/sedge marsh, but less than that measured in mixed herbaceous marsh that is dominated by *Typha* sp. All plant communities had higher load for CO_2 and CH_4 than open water (Figures 22 and 23; Bochnak et al, 2015).

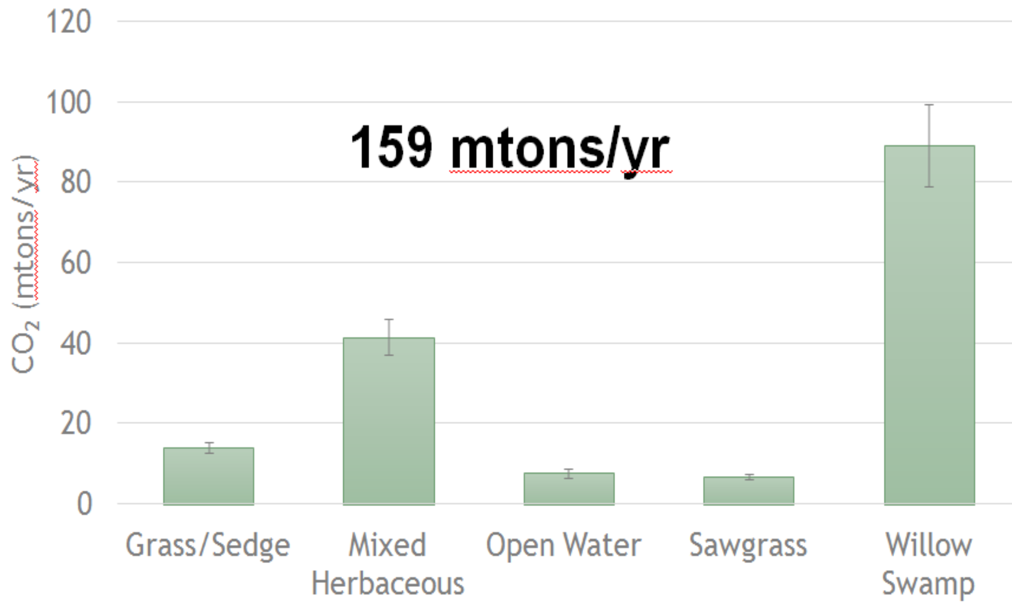

Figure 22. Carbon dioxide (CO_2) loading from different plant communities in St. Johns Marsh Conservation Area (Bochnak et al. 2015).

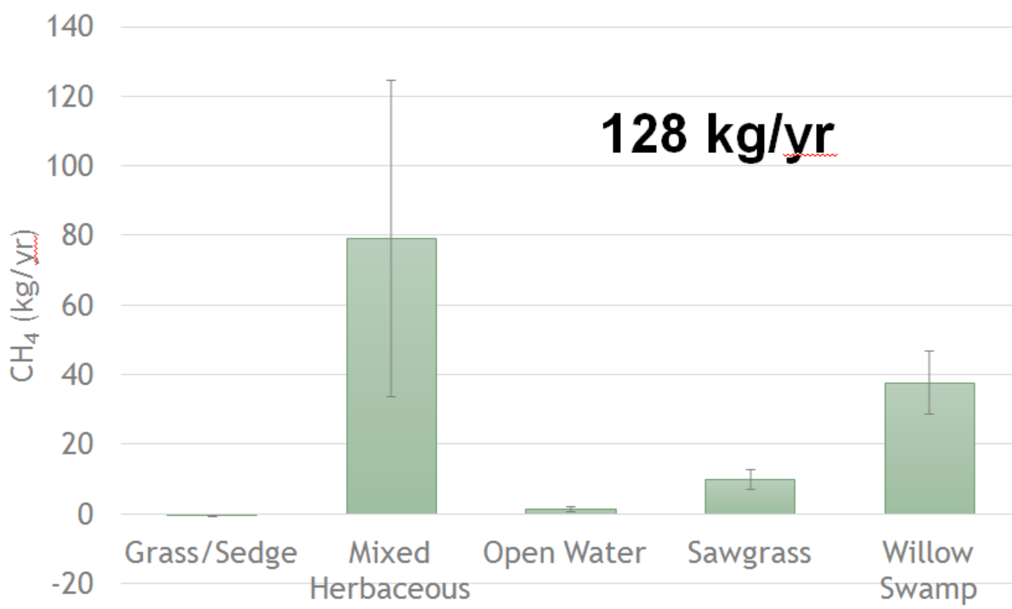

Figure 23. Methane (CH_4) loading from different plant communities in St. Johns Marsh Conservation Area (Bochnak et al. 2015).

Evapotranspiration rates are highly dependent on irradiation, temperature and water supply (Kabenge et al. 2013) and nutrient enrichment increases evapotranspiration (Guidi et al. 2008, Ens et al. 2013, Nissim et al. 2014). Water is usually not a limiting factor in wetland environments where Carolina willow occurs and evapotranspiration rates have been shown to be higher in wet conditions (van Splunder et al. 1996 for almond willow [*S. triandra*] and basket willow [*S. viminalis*]). Guidi and Labrecque (2010) indicated that white willow (*Salix alba*) had greater plant productivity and higher water use efficiency (i.e., the amount of carbon dioxide assimilated by leaves per unit of water vapor transpired) under soil saturation, rather than under excessive moisture levels. However, in times of drought or water stress, willow has the advantage of tight regulation of water loss through stomatal closure (Horton et al. 2001). In comparison to sawgrass, Carolina willow has been shown to have lower water use efficiency and higher leaf area and therefore uses more water for photosynthesis and growth (Budny and Benscoter 2016). This means willow uses more water than sawgrass per carbon molecule assimilated into biomass. When leaf level measurements of water usage is scaled up to a landscape scale, conversion of sawgrass communities to Carolina willow in Blue Cypress Marsh Conservation Area in the USJRB could translate into an increase in water usage and a decrease in water availability for other ecosystem purposes (Figure 24; Budny and Benscoter 2016). Since willow has deeper roots than herbaceous species (Svejcar and Trent 1995, McLaughlin et al. 2012), it can access water at lower levels in the soil profile (e.g., Lemmon's willow [*S. lemmonii*] versus Nebraska sedge [*Carex nebrascensis*] whose roots only extend to 40cm deep in the soil profile). Because willow evapotranspiration has been documented to surpass the amount of water supplied through rainfall, increased water demand lowers the water table (Ens et al. 2013) and results in a reduction in water quantity for other ecosystem needs (Lindroth and Bath 1999, Nissim et al. 2014). In addition, Carolina willow has a high water holding capacity thus making it very difficult to burn (Quintana-Ascencio et al. 2011). Consequently, the expansion of willow into marshes, normally dominated by flammable herbaceous vegetation like sawgrass, changes the susceptibility of the marsh to fire and, in turn, changes the soil profile and soil processes associated with the herbaceous vegetation. Jablonska et al. (2014) suggested this change in plant community composition slows down peat formation, which contributes to potential positive feedbacks for willow. Because Carolina willow has higher water usage and a greater ability to reach water well below the soil surface, self-generated (autogenic) drying by Carolina willow may further accelerate shrub encroachment and eventual succession to drier plant communities (Budny and Benscoter 2016) or may lead to the formation of a hardwood swamp (Rushton 1988).

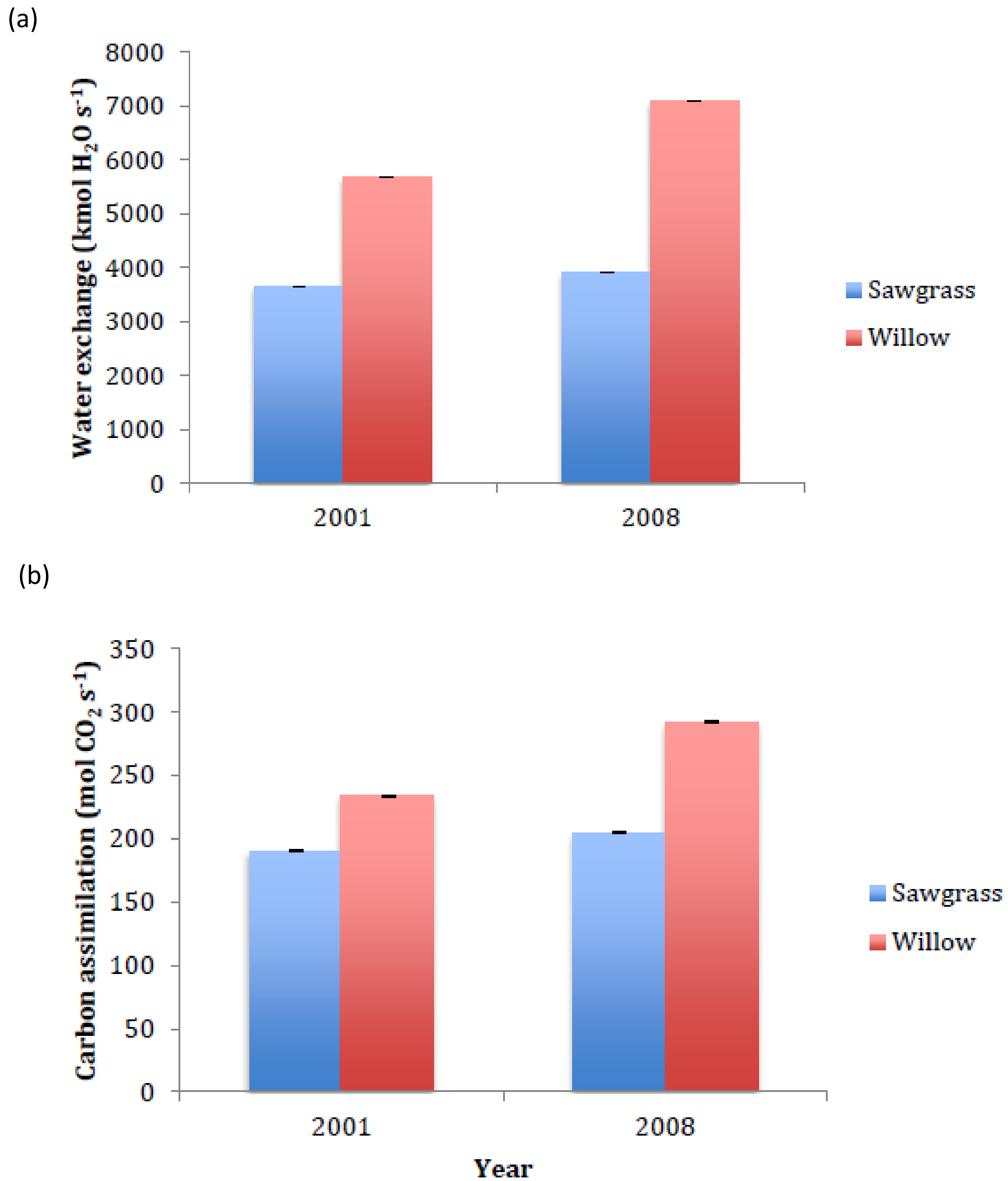

Figure 24. Comparison of extrapolated (a) water and (b) carbon exchange for the entire community dominated by sawgrass and willow in Blue Cypress Marsh Conservation Area in 2001 versus 2008. Reprinted from Budny and Benscoter (2016).

THE ECOLOGY OF CAROLINA WILLOW

DISTRIBUTION

Carolina willow (*Salix caroliniana*) is distributed throughout the southeastern United States, ranging as far north as southern Pennsylvania, south through Florida, and westward into eastern Oklahoma and Kansas (see Figure 5 on page 7; Argus 2007). It is found in most wetland habitats including lowlands, swamps, marshes, river banks and sand bars, natural swales, pond and lake shores, canal banks, and ditches (Godfrey 1988, Wunderlin and Hansen 2011). As with most species of willow, it is an opportunistic species that can quickly colonize open habitats in areas with moist soils that are seasonally flooded (Craighead 1971, Connor et al. 2002, Kuzovkina and Quigley 2005).

ESTABLISHMENT AND EXPANSION

As mentioned in earlier sections and as observed in other willow species (Seiwa et al. 2008), the ease with which Carolina willow colonizes open habitats is a result of its small seeds with fine, water-repellent, attached hairs that can be windblown for long distances and readily float (Craighead 1971). In their study investigating the restoration of tree islands in the Everglades, van der Valk et al. (2008) observed that Carolina willow was the only tree species that naturally colonized the islands and determined that planting of this species was unnecessary for its recruitment.

Given the short viability of Carolina willow seeds (Castro-Morales et al. 2014) and their consequent absence from the seed bank (Lee 1994, Hanselman et al. 2005), the availability and suitability of open soil are major constraints on the establishment and survival of new plants. Carolina willow is shade-intolerant (Craighead 1971, Conner et al. 2002) and seedlings quickly die when over-shaded by other marsh species (Quintana-Ascencio et al. 2011). Consequently, like many willow species (McLeod and McPherson 1973, Shaw et al. 2010, Radtke et al. 2012), Carolina willow only successfully colonizes areas of moist open soils. In the past, creation of open soil areas was primarily associated with the drainage of wetlands, and subsequent anthropogenic disturbance, such as cultivation, mining, logging, arson fires, and the passage of off-road vehicles (Craighead 1971, Clewell 1999). Similarly, areas of open moist soil in the Upper St. Johns River Basin (USJRB; see Figure 3 on page 4) have been created by anthropogenic alterations of historic hydrologic regimes. This has led to the exposure of moist soil areas simultaneous with willow seed dispersal. In an analysis of the distribution of shrubs (mostly Carolina willow) within a portion of the Blue Cypress Marsh Conservation Area (BCMCA; Figure 25) in Indian River County between 1971 and 1993, Kinser et al. (1997) found a 6% increase (477 ac) in shrub cover between 1971 and 1993. Subsequent analysis of the same area by other St. Johns River Water Management (SJRWMD) staff, showed a 12% increase (981 ac) in shrub cover between 1993 and 2008 (Figure 26). Since BCMCA has never been drained for agriculture, the expansion of willow is likely due to changes in hydrology associated with extended spring drawdowns by managers (Kinser et al. 1997), periods of drought, changes in fire regimes, or a combination of these events.

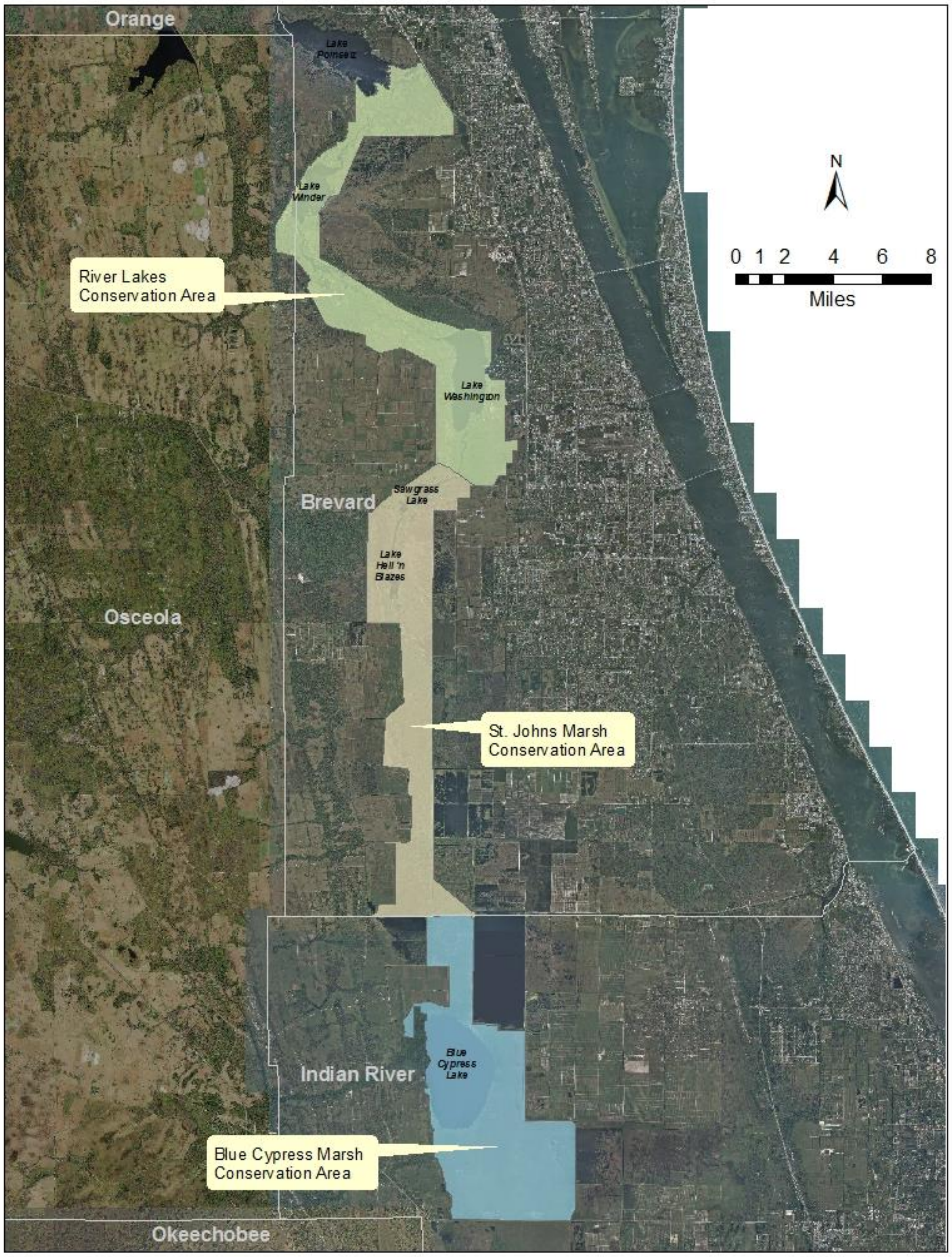

Figure 25. Location of Blue Cypress Marsh, St. Johns Marsh, and River Lakes Conservation Areas within the Upper St. Johns River Basin.

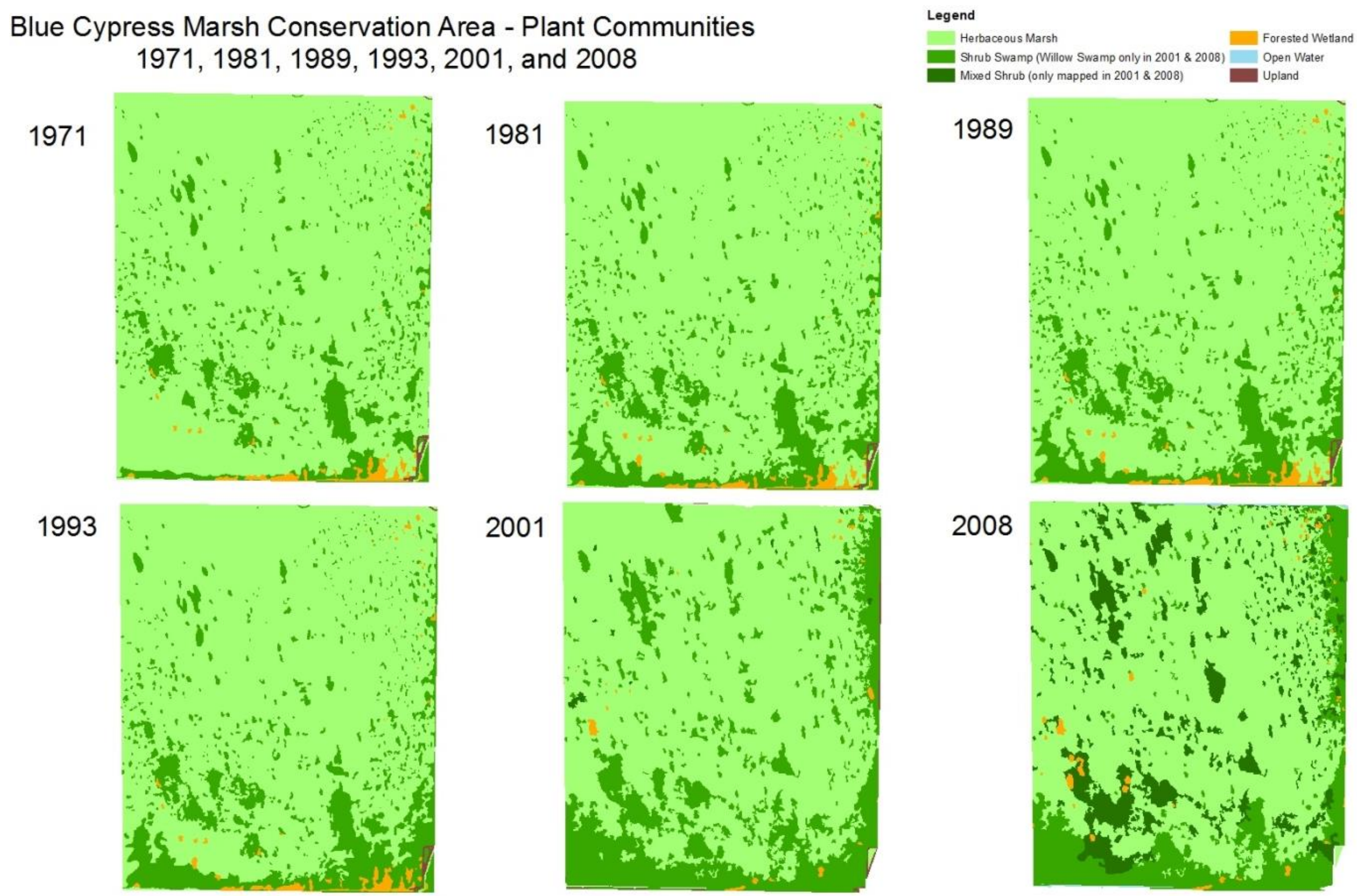

Figure 26. Change in the spatial distribution of shrub swamp (willow and mixed shrub) in the southern portion of Blue Cypress Marsh Conservation Area (BCMCA) between 1971 and 2008 (SJRWMD unpublished data).

Similarly, expansion of shrub cover (again, mostly Carolina willow) has been documented further downstream in the USJRB. Lowe et al. (1984) found an 89% increase in shrub coverage in some areas of the USJRB in Brevard County between 1943 and 1981 associated with a decline in surface water levels in those areas. This decline in water levels was probably associated with the removal of large amounts of vegetation within the river channel north of Lake Washington in Brevard County (commonly referred to as “the jams”). This vegetation was removed to facilitate boat traffic upstream to Lake Washington. However, removal of “the jams” caused water levels upstream in the SJMCA to fall by over two feet (Figure 27) and water levels have remained at this lower level even after installation of a permanent weir to mimic the water-retention function of “the jams” (Figure 28).

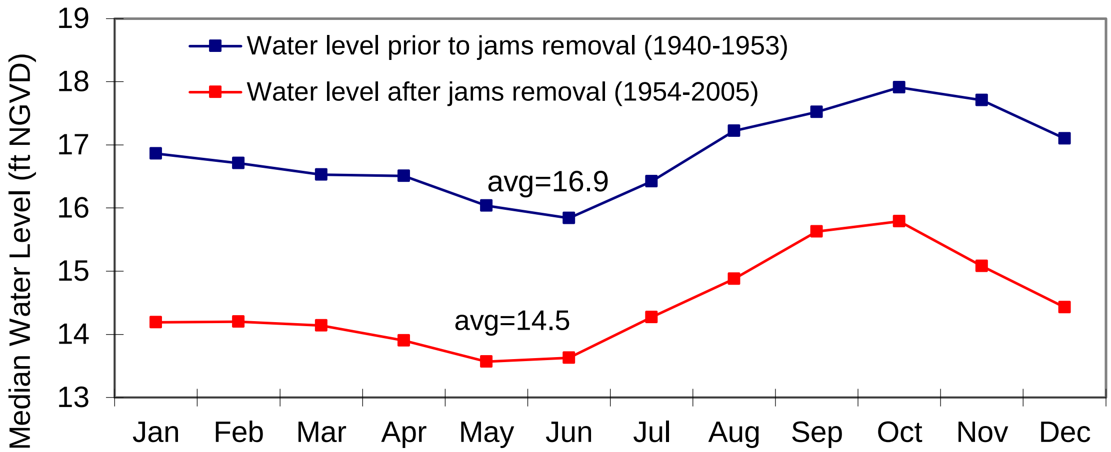

Figure 27. Median monthly water levels at U.S. Hwy. 192 in Brevard County south of Lake Washington before and after removal of “the jams”.

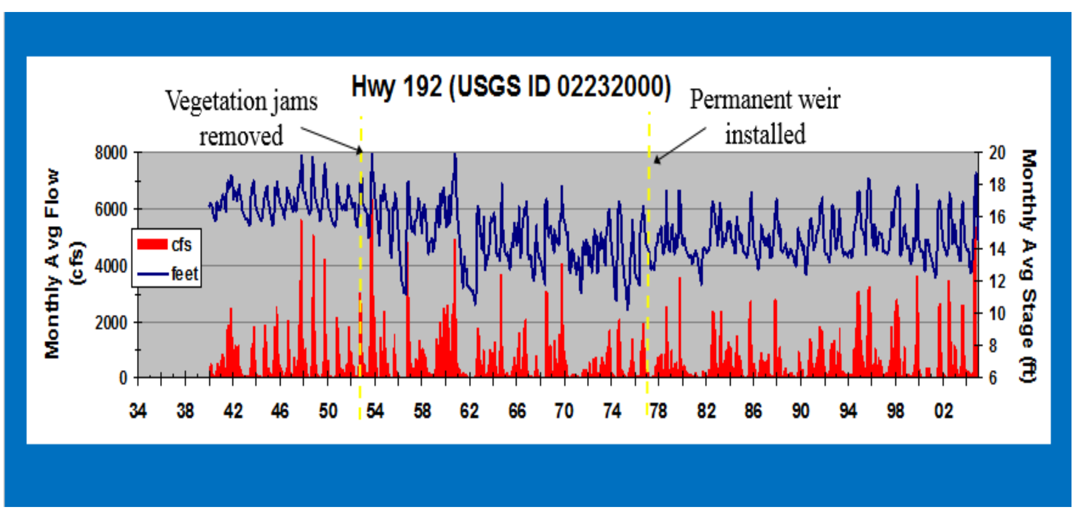

Figure 28. Average monthly water levels at U.S. Hwy. 192 in Brevard County south of Lake Washington between 1940 and 2004 showing water levels before and after removal of “the jams” and installation of the permanent weir.

More recently, shrub cover (mostly willow) expanded by approximately 6,000 ac between 1989 and 2009 in the St. Johns Marsh Conservation Area (SJMCA), an area with large drainage canals on both the east and west sides. The greatest expansion (3,569 ac) occurred between 1989 and 1997 (SJRWMD unpublished data; Figure 29). Other willow species have shown similar expansion abilities (Choi and Wali 1991, Brzosko 2001).

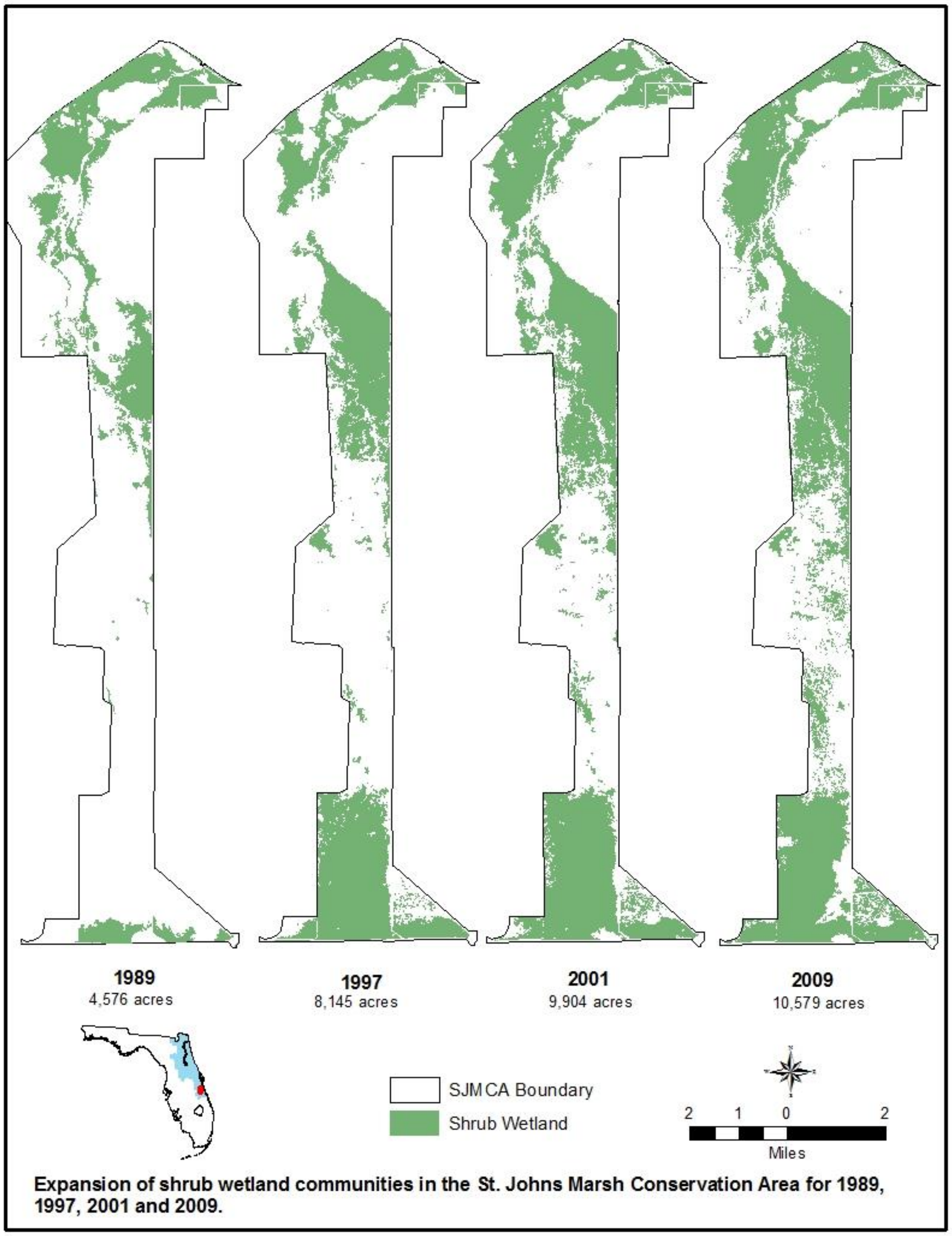

Figure 29. Change in the spatial distribution of shrub swamp (willow and mixed wetland shrub) in St. Johns Marsh Conservation Area (SJMCA) between 1989 and 2009 (SJRWMD, unpublished data).

Expansion of shrub swamp has also occurred in the central part of the St. Johns River system. The Ocklawaha River is the main tributary of the St. Johns River in central Florida and expansion of shrub swamp (mostly dominated by willow, buttonbush (*Cephalanthus occidentalis*) or Peruvian primrosewillow (*Ludwigia peruviana*)) has also been noted in three areas of the Upper Ocklawaha River Basin (UORB) within the SJRWMD: Emeralda Marsh Conservation Area (EMCA), Ocklawaha Prairie Restoration Area (OPRA), and Sunnyhill Restoration Area (SRA). Prior to conversion to agriculture, these areas along the river floodplain and its lakes were dominated by extensive expanses of sawgrass. With the advent of agriculture, portions of these areas were diked and drained, and sawgrass was replaced by crops. With the cessation of agricultural practices, these areas regained a more natural hydroperiod and soils became saturated or inundated based on rainfall patterns and seepage from the adjacent floodplain and its lakes. However, due to the loss of the organic soils caused by extended draining, which led to longer periods of inundation post-agriculture, and without the presence of flammable vegetation, such as sawgrass, the effects of prescribed burning were limited and shrubs began to colonize the former agricultural fields. Between 2005 and 2013, the acreage of shrub swamp more than doubled in most of these areas, increasing from 698 to 1,270 ac in EMCA (Figure 30), from 165 to 592 ac in OPRA (Figure 31), and from 431 to 1,106 ac in SRA (Figure 32).

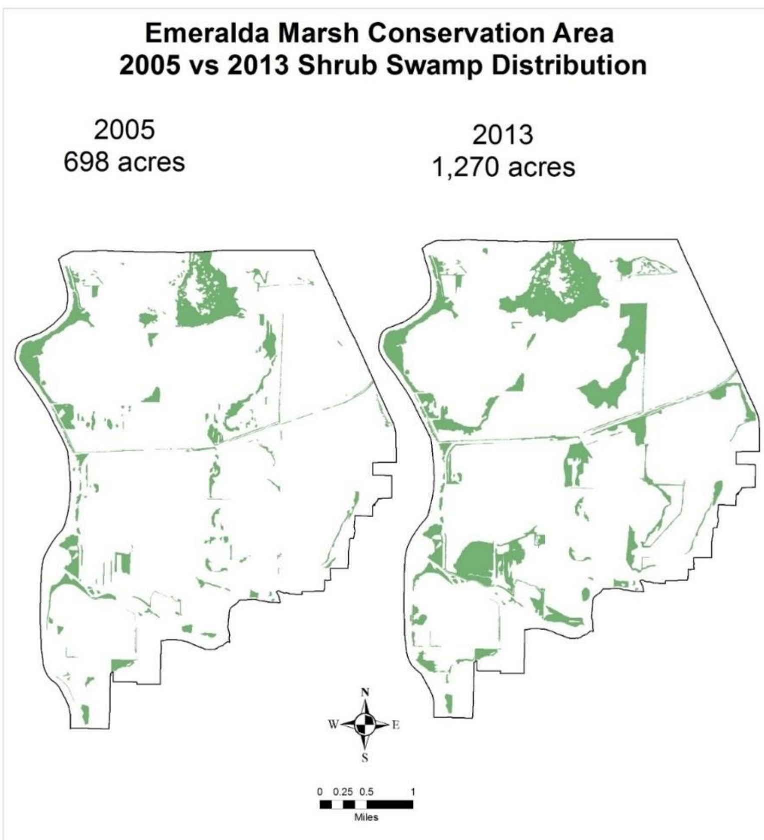

Figure 30. Change in the spatial distribution of shrub swamp in Emeralda Marsh Conservation Area between 2005 and 2013 (SJRWMD, unpublished data).

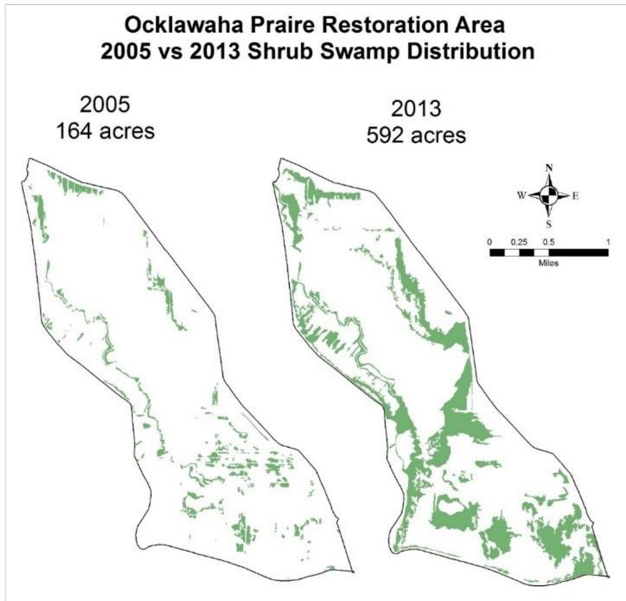

Figure 31. Change in the spatial distribution of shrub swamp in Ocklawaha Prairie Restoration Area between 2005 and 2013 (SJRWMD, unpublished data).

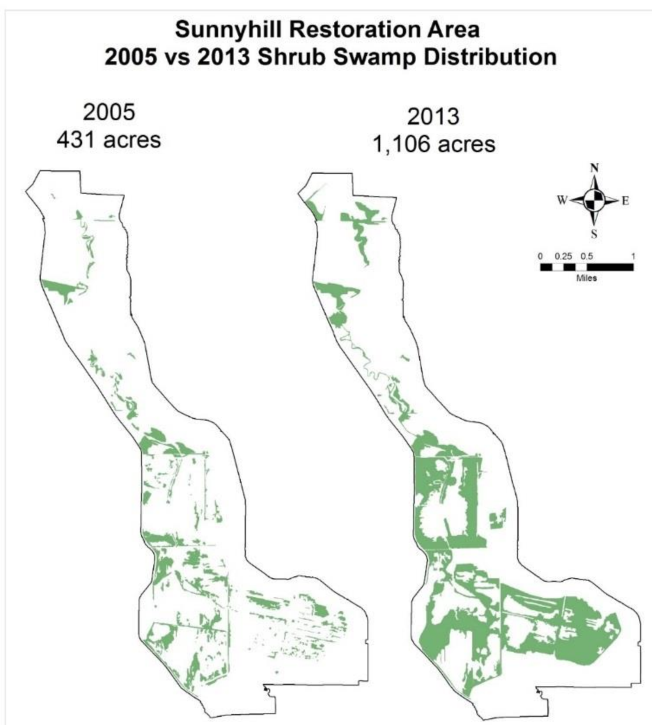

Figure 32. Change in the spatial distribution of shrub swamp in Sunnyhill Restoration Area between 2005 and 2013 (SJRWMD, unpublished data).

HYDROLOGY

The distribution of Carolina willow seems to be constrained by the hydrologic requirements of its seedlings and young plants (Quintana-Ascencio et al. 2013, Castro-Morales et al. 2014), like many other willow species (Hupp 1992, Gage and Cooper 2004, Asaeda et al. 2011). Using a maximum entropy model to predict willow colonization as a function of soil type, prior land use, and proximity to transportation corridors and water-control systems, Quintana-Ascencio et al. (2011) found that soil type was the most important determinant of willow distribution in the USJRB with willows preferentially colonizing organic peaty soils. Soil type accounted for 65.2% of the variation in willow coverage in their model.

This agrees with the findings of Craighead (1971), Pesnell and Brown (1977), and Gunderson and Loope (1982), who found that Carolina willows preferred mucky peat soils. This has led some to speculate that the nutrient content of peat and muck soils contributed to Carolina willow survival and growth. However, Clewell (1999) and McLaughlin et al. (2012) found that Carolina willows grew exceptionally well on clay soils with little organic matter content. McLaughlin et al. (2012) noted that strong capillary forces in clay soils in Central Florida could elevate moisture in soils 0.85 m above the water table and promote deeper rooting of Carolina willow than is observed in sandier soils within clay-settling areas. Subsequent work by Quintana-Ascencio et al. (2011) showed that germination, growth and survival of Carolina willow seedlings was dependent on the presence of suitable hydrology, rather than organic or nutrient content of the soils. They examined the role of nitrogen, phosphorus, potassium and other assorted micronutrients in the growth of Carolina willow planted on organic and inorganic soils and found that willow grew just as well on sand as peat, as long as the soil remained moist; addition of nutrients made little difference. The lack of sensitivity to nutrients may be a result of fungi found in the roots of Carolina willow in the USJRB, which may allow it to persist under low-nutrient conditions (Ipsilantis 2005). Other willow species have been found to harbor nitrogen-fixing bacteria to cope with low-nutrient conditions (Doty et al. 2009, Hrynkiewicz et al. 2009, Von Wuehlisch 2011). Under normal field conditions, peat and muck soils have better water-retention capacity than sand, which explains why most Carolina willow in the USJRB is restricted to peaty or mucky soils. The importance of the water-holding capacity of soils has been found for other willow species as well (Gage and Cooper 2004, Molina et al. 2004, Caplan et al. 2013).

While Carolina willow requires moist soil to germinate and grow during the early life stages, too much water during this time is as much a detriment as too little. Research concerning the hydrologic requirements of Carolina willow seeds, found reduced germination under flooded conditions and limited survival of seeds that did germinate under flooded conditions (Quintana-Ascencio et al. 2011, Castro-Morales et al. 2014). In addition, research on Carolina willow seedlings showed that high water levels were detrimental to the survivorship of seedlings and small willows, causing death by overtopping and from scouring by floating vegetation (Quintana-Ascencio et al. 2011 and 2013). This research showed that the early developmental stages of Carolina willow are the most susceptible to hydrologically-induced mortality.

Once Carolina willows are tall enough to escape prolonged submergence and have developed root systems extensive enough to tap ground water, they are highly resistant to hydrologically-induced mortality, like many other species of willow (Kuzovkina and Quigley 2005). In their study investigating the restoration of tree islands in the Everglades, van der Valk et al. (2008) found that Carolina willow was highly tolerant of both drought conditions and flooded conditions, capable of surviving an inundation frequency of 50%, as well as drought conditions. This confirmed Conner et al.'s (2002) earlier work on water depth tolerances of Everglades tree island species. Similarly, mature Carolina willows have been observed to survive in persistently flooded habitats of the USJRB for several years (Ponzio and Hall, pers. obs.), as long as portions of the plant remain above water. Moreover, drought conditions in the USJRB have not produced any noticeable loss of mature Carolina willow (Ponzio and Hall, pers. obs.).

However, Carolina willow mortality and thinning was noticed in the littoral zone of Lake Okeechobee in 1984–1989 (David 1994). It was thought that this could be due to the increase in regulation schedule for Lake Okeechobee in 1978, which raised water levels by an average of 1.5 ft However, Milleson (1987) did not note any changes in willow coverage between 1978 and 1980, and by 1992, willow coverage had rebounded to levels seen in 1973 (Richardson and Harris 1995), prior to the increase in water levels. David (1994) suggested that the mortality and thinning might be due to the extensive annual use of the willow area as a rookery for wading birds, where some years there were more than 10,000 nests in an approximately 1,500 ac area. This density could have led to extensive physical damage of the willow. The extensive use of willow in the littoral zone by wading birds in between 1970 and 1982 (David 1994), coupled with a drought and major freeze in 1989, and extensive spring and summer burns in 1990 (Richardson and Harris 1995) could have resulted in the temporary loss of willow coverage observed.

FIRE

Another way of creating areas of open soil in marsh habitats that could be invaded by Carolina willow is through fire. Fire is a natural component of freshwater marshes in the Southeast and naturally occurs approximately once every three to five years in floodplain marshes (FNAI 2010), although some have suggested longer fire return intervals may be appropriate (Snyder 1991). Natural fires usually occur in the late spring to early summer associated with thunderstorms at the end of the dry season and the beginning of the wet season (Kushlan 1990). Although fires are usually thought of as preventing the invasion of woody species into marshes (Kushlan 1990, Lodge 1994), this is not always true. Carolina willow has been observed to colonize areas that have been freshly burned (Loveless 1959), taking advantage of open areas created by fires that kill competing vegetation at the same time that willow seeds are dispersing (Gunderson and Loope 1982, Kinser et al. 1997). Colonization of Carolina willow in open areas after fires has been observed in both herbaceous (Loveless 1959) and wooded areas (Gunderson 1977, Gunderson and Loope 1982). Loveless (1959) characterized Carolina willow as a "fire-follower" and concluded that Carolina willows had replaced much of the original vegetation on some tree islands in the Everglades as a result of repeated fires. Lodge (1994) suggested that habitats dominated by

Carolina willow in the Everglades are maintained by fire. Conversely, recent work by Quintana-Ascencio et al. (2011) found no recruitment of Carolina willow onto open soil areas created by fire during the dry season. In their study, over 1860 viable seeds were sown into various-sized patches of exposed soil after a fire in mid-February. Less than 7% of seeds geminated and none survived through the end of May. However, these results my have been confounded by an extreme dry season (January–May), in which water levels fell well below the soil surface and well below the young roots of developing willow seedlings. The establishment of other willow species has been shown to be facilitated by fire (McDougall et al. 2005, McDougall 2007) and fire frequency has been shown to be one of the main drivers of willow invasion into formerly treeless plant communities (Moore and Runge 2012).

As with hydrology, seedlings and young Carolina willows are highly susceptible to fire-induced mortality, while mature willows are not. Young Carolina willows can be killed by fire if they are surrounded by flammable vegetation, such as sawgrass (*Cladium jamaicense*), sand cordgrass (*Spartina bakeri*) or if surrounding vegetation, such as maidencane (*Panicum hemitomon*), has been killed by a freeze (Figure 33). However, in areas where there is little or no surrounding flammable vegetation, young willows can survive fire.

Figure 33. Small Carolina willow surrounded by flammable marsh vegetation.

Once Carolina willows mature, they are relatively unaffected by fire (Loveless 1959, Wade et al. 1980, Epanchin et al. 2002, Quintana-Ascencio et al. 2011). This may be due to the high water content of Carolina willow, mentioned earlier in this document in regards to transpiration rates, and the lack of understory vegetation to carry fire (Kinser et al. 1997, Quintana-Ascencio et al. 2011), as has been found with other willow species (Cremer 2003).

In the USJRB, fire effects on mature willow have shown some reduction in canopy cover and density of willows > 1.5 m in height with a concomitant increase in species richness of understory plants, although this increase in understory plant species richness may be short-lived (Miller et al. 1998). However, regardless of whether fires are conducted in the dormant or growing season, significant re-sprouting of willow can occur within a year after a prescribed fire, with stem density and canopy cover returning to pre-burn levels within one to two years (Miller et al. 1998, Lee et al. 2005a, Lee et al. 2005b; Figure 34). In contrast, fires that occur during periods of drought, resulting in peat fires, can kill mature willows (Figure 35; Loveless 1959, Wade et al. 1980) and result in significant changes in plant community composition.

Figure 35. USJRB marsh after a peat fire. Note the sand substrate where the peat has been consumed and the dead mature willows in the background and to the left.

Figure 34. Prolific basal re-sprouting of Carolina willow after fire.

Similar to changes in the hydrologic regime of the USJRB marshes between 1989 and 1997, the fire regime of the marshes changed as well. Prior to 1993, most fires within the USJRB were either ignited by lightning strikes during the growing season or by arsonists during the dormant season, with the majority of fires due to arson (Lee et al. 1995). Between 1985 and 1989, more than 9,900 acres of a 55,800-acre area of the USJRB burned due to arson and another 4,600 acres burned due to unknown causes (probably arson), with only nine acres burned through lightning strikes. Most of the arson fires occurred between November and January, while lightning fires occurred in June and July (Florida Division of Forestry, Orlando District — unpublished fire records). Fires occurring between November–March would create open areas of soil at the same time willows are releasing their seeds (~February–March in the USJRB). By the time a prescribed burn program was established for the USJRB in 1993, willows that colonized prior to that time had probably grown too large to be significantly impacted by fire and continued drainage (brought about by the removal of "the jams") in SJMCA probably enhanced Carolina willow survival and expansion in that area.

HABITAT VALUE

Although expansion of Carolina willow at the expense of other marsh plant communities can diminish the overall community diversity of an area, Carolina willow in the USJRB has been found to harbor a rather large diversity of biota (SJRWMD, unpublished data). Research into the diversity of birds, frogs, insects, and other plant species associated with areas of Carolina willow in BCMCA found that Carolina willow supported a greater number of other plants and insects than communities dominated by maidencane (*Panicum hemitomon*), sawgrass (*Cladium jamaicense*) or cattail (*Typha* sp.). In addition, Carolina willow communities were second only to cattail communities in the number of bird species observed but seemed to be depauperate of frogs. However, only three species of frogs were observed in all the communities and the researchers suggested that the low number of species observed could be due to their sampling methodology rather than differences among the community types. Carolina willow communities were especially rich in insect taxa (234 spp.), containing over 50% of the insect taxa collected during the study. Twenty percent of the insect taxa (88 spp.) collected were not found in the other three plant communities sampled. Common insect taxa found on Carolina willow include pollinators, such as Viceroy butterflies (*Limenitis archippus*) and stable flies (*Stomoxys calcitrans*; Jarzen and Hogsette 2008). Carolina willow also harbors a large number of insect herbivores (Figures 36 and 37), such as cottonwood leaf beetles (*Chrysomela scripta*), cottonwood borers (*Plectrodera scalator*), fall webworms (*Hypantria cunea*), salt marsh moths (*Estigmene acrea*), white tussock moths (*Orgyia leucostigma*), dagger moths (*Acronicta* sp.), and carpenterworm moths (*Prionoxystus robinae*) (Craighead 1971, Minno et al. 2005, Hall and Ponzio, pers. obs.).

Figure 36. Larvae of the cottonwood leaf beetle (*Chrysomela scripta*) consuming willow leaves.

Figure 37. Salt marsh moth (*Estigmene acrea*) caterpillar consuming willow leaves.

The high diversity of insects found in Carolina willow could be due to the higher structural complexity of this species compared to maidencane, sawgrass or cattail (SJRWMD, unpublished data), as has been noted elsewhere (Lawton and Schröder 1977, Strong and Levin 1979). Nonetheless, the large number of insect taxa observed in Carolina willow is similar to what has been found in association with other species of willow, when compared to other structurally complex shrubs and trees (Kennedy and Southwood 1984).

Other than the previous study, there has been little research done on Carolina willow as a habitat for other species. Although the Florida Fish and Wildlife Conservation Commission (2012) has produced a list of species of greatest conservation need associated with shrub swamps, this plant community designation may or may not include Carolina willow. In the Everglades, willow heads surrounding “solution holes”, deeper areas where the underlying limestone has dissolved away, have been noted as important habitat for alligators (Craighead 1971). Carolina willow colonizes the edges of these “solution holes” where water is available during the dry season when willow seeds disperse.

Carolina willow communities provide important nesting sites for wading birds (David 1994, Epanchin et al. 2002, Bryan et al. 2003). Due to Carolina willow’s resistance to fire, Epanchin et al. (2002) suggest that wading birds, such as ibises, night herons, egrets, spoonbills, anhingas, and herons, preferentially select tree islands dominated by Carolina willow and buttonbush as nesting sites in the Everglades. David (1994) documented the importance of Carolina willow in the littoral zone of Lake Okeechobee to the thousands of great egrets, snowy egrets, white ibis, cattle egrets, great blue herons, little blue herons, and glossy ibises that nested there between 1977–1988. Consequently, Carolina willows provide important habitat for a wide variety of species, that can enhance overall marsh biodiversity.

SUCCESSION

Although Carolina willow, like other willows (Jumpponen et al. 1998, Brzosko 2001), can have an adverse effect on other plant species due to shading, Carolina willow can facilitate the colonization and persistence of shade-tolerant tree species (Gunderson 1977, Rushton 1988). This may explain the large number of other plant species found in willow communities in the USJRB in the aforementioned unpublished work. The ability of willows to act as a “nurse crop” has been noted in other willow species as well (Dulohery et al. 2000, Spencer et al. 2001, Rahmonov et al. 2004, Kuzovkina and Quigley 2005). Gunderson (1977) found pond apple (*Annona glabra*), red maple (*Acer rubrum*), and bay (*Persea* sp.) seedlings growing in a previously logged and burned bald cypress (*Taxodium distichum*) forest that had been invaded by Carolina willow. Rushton (1988) found that the restoration of hardwood swamp species such as red maple, loblolly bay (*Gordonia lasianthus*), laurel oak (*Quercus laurifolia*), bald cypress, and swamp tupelo (*Nyssa sylvatica* var. *biflora*) in reclaimed clay settling ponds in central Florida could be accelerated by planting seedlings under a canopy of Carolina willow. However, natural regeneration of hardwood species only occurred when there was a nearby (~ 200 m) seed source and early successional species consisted of willow, wax myrtle (*Myrica cerifera*) and saltbush (*Baccharis halimifolia*), followed by red maple and American elm (*Ulmus americana*). Similarly, a study on the regeneration of a hardwood swamp, damaged by prolonged inundation, in the USJRB showed several species of trees, including bald cypress, water locust (*Gleditsia aquatica*), red maple, and Carolina ash (*Fraxinus caroliniana*), colonizing and developing in gap areas of a hardwood swamp along with Carolina willow (SJRWMD, unpublished data; Figure 38). Without fire, Carolina willow-dominated areas succeed to hardwood swamp (Gunderson 1977; Figure 39), usually within 10–20 years (Craighead 1971), causing the eventual loss of Carolina willow, due to its intolerance to shading (Quintana-Ascencio et al. 2011). Shade-intolerance is seen in other willow species as well (Spencer et al. 2001, Shaw et al. 2010, Radtke et al. 2012).

Figure 38. Regeneration of hardwood swamp with Carolina willow present in 2007 and eventually giving way to red maple (*Acer rubrum*) in 2008, 2010 and 2013 in the USJRB.

The succession of shrub communities to forest communities is seen with many willow species. Riparian areas dominated by basket willow (*Salix purpurea*) and Elaeagnus willow (*Salix elaeagnos*) in Spain have been observed to precede the establishment of riparian forests (Molina et al. 2004). Likewise, Cline and McAllister (2012) described a general pattern of succession along the Willamette River that began with the colonization of open substrate by willows (*Salix* sp.) to the establishment of a willow — cottonwood (*Populus sp.*) community and eventual dominance in the riparian area of a cottonwood, maple (*Acer spp.*), and ash (*Fraxinus* spp.) community. Similarly, Spencer et al. (2001) documented the secondary succession of a bottomland hardwood forest in southeastern Virginia from dominance by black willow (*Salix nigra*) to a mixed hardwood forest dominated by red maple and ash.

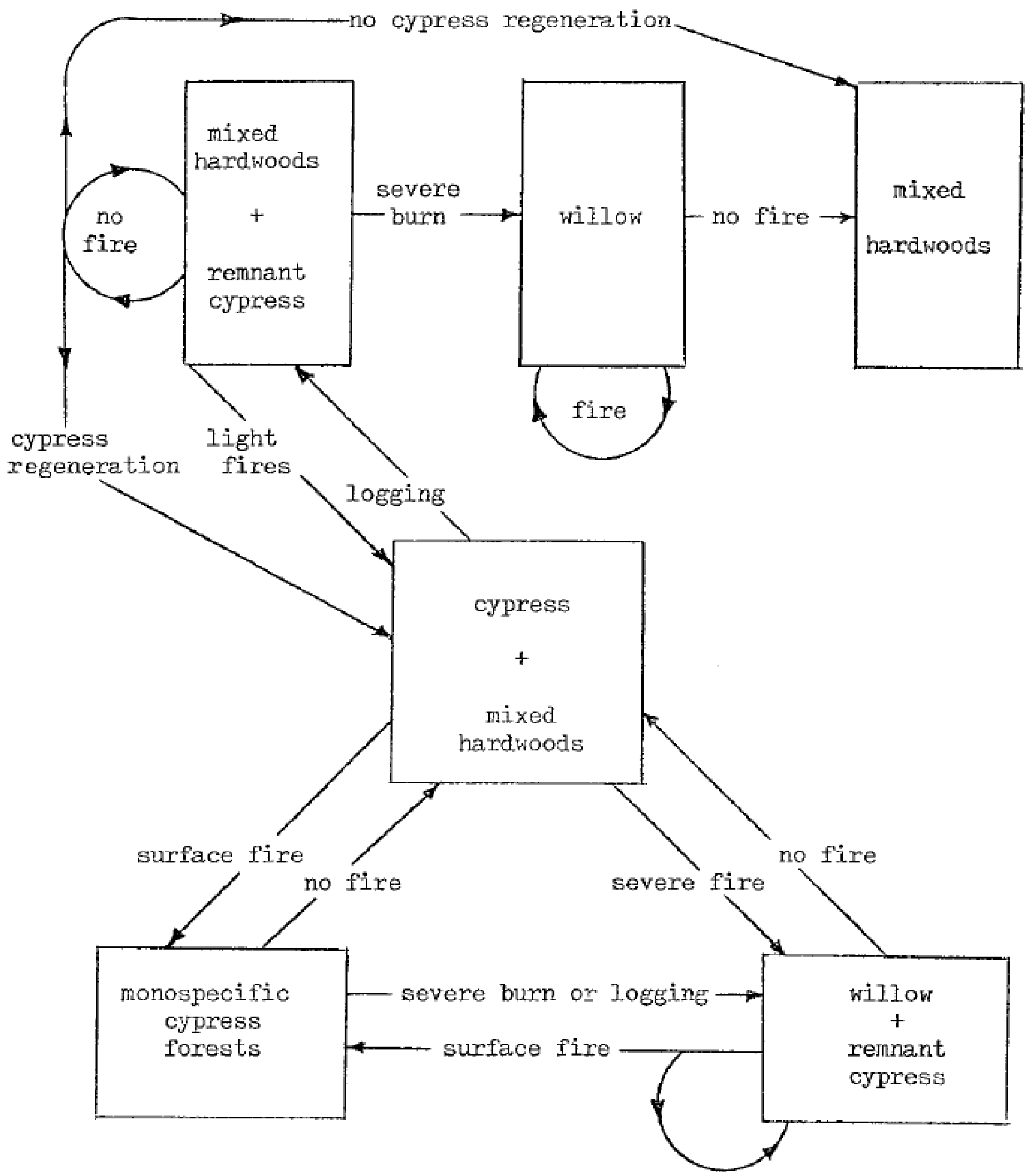

Figure 39. Diagram showing the successional relationship between willow communities and cypress and hardwood forests as a result of logging or fire. Note that a severe burn can cause a replacement of cypress and hardwood trees with willow and can also maintain a willow-dominated community — reprinted from Gunderson (1977).

HERBIVORY

As mentioned previously, Carolina willow harbors a wide variety of insect species and many of these are herbivorous during some or all of their life stages. However, no significant loss of willow coverage in the USJRB has been associated with insect herbivores, although instances of defoliation have occurred. Craighead (1971) noted a negative effect of Carpenter moths (*Prionoxystus robinae*), also known as carpenter worms, on Carolina willows in South Florida. Wood boring (i.e., sapwood consumption) by the larvae of this species caused willow stems to break in heavy winds and affected the overall height of willow stands. The lack of wide-spread damage from herbivory may be attributable to a phenolic compound, known as salicortin, that *Salix* species produce, which is unpalatable and effective in reducing insect and mammalian herbivory (Orians et al. 2003, Kudo 2003). This is especially true in low nitrogen environments where an increase in the phenolic content of the leaves has been documented (Hakulinen 1998).

Most research concerning herbivory on willows has focused on vertebrates and most of the research that has been done in North America has focused on herbivory by native ungulates. Hygnstrom et al. (2009) documented limited browsing of Peking willow (*Salix matsudana*) and goat willow (*Salix caprea*) by white-tailed deer (*Odocoileus virginianus*) and Myer-Smith et al. (2011) found no evidence of herbivory by caribou (*Rangifer tarandus*) or musk oxen (*Ovibos moschatus*) on Richardson’s willow (*Salix richardsonii*), grayleaf willow (*Salix glauca*), or tealeaf willow (*Salix pulchra*) in Canada, despite increases in abundance of large herbivores. There have been several studies of elk (*Cervus canadensis*) herbivory on willow in Yellowstone National Park and the role of top predators in limiting herbivore abundance. However, the effect of elk browsing on willow remains equivocal with some studies showing negative effects (Kay 1997, Peinetti et al. 2001) and others more neutral effects (Johnston et al. 2007, Tercek et al. 2010)

Additional research has focused on the effects of non-native herbivores on willow, especially cattle, but again, the results are equivocal. Willow cover increased in summer grazing studies by Clary (1999) in Idaho (with or without grazing) and Booth et al. (2012) in Nevada, suggesting a neutral or positive effect of grazing on willow. However, in an 11-year grazing exclusion study in Colorado, riparian willows — diamondleaf (*S. planifolia*), Geyer (*S. geyeriana*), peachleaf (*S. amygdaloides*), narrowleaf (*S. exigua*), and yellow (*S. lutea*) — were greater in height, exhibited lower diversity of willow species, and showed self-thinning as evidence by lower stem density. In grazed plots, riparian willows were able to respond quickly to the removal of grazing and showed rapid increases in canopy cover, height and stem density within five years (Holland et al. 2005). This suggests mixed effects of grazing - negative in the short-term due to effects on growth, but positive in the long-term due to effects on diversity. Similarly, Schulz and Leininger (1990) observed an 8.5 times greater cover of riparian willows (*Salix* spp.) in an ungrazed riparian area in Colorado after 29 years of grazing exclusion. However, Conroy and Svejcar (1991) found no significant effect of cattle grazing on planted Geyer willow (*Salix geyeriana*) cuttings near streams in the Sierra Nevada Mountains in California, although there was 3.5–5 times more defoliation of willows that were grazed.

There are limited data on vertebrate herbivory on Carolina willow (Quintana-Ascencio et al. 2011). Quintana-Ascencio et al. (2011) examined the effects of cattle grazing on transplanted willow seedlings and cuttings in a floodplain marsh of the USJRB. Seedlings and cuttings were transplanted into enclosures or into nearby unenclosed areas. Most seedlings did not survive regardless of location and they were unable to locate any seedlings outside the enclosures due to excessive trampling. Survival of cuttings inside the enclosures was substantially higher than those planted outside and some cuttings inside the enclosures had reached one meter in height in six months. Cuttings outside the enclosures had higher mortality and stunted growth (Figure 40) due to browsing by both cattle and white-tailed deer. Nearby mature willow showed no significant impact of grazing beyond a browse line along the lower edge of the canopy. Although some have suggested using cattle to manage willow, the lack of grazing impact on mature willow, soil erosion and compaction problems due to trampling by cattle, and manure deposition in the floodplain would be problematic (Quintana-Ascencio et al. 2013).

Figure 40. Carolina willow cutting planted outside an enclosure showing browsing damage by cattle and deer.

COMPETITION

Although little research has been done on the competitive abilities of Carolina willow per se, research that has been done on other willow species and the general characteristics of willow species make them strong competitors once they become adults. As mentioned earlier, young Carolina willows are susceptible to many environmental factors, such as competition for light, excess or lack of water, fire, herbivory, trampling, etc. However, as adults, these factors are not as relevant to willow persistence. The ability of adult Carolina willow to sequester nutrients through the use of extensive root systems (McLaughlin et al 2012) and fungi that live in their roots (Ipsilantis 2005) allow them to persist and grow under low-nutrient conditions. In addition, their transpiration rate (as discussed earlier) and deep roots enable them to survive under both drought and flood conditions. Finally, their high water content and spreading canopy allow them to resist fire through the inflammability of their stems and leaves (Fauth per obs.) and the paucity of fine fuels in their understory (Kinser et al., 1997, Quintana-Ascencio et al. 2011) due to canopy shading. These same traits have been documented in other willow species (Kuzovkina and Quigley 2005, Adler et al. 2008, Ens et al. 2013) and account for the extraordinary ability of willow species to colonize, persist and expand in wetland and littoral habitats.

CAROLINA WILLOW MANAGEMENT IN THE ST. JOHNS RIVER WATER MANAGEMENT DISTRICT

Although native to Florida wetland landscapes, Carolina willow must be controlled if its encroachment poses a threat to existing natural communities and ecosystem processes. As mentioned in the earlier sections of this document, Carolina willow, and willows in general, possesses several characteristics that make them successful pioneer species. These characteristics include:

- Fast growth
- Efficient nutrient uptake
- Flood tolerance, including tolerance of anaerobic conditions
- Resistance to fire
- Efficient sexual reproduction and seed dispersal
- Efficient vegetative reproduction
- Robust re-establishment after disturbance

These same characteristics have allowed Carolina willow to take advantage of anthropogenic disturbances on St. Johns River Water Management District (SJRWMD) lands (see Figures 29 and 30–32 on pages 37 and 38–39, respectively) and to expand their distribution within marsh habitats to the detriment of other plant communities, mainly herbaceous marsh. In other words, they have become native invaders (Valéry et al. 2009, Carey et al. 2012). As mentioned earlier in the document, the high transpiration rate of willow gives it the ability to change the moisture content of marsh soils and impede the persistence and colonization of more shallowly rooted species during the dry season. In addition, shade provided by the willow canopy inhibits the persistence and colonization of shade-intolerant species, which are usually grasses. Both of these characteristics hamper the use of fire to maintain the diversity of the marsh: 1) high transpiration rates cause willows to naturally retain more water than other marsh vegetation retarding their flammability, and 2) shading deters most herbaceous growth underneath willows and thereby prevents the accumulation of fuels necessary for successful burns. The expansion of willow, at the expense of other plant communities, which harbor their own suite of species (SJRWMD unpublished data), lowers the overall landscape diversity of the habitat, including the diversity of animals reliant on specific host plants. For example, replacement of sawgrass (*Cladium jamaicense*) communities by willow would preclude the occurrence of Palatka skippers (*Euphyes pilatka;* skippers are related to moths and butterflies) in the marsh, because their larvae feed solely on sawgrass. Willow-dominated communities in the Upper St. Johns River Basin (USJRB) were found to be only 25% similar in their plant community composition to cattail-dominated communities, 41% similar to maidencane (*Panicum hemitomon*) communities and 50% similar when compared to sawgrass communities (SJRWMD, unpublished data). Given the propensity of willow to dominate and completely replace other historically dominant plant associations and the potential loss of overall landscape diversity on District property, the expansion of willow should be constrained.

MANAGEMENT TECHNIQUES

To that end, the District has utilized four methods to control and reverse the expansion of Carolina willow: 1) prescribed burns, 2) herbicides, 3) roller chopping, and 4) hydrologic change. Although these methods have been used alone to control willow, some of the most successful treatments have involved the use of a combination of these methods.

Prescribed Burns

As mentioned in earlier sections, burning has long been thought to prevent shrub expansion into herbaceous areas. However, in wetland areas, Carolina willow has been described as a "fire-follower" (Loveless 1959) and some researchers have suggested that areas dominated by Carolina willow in the Everglades may be maintained by fire (Lodge 1994). Prescribed burns have been of limited success in preventing or reversing willow expansion in District wetlands (Miller et al. 1998, Lee et al., 2005a, Lee et al. 2005b) except where sufficient flammable vegetation, such as sawgrass and sand cordgrass (*Spartina bakeri*) exist or in areas where peat fires have occurred through lightning strikes. Most prescribed burns take place during the dry season when water levels are low, frost-killed vegetation may be present, and prevailing winds are optimal to protect surrounding areas from smoke and stray embers. It is not known to what extent the timing of these prescribed burns may facilitate the establishment of willow seedlings by removing competitors and exposing bare, moist soil for colonization (Quintana-Ascencio et al. 2011). Where possible, the District attempts to schedule prescribed burns to mimic the occurrence of lightning season fires, which predominantly occur between May and August, when water levels are increasing and plant communities are actively growing.

Herbicides

The widespread use of herbicides to control and reverse the expansion of Carolina willow on District lands is relatively new (~2010). However, smaller scale studies have been done since 2005 to evaluate the efficacy of certain herbicides and their off-target effects on other desirable native plant species (Figure 41). Hutchinson and Langeland (2010) looked at the effects of metsulfuron methyl, imazapyr, and imazapyr + triclopyr on Carolina willow stem density, canopy cover, and herbaceous ground cover in the USJRB (Figure 41; yellow circle). Willow stem density and canopy cover decreased and ground cover of herbaceous species, overall plant species richness, and plant species diversity increased within two-years post-treatment. A smaller scale study initiated by the District in the USJRB showed limited effectiveness of triclopyr when used alone (Figure 41; blue circle). Willow coverage ranged from 55–75% in study plots before application and from 35–50% coverage three months after application with significant re-sprouting of leaves from trunks and stems. Similarly, study plots with 60% willow coverage prior to treatment with ammonium salt of imazamox, showed 40–50% willow coverage seven months after treatment (Figure 41; green and orange circles). Both of these studies were terminated due to lack of significant effects on willow (SJRWMD

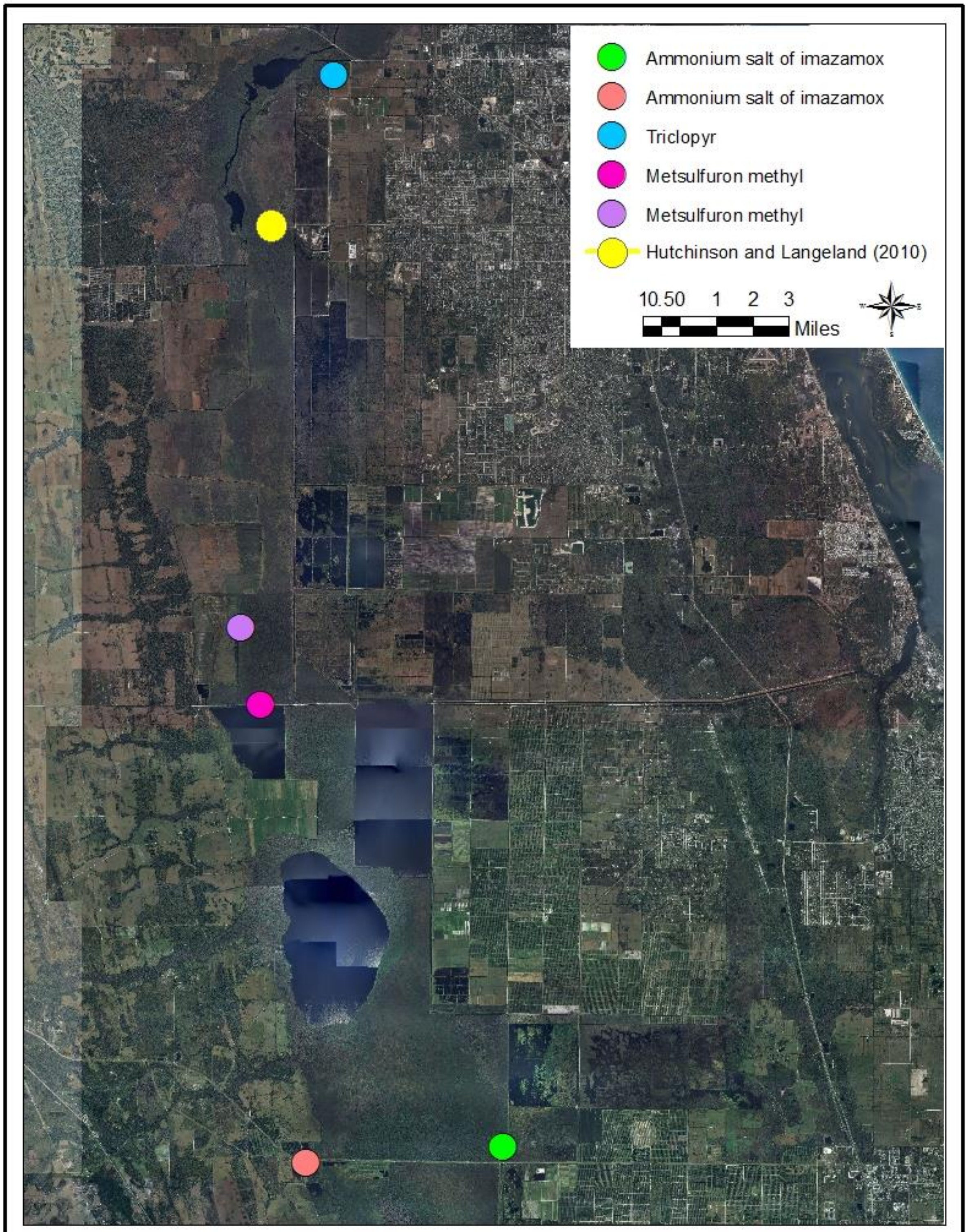

Figure 41. Small-scale study sites in the USJRB where the effects of specific herbicide treatments have been evaluated over time.

unpublished data; Table 9). Other earlier herbicide work (~2008) in the USJRB to control old world climbing fern (*Lygodium microphyllum*) in marshes revealed that Carolina willow is susceptible to metsulfuron methyl. However, this herbicide is only labeled for use in marshes to control old world climbing fern and the results of its use on willow are equivocal. In a larger-scale study (50 ac) that took advantage of a single application of metsulfuron methyl for the control of old world climbing fern, a significant decline in the coverage of Carolina willow was documented on plots within the treatment area, however, wax myrtle (*Myrica cerifera*) coverage was not affected (Figure 41; purple circle; SJRWMD unpublished data). The reduction in willow cover persisted throughout the five-year study. However, using a linear growth estimate, the willow canopy was projected to recover within 8 to 14 years after treatment. Coverage of herbaceous species increased in study plots within the herbicided area. In a second, smaller study examining the non-target effects of multiple applications of metsulfuron methyl for the control of old world climbing fern on other plant species, the loss of willow was not documented until after five treatments of the area over a seven-year period (Figure 41; pink circle; SJRWMD unpublished data). The study plots were surveyed for four years after the last treatment and loss of willow was documented within the first year. This loss was followed by an increase in wax myrtle coverage on all plots over the subsequent two years before most of it was lost as well and replaced by Peruvian primrosewillow (*Ludwigia peruviana*) as the dominant canopy species in almost all of the study plots. During the study period patches of sawgrass and soft rush (Juncus *effusus*) expanded beyond the study plots and old world climbing fern continued to persist in the study plots. Additional studies that are examining the effects of herbicides (i.e., multiple applications of ammonium salt of imazamox, isopropylamine salt of imazapyr, and 2,4-D + triclopyr) on willows and non-target plant species are ongoing and results of those studies will be added to this compendium as they become available.

Roller Chopping

Roller chopping has been used on District land to remove Carolina willows from floodplain marshes. However, its usefulness may be limited unless followed by extended inundation of the area. In the USJRB in Brevard and Indian River County, roller chopping is only possible during periods of drought, when the marsh soils are dry enough to support the weight of machinery (Ponzio et al. 2006; SJRWMD unpublished data). However, based on work done in the St. Johns Marsh Conservation Area (SJMCA), the heavy machinery may alter topography and drainage patterns and compact wetland soils (Ponzio et al. 2006). Based on the results of a study on roller chopping of Carolina willow in the River Lakes Conservation Area (RLCA), roller chopping with no subsequent inundation does not seem to radically alter willow coverage or stature (Figure 42 and 43; SJRWMD unpublished data). In the RLCA study, willow coverage prior to roller chopping ranged from 30–90% and one year after roller chopping ranged from 25–90%.

Table 9. Summary of chemical application studies in the USJRB conducted by the SJRWMD. Indications of "leaf on" and "leaf off" conditions have been noted for the study using repeated applications of metsulfuron methyl. Table colors correspond to Figure 41.

Study / Location	Dominant plant community	Major findings	Application Mixture
Effects of Clearcast (imazomox) treatment BCMCA	Carolina willow	*Salix caroliniana* decreased from 60 to 50-40%: *Osmunda regalis* decreased from 30 to 5%; little to no effect on other shrubs; fewer understory species; *Cladium jamaicense* increased from 50 to 65%; *Schinus terebinthifolius* decreased from 30 to 15%	64 oz Clearcast, 25.6 oz DLZ, 12.5 gal H_2O/ac
Effects of Clearcast (imazomox) treatment FDMCA	Brazilian pepper	Sites 1-2 rollerchopped between baseline and post-treatment sampling, so could not assess actions of herbicide; Site 3 had no change in *Schinus terebinthifolius* coverage; fewer understory species	64 oz Clearcast, 25.6 oz DLZ, 12.5 gal H_2O/ac
Effects of Garlon 3A (triclopyr) treatment SJMCA	Carolina willow	*Salix caroliniana* decreased from 75 to 50-35%, but resprouted from lower portion of trunks/branches; *Myrica decreased from 15 to <5%; Sagittaria lancifolia* increased from <5 to 10 %; *Cephalanthus occidentalis* increased from <5 to 10-25%.	2 gal Garlon 3A, 5.12 oz Interlock, 25.6 oz Sun Wet, 20 gal H_2O/ac
Effects of Garlon 3A (triclopyr) treatment SJMCA	Sand cordgrass	*Spartina bakeri* - minor increase at Site 1 (70 to 85%) and minor decreases at Site 2 and 3 (55 to 45% and 75 to 50%); *Sagittaria lancifolia* increased from <5 to 15%; *Sarcostemma clausem* exhibited a major increase from 5 to 25%-50%.	2 gal Garlon 3A, 5.12 oz Interlock, 25.6 oz Sun Wet, 20 gal H_2O/ac
Effects of multiple Escort (metsulfuron methyl) treatments SJMCA	Mixed shrub/ herbaceous	*Salix caroliniana* remained unaffected until 2012 and disappeared by 2013; *Lygodium* was unaffected until 2012 when there was a decrease in cover; *Myrica cerifera* was unaffected until 2012 and disappeared by 2013. There were some off-target species effects by 2013 where native, herbaceous species showed increases (*Cladium jamaicense* and *Juncus effusus*) and an exotic shrub (*Ludwidgia peruviana*) invaded and increased in cover.	2004: 2 oz Escort XP, 1.6 oz Sil-Energy, 20 gal H_2O/ac (Leaf off) All Quads 2005: 2 oz Escort XP, 1.6 oz Sil-Energy, 20 gal H_2O/ac (Leaf on) Quads 3-6 2006: 2 oz Escort XP, 25.6 oz Sun Wet MSO, 20 gal H_2O/ac (Leaf on) Quads 4-6 2009: 2 oz Escort XP, 20 oz Sun Wet MSO, 15 gal H_2O/ac (Leaf on) All Quads 2010: 2 oz Escort XP, 1.6 oz Sil Energy, 4 oz Interlock, 20 gal H_20/ac (Leaf on) - Quads 2-6 2011: 2 oz Escort XP, 1.6 oz Sil Energy, 4 oz Interlock, 20 gal H_2O/ac (Leaf on) - All Quads 2013: 2 ozs Escort XP, 25.6 oz DLZ,20 gal H_2O/ac (Leaf on) - All Quads
Effects of single Escort (metsulfuron methyl) treatment	Carolina willow/ Mixed Shrub	*Salix caroliniana* - treatment plots had a significant reduction in cover up to 5-yrs post-treatment, whereas control plots showed no significant change. Total canopy had no significant change in either treatment or control plots because of other woody species cover (e.g. *Myrica cerifera*). Understory in treatment plots - increased # of species, increased cover of forbs and graminoids, reduction in ferns, loss of vines.	2 oz Escort XP, 4 oz Interlock, 25.6 oz Sun Wet, 20 gal H_2O/ac

Figure 42. RLCA study plot in May 2007 before first roller chopping (SJRWMD unpublished data).

Figure 43. RLCA study plot in May 2008, one year after first roller chopping and before second roller chopping (SJRWMD unpublished data).

If roller chopping is followed by an extended period of total inundation, total elimination of willow can occur. In the study by Ponzio et al. (2006) in SJMCA, roller chopping followed by complete inundation by 1.6 ft water or deeper for five months, completely eliminated willow for at least five years after inundation (Figure 44).

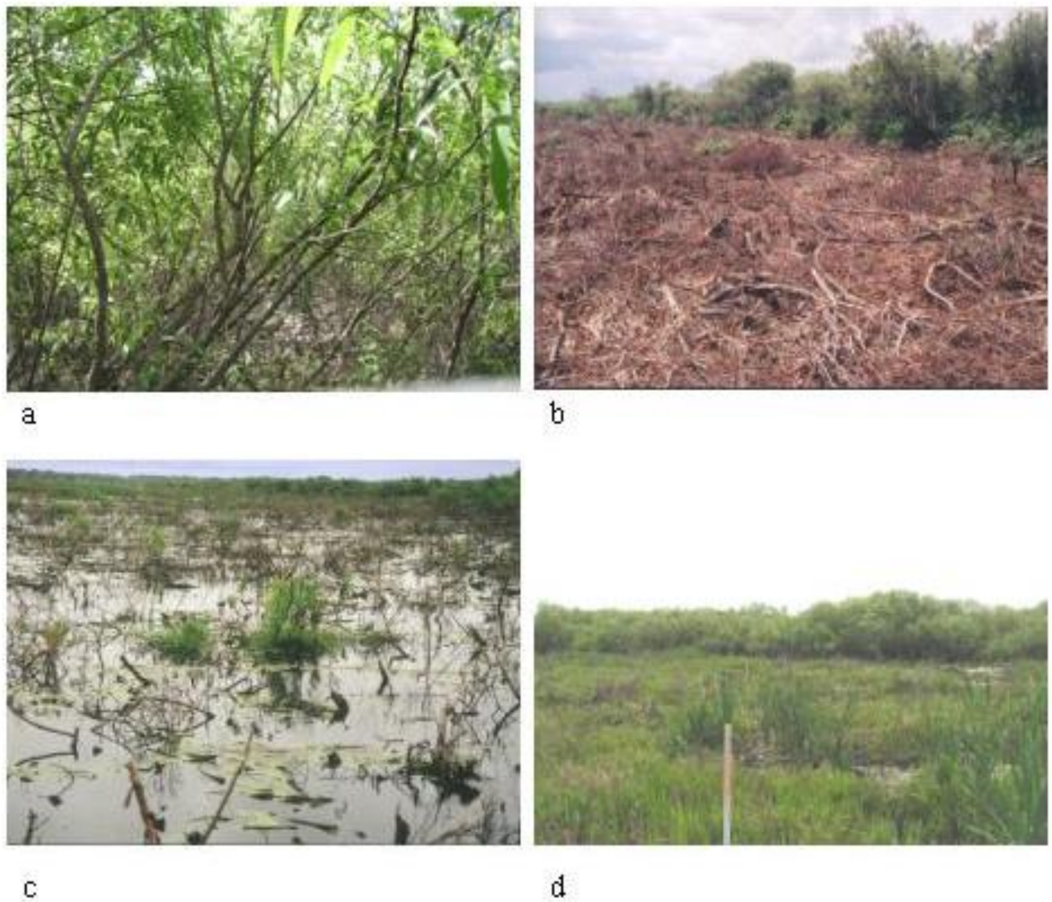

Figure 44. Progression of herbaceous marsh restoration in willow roller chopped areas in SJMCA: (a) willow coverage prior to chopping in March 2001; (b) willow chopped area one week following chopping in June 2001; (c) deep water (2.6 ft) conditions in September 2001; and (d) herbaceous plant re-establishment in Mar 2004.

Similarly, in RLCA, roller chopping followed by water levels at least 1 ft deep for three months completely eliminated willow (Figure 45) with little to no recolonization of willow after seven years (Figure 46; SJRWMD unpublished data). In the RLCA study, willow coverage prior to the second application of roller chopping ranged from 25–90%. Two months after the second roller chopping in 2008, the area was deeply inundated by Tropical Storm Fay. One year later, willow coverage ranged from 0-10%, with 75% of plots having no willow coverage at all (Figure 45). Six years post roller chopping and extended inundation, there was no willow coverage on 83% of the plots and 17% of the plots had no more than 1% willow cover (Figure 46).

Figure 45. RLCA study plot in 2009, one year after second roller chopping and five months after 3-month continuous inundation due to Tropical Storm Fay. Notice the non-roller chopped willow area in the background (SJRWMD unpublished data).

Figure 46. RLCA study plot in 2014, six years after second roller chopping and extended inundation. Notice the non-roller chopped willow area in the background (SJRWMD unpublished data).

Ponzio et al. (2006) found increased richness of plant species on all roller chopped plots during all four years of the study. However, free-floating plants became the dominant species on roller chopped plots and sawgrass plants, which were a small component of the community, did not survive roller chopping nor recolonize afterwards. On the RLCA study plots, plant species richness did not differ substantially pre- versus post-roller chopping. However, a significant loss of plant species richness occurred after the second roller chopping and the subsequent extended inundation by Tropical Storm Fay. Nevertheless, coverage of the main understory plants, maidencane (*Panicum hemitomon*) and sand cordgrass (*Spartina bakeri*), achieved pre-roller chopping levels by two to four years and the entire study area was able to carry a prescribed burn four years after the roller chopping/inundation event. Consequently, roller chopping can be used to remove adult Carolina willow with limited effects on plant species richness, but must occur during extremely dry periods to support machinery on muck/peat soils and must be followed by an extended period of inundation, conditions that are not easy to anticipate or manipulate.

On other District property, a combination of roller chopping and herbiciding has been successful in removing Carolina Willow and other undesirable woody vegetation. In 2012, 329 ac of primarily willow were roller chopped on the Lake Apopka North Shore in Orange/Lake County (Figure 47). Most Carolina willow and elderberry (*Sambucus nigra* ssp. *canadensis*) were successfully removed by the roller chopping alone. However, immediately following roller chopping, castor bean (*Ricinus communis*) invaded portions of the treated area. Less than a year later, areas where Carolina willow had persisted, primarily along canals and ditches, and where castor bean had colonized, were herbicided using 2,4-D and imazapyr. This herbicide treatment resulted in the removal of the remaining woody vegetation (SJRWMD unpublished data). Similarly, 35 ac of Carolina willow were roller chopped in the Sunnyhill Restoration Area (SRA, Figure 47) in Marion County in June 2013 and drainage ditches within the area were backfilled in July of that same year. In the fall of 2013, the area was herbicided with imazapyr. By summer 2014, no willow remained in the treated area. During that same time period, water levels within the area increased by 1.5 ft and then increased another 1.5 ft between 2014 and 2015. The relatively sudden increase in water levels on the roller chopped and herbicided area probably assisted in the prevention of the regrowth and recolonization of the area by Carolina willow (Figure 48, SJRWMD unpublished data).

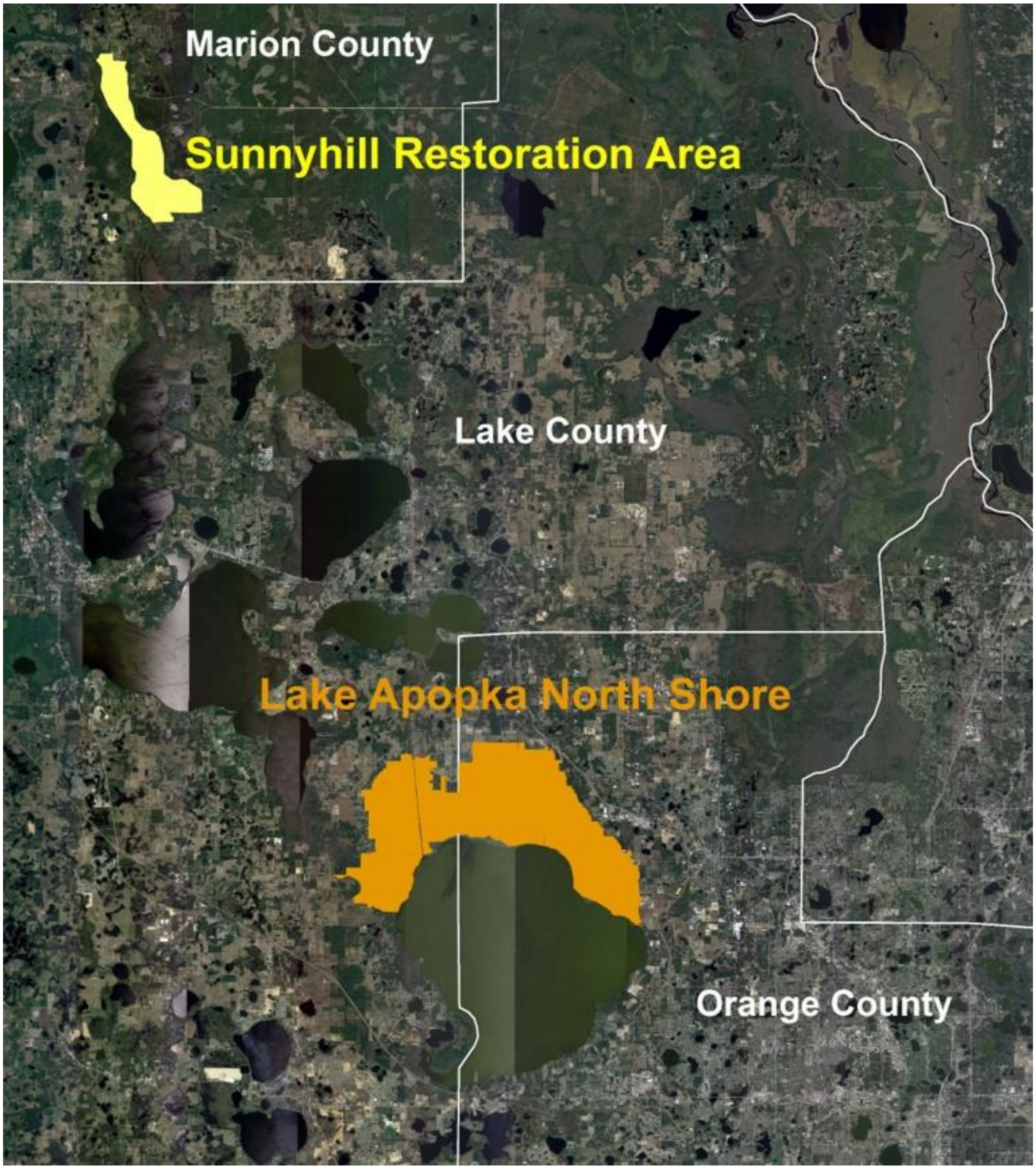

Figure 47. Location of Sunnyhill and Lake Apopka North Shore Restoration Areas in the Upper Ocklawaha River Basin in Central Florida.

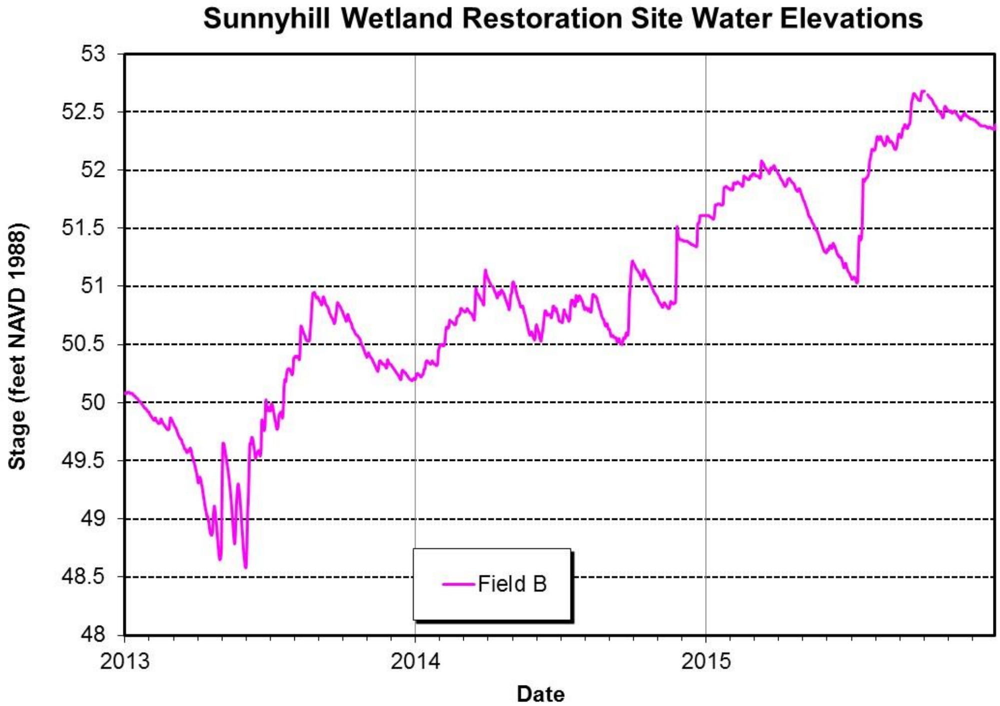

Figure 48. Water level data from Sunnyhill Recreation Area between 2013 and 2016 showing the extended increase in water levels.

Hydrologic Change

Of all the techniques the District has implemented to prevent or reverse the spread of Carolina willow, targeted manipulation of water levels has been the hardest and most expensive, which is probably why it is only now being initiated. It is difficult to control the amount of water on a specific area if it is not isolated and isolation is only possible with the construction of levees, which are expensive and may lead to undesirable open water communities. Even when there is hydrological control of an area, discharge is sometimes dictated by water supply releases and U.S. Army Corps of Engineers flood control schedules and regulations. In areas where water levels are controlled by structures, such as Blue Cypress Marsh Conservation Area, the District is attempting to hold more water in the area during March and April, when most Carolina willow seeds are released, to prevent the exposure of moist soil where willow seeds could germinate. In SJMCA, which is further downstream and where discharges are not controlled by structures, canal filling, plugs, and weirs have been established in an effort to retain more water in areas that have consistently suffered from shortened periods of inundation and where the greatest expansion of Carolina willow has occurred. These hydrologic changes have only been initiated in the past few years and the results of these modifications will probably not be realized for several more years. In addition, hydrologic change by itself will not be enough to kill adult willows that are already present and will have to be coupled with the other willow management techniques as circumstances allow.

In summary, the District uses several techniques, including prescribed fire, herbicides, roller chopping, and manipulation of water levels, sometimes alone and some times together, for controlling the expansion of willow with varying degrees of success. Prescribed burning can control willows when they are young and surrounded by flammable vegetation but does not kill adult willows due to the high water content of their stems and branches and the lack of flammable vegetation in their understories due to shading. Peat fires will kill adult willows by destroying their roots. However, peat fires will also kill desirable vegetation as well as the peat substrate. Herbicides can be used to kill adult willows but may also kill off-target desirable plant species. In addition, the direct and indirect effects of herbicides on much of the marsh fauna is unknown. Roller chopping can kill adult willows but only in conjunction with subsequent high-water events or herbiciding and this technique can only be used during extremely dry periods when marsh soils can support the weight of heavy machinery. Finally, increasing water levels have been shown to kill small willow by complete inundation and to prevent the germination and establishment of willow seedlings. In addition, willow seeds will not germinate on dry substrate, so extremely low water levels should preclude the colonization of willow. However, low water levels are not commonly obtained in marsh environments. In addition, as mentioned in earlier sections, neither inundation or drought can kill adult willows. Consequently, successful management of willow will be dependent on matching management techniques to willow life stages where they are most susceptible, such as burning willows when they are small and surrounded by flammable vegetation or successfully manipulating water levels to extend periods of high water when willows are small. Once willows are mature, management will be reliant on roller chopping followed by extended inundation and herbiciding or multiple herbicide applications in successive years. Finally, there may be some instance were the treatment of willow is not desirable and a succession of willow through shrub swamp to hardwood swamp may be preferable.

CAROLINA WILLOW MANAGEMENT BY OTHER AGENCIES AND ORGANIZATIONS

Information on the methodology and efficacy of willow control was solicited from other agencies and organizations. In 2015, the Florida Exotic Pest Plant Council's (FLEPPC) listserv was contacted requesting information from land managers from around the state of Florida and the southeastern United States regarding the control of Carolina willow (*Salix caroliniana*). In particular, information was requested about herbicide and mechanical treatment efforts and their attendant successes and failures. In addition, a number of land managers throughout Florida were contacted directly and asked if they had any experience controlling willow.

Responses were received from the following entities: Everglades National Park, Florida Department of Environmental Protection, Florida Park Service (Jonathan Dickinson State Park, Paynes Prairie Preserve State Park), Alachua County Environmental Protection Department, Martin County Board of County Commissioners, Audubon of Florida (Corkscrew Swamp Sanctuary), Office of Environment and Heritage (New South Wales, Australia), Florida Fish and Wildlife Conservation Commission, and the South Florida Water Management District. The locations of the sites in Florida appear in the map (Figure 42) on the following page.

An overview of the 31 responses that were received from other agencies and organizations appears in Table 9. The table is organized based on the management technique used in the treatment [fire (n=2), herbicide (n=23), inundation (n=1), mechanical (n=4), or various (n=1)]. The most frequently reported treatments involved the use of herbicides. The table also includes information on the type of herbicide, the application rate, active ingredients, and method of application. Glyphosate, imazapyr, or a combination of these two herbicides, along with 2,4-D in some cases, were the most frequently reported herbicide treatments. They accounted for 47.8% of the herbicide treatments reported. Statements regarding the effect that this combination of herbicides had on Carolina willow varied. In some cases, treatments were 90% effective in treating willow and in others there was no effect on willow at all. In some cases, information on non-target plant species was also provided. If no information was provided on a certain field in the table, that column was left blank.

More details about each of the treatments included in Table 9 can be found in Appendix B which includes the original responses received from the contacts for each agency or organization. Further details about each treatment may be found in the original responses. In the case of Corkscrew Regional Ecosystem Watershed Wildlife and Environmental Area (CREW WEA), additional information can also be found in Appendix C which includes highly detailed information about treatments on this site, a map of the treatments, and a table that provides information on the treatments and their effects on willow (*Salix caroliniana*), cattail (*Typha* spp.), and sawgrass (*Cladium jamaicense*).

An email address is included in Table 9 for each of the individuals who provided information on these treatments. Additional contact information, such as phone numbers and mailing addresses may be found in Appendix B along with the original response.

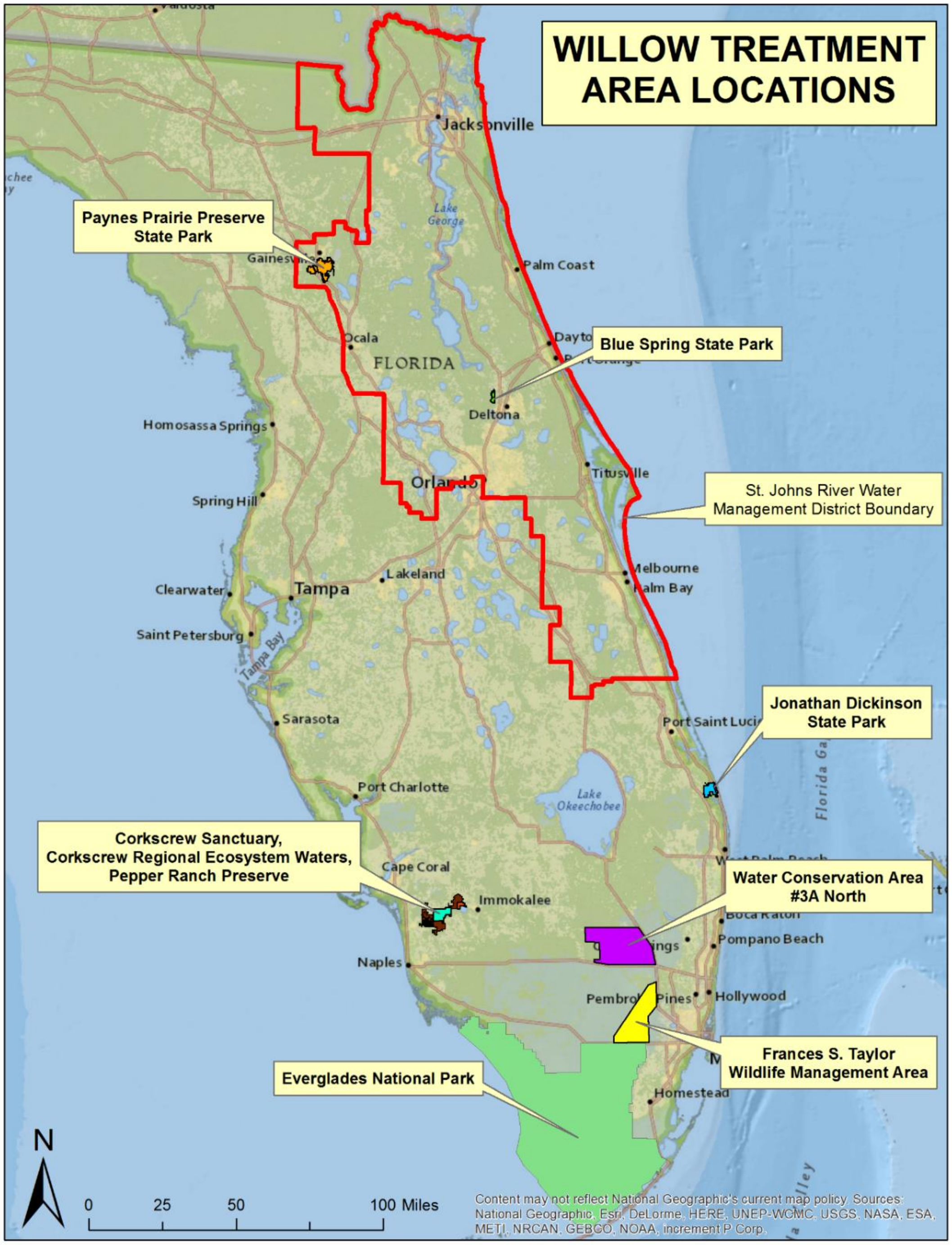

Figure 49. Sites in Florida where other agencies and organizations have taken action to control Carolina willow.

Table 10. An overview of the information provided by other agencies and organizations of work done to control Carolina willow. This table was created from the information provided by each organization's contact. If no information was provided about a certain field, that column was left blank.

Management technique	Entity	Contact	Area	Acres	Treatment	Rate	Active ingredients	Application	Effect on willow	Effect on non-target species	Notes
fire	Everglades National Park	Jonathan Taylor; Jonathan_E_Taylor@nps.gov	Hole-in-the-Donut wetland mitigation project	Not stated	prescribed	Not applicable	Not applicable	Not stated	mature willow - top killed, re-sprouting in 4-5 wks; plants < 2-3 ft - killed	Not stated	mature plants are more multi-stemmed post fire; killing of immature plants is increased if fire is hot or has extended residency time
fire	Jonathan Dickinson State Park	Rob Rossmanith; Robin.Rossmanith@dep.state.fl.us	Jonathan Dickinson State Park	Not stated	prescribed	Not applicable	Not applicable	Not stated	will kill the willow back	regrowth of sawgrass and *Pontederia*	
herbicide	Everglades National Park	Jonathan Taylor; Jonathan_E_Taylor@nps.gov	Hole-in-the-Donut wetland mitigation project	Not stated	Garlon 4	10%	triclopyr-2-butoxyethyl ester (60.5%); ethylene glycol monobutyl ether (0.5%)	basal bark & cut stump application	100% effective	Not stated	must be done during the dry season
herbicide	Everglades National Park	Jonathan Taylor; Jonathan_E_Taylor@nps.gov	Hole-in-the-Donut wetland mitigation project	Not stated	Renovate	3–6%	triclopyr triethylamine salt (44.4%); ethanol (2.1%); alkylphenol alkoxylate (1%)	cut stump application	ineffective; re-sprouting from base in 4–6 wks	Not stated	applied during wet season when water levels were <1 ft
herbicide	Everglades National Park	Jonathan Taylor; Jonathan_E_Taylor@nps.gov	Hole-in-the-Donut wetland mitigation project	Not stated	Element 3	19%	triclopyr triethylamine salt (44.4%); triethylamine (3%); ethanol (2.1%)	cut stump application	re-sprouting is occurring	Not stated	done during the dry season
herbicide	Florida Department of Environmental Protection, Mining and Mitigation	Casey J. Beavers; Casey.Beavers@dep.state.fl.us	forested wetland	Not stated	Habitat	label rate	isopropylamine salt of imazapyr (27.77%)	Not stated	re-sprouting within a year	Not stated	young trees underneath willow were not affected by shading; trees have now overtopped the willow and willow is diminishing
herbicide	Jonathan Dickinson State Park	Rob Rossmanith; Robin.Rossmanith@dep.state.fl.us	Jonathan Dickinson State Park	Not stated	Not stated	3%	glyphosate	foliar application	worked pretty well	Not stated	applied after first green-up in the spring; worked well as long as there was 90% coverage
herbicide	Alachua Co. Environmental Protection Department	Kelly McPherson; kmcpherson@alachuacounty.us	Alachua County	Not stated	Not stated	Not stated	triclopyr	Not stated	willows browned but many re-sprouted from stems or root collar within a year	Not stated	

Management technique	Entity	Contact	Area	Acres	Treatment	Rate	Active ingredients	Application	Effect on willow	Effect on non-target species	Notes
herbicide	Alachua Co. Environmental Protection Department	Kelly McPherson; kmcpherson@alachuacounty.us	Alachua County	Not stated	Not stated	2%	triclopyr	Not stated	re-sprouting	Not stated	applied one year after mulching; concludes that triclopyr does not work very well
herbicide	Corkscrew Swamp Sanctuary	Jason Lauritsen; jlaurtisen@audubon.org	Corkscrew Swamp Sanctuary	60	Not stated	Not stated	Not stated	aerial application	willow remained	primarily native species beneath willow, although mostly broadleafs, few sedges; exotics (mainly primrose willow) found near canals/ditches; few internal to plot	
herbicide	Florida Fish and Wildlife Conservation Commission	Marsha Ward; Marsha.Ward.MyFWC.com	Everglades National Park, Water Conservation Area 3A North and Francis S. Taylor Wildlife Management Area	600	glyphosate		glyphosate (96 oz/ac) + methylated seed oil (30 oz/ac) = 10 gal mix/ac	aerial application	8 mo post-treatment - no effect on willow (100% survival)	8 mo post-treatment; damage to cattail and sawgrass; other native plants, such as *Sagittaria lancifolia*, were unaffected or recovered quickly	
herbicide	Florida Fish and Wildlife Conservation Commission	Marsha Ward; Marsha.Ward.MyFWC.com	Everglades National Park, Water Conservation Area 3A North and Francis S. Taylor Wildlife Management Area	600	glyphosate / imazapyr		glyphosate (80 oz/ac) + imazapyr (24 oz/ac) + methylated seed oil (30 oz/ac) = 10 gal mix/ac	aerial application	8 mo post-treatment - 90% effective (10% survival)	8 mo post-treatment; damage to cattail and sawgrass; other native plants, such as *Sagittaria lancifolia*, were unaffected or recovered quickly	
herbicide	Florida Fish and Wildlife Conservation Commission	Marsha Ward; Marsha.Ward.MyFWC.com	Everglades National Park, Water Conservation Area 3A Northand Francis S. Taylor Wildlife Management Area	600	imazapyr		imazapyr (32 oz/ac) + methylated seed oil (30 oz/ac) = 10 gal mix/ac	aerial application	8 mo post-treatment - 95% effective (5% survival)	8 mo post-treatment; damage to cattail and sawgrass; other native plants, such as *Sagittaria lancifolia*, were unaffected or recovered quickly	
herbicide	Florida Fish and Wildlife Conservation Commission	Beachem Furse; john.furse@myfwc.com		592	glyphosate / imazapyr		glyphosate (80 oz/ac) + imazapyr (24 oz/ac) + methylated seed oil (16 oz/ac)	Not stated	Not stated	Not stated	

Management technique	Entity	Contact	Area	Acres	Treatment	Rate	Active ingredients	Application	Effect on willow	Effect on non-target species	Notes
herbicide	Florida Fish and Wildlife Conservation Commission; South Florida Water Management District	Kathleen Smith, Kathleen.Smith@myfwc.com; Joe Bozzo, jbozzo@sfwmd.gov	Cockscrew Regional Ecosystem Watershed Wildlife and Environmental Area	Appendix B							
herbicide	Florida Fish and Wildlife Conservation Commission	Megan Keserauskis; Megan.Keserauskis@myfwc.com	Blue Springs State Park	206	glyphosate / imazapyr		glyphosate (112 oz/ac) = imazapyr 64 oz/ac) + methylated seed oil (32 oz/ac)	aerial application in October	looks promising	Not stated	a prescribed burn is planned for the area in the near future
herbicide	South Florida Water Management District	LeRoy Rodgers; lrodgers@sfwmd.gov	Corkscrew Marsh	Not stated	glyphosate & surfactant		Not stated	aerial application in July, August or September; treatments in 2008 or 2009; retreated in 2011	killed large willows in canopy but probably not those in understory	primrose willow, cattails, and Carolina willow recolonized; no improvement in graminoid cover	
herbicide	South Florida Water Management District	LeRoy Rodgers; lrodgers@sfwmd.gov	Water Conservation Areas	Not stated	Clearcast	32 oz/ac	ammonium salt of imazamox (12.1%)	aerial application	willow not effectively controlled; defoliation occurs but recovery w/in 6 mo	Not stated	applied rate was well below maximum labeled rate
herbicide	South Florida Water Management District	Lou Toth; ltoth@sfwmd.gov	Stormwater Treatment Areas	Not stated	triclopyr	1 gal	Not stated	Not stated	not as effective	Not stated	
herbicide	South Florida Water Management District	Lou Toth; ltoth@sfwmd.gov	Stormwater Treatment Areas	Not stated	triclopyr	2 gal	Not stated	Not stated	not as effective	Not stated	
herbicide	South Florida Water Management District	Lou Toth; ltoth@sfwmd.gov	Stormwater Treatment Areas	Not stated	imazapyr / glyphosate		Not stated	Not stated	effective kill and long-term control	Not stated	re-sprouting observed as long as four years after treatment; prompt retreatment effective; aerial treatments more effective than ground treatments
herbicide	Florida Fish and Wildlife Conservation Commission	Bruce Jaggers; bruce.jaggers@MyFWC.com	Paynes Prairie	330	glyphosate / 2,4-D		10 gal solution/ac	mid-June	okay treatment but somewhat spotty kill overall	treating Chinese tallow, Carolina willow, Peruvian primrose willow, red maple, persimmon, water oak, saltbush	

Management technique	Entity	Contact	Area	Acres	Treatment	Rate	Active ingredients	Application	Effect on willow	Effect on non-target species	Notes
herbicide	Florida Fish and Wildlife Conservation Commission	Bruce Jaggers; bruce.jaggers@MyFWC.com	Paynes Prairie	Not stated	imazapyr	3 pints/ac	w/ methylated or ethylated seed and paraffin oil (1%); 20 gal solution/ac	mid-June	good results; much better than glyphosate / 2,4-D	treating Chinese tallow, Carolina willow, Peruvian primrose willow, red maple, persimmon, water oak, saltbush	
herbicide	Florida Park Service	Andrea Christman	Paynes Prairie Preserve State Park	Not stated	glyphosate + 2,4-D (2012)	10 gals/ac	glyphosate + 2,4-D	2012	not stated	Not stated	
herbicide	Florida Park Service	Andrea Christman	Paynes Prairie Preserve State Park	Not stated	glyphosate + 2.4-D; imazapyr	20 gals/ac; 3 pints/ac	glyphosate + 2.4-D; imazapyr	2013	not stated	Not stated	
inundation	Alachua Co. Environmental Protection Department	Kelly McPherson; kmcpherson@alachuacounty.us	Alachua County	Not stated	Not applicable	Not applicable	Not applicable	flooded	willows that were flooded after mulching and herbiciding died	Not stated	
mechanical	Alachua Co. Environmental Protection Department	Kelly McPherson; kmcpherson@alachuacounty.us	Alachua County	Not stated	mulching		Not applicable	mulched in ground	re-sprouted from root collars	Not stated	mulched after initial re-sprouting from triclopyr
mechanical	Alachua Co. Environmental Protection Department	Kelly McPherson; kmcpherson@alachuacounty.us	Alachua County	Not stated	mowing	yearly	Not applicable	along levees	re-sprouts after mowing	Not stated	
mechanical	Corkscrew Swamp Sanctuary	Jason Lauritsen; jlauritsen@audubon.org	Corkscrew Swamp Sanctuary	Not stated	mulching w/ subsequent inundation		Not applicable	in May w/ gyro-trac (trac skid vehicle w/forestry cutter head); inundation w/in 10 days	little to no regrowth	diverse herbaceous native plant community developed from seed bank	
mechanical	Corkscrew Swamp Sanctuary	Jason Lauritsen; jlauritsen@audubon.org	Corkscrew Swamp Sanctuary	10	mulching w/ and w/o subsequent inundation	Not applicable	Not applicable	in May w/ gyro-trac (non-inundated plots) and closer to rainy season (inundated plots)	w/o inundation - thick regrowth from roots; w/ inundation - no regrowth	not stated	
various	Weeds of National Significance, New South Wales, Australia	Hillary Cherry; hillary.cherry@environment.nsw.gov.au	Australia	Not applicable							see Best Practice Guide at http://www.weeds.org.au/WoNS/willows/

GAPS IN KNOWLEDGE

While District staff have expanded their understanding of the biology, ecology and management of Carolina willow, there is still much to know to manage this species as an integral part of wetland habitats. Listed below are some of the questions that still need to be addressed.

- How do Carolina willow communities compare with other wetland plant communities in the ecosystem services that they provide (e.g., habitat, water quality, water supply, biofuel, etc.)?
- How does Carolina willow “engineer” the ecosystem (i.e., through drying, allelopathy, etc.) and will it eventually succeed to hardwood swamp or drier community types if not controlled or managed?
- What are the off-target effects of large-scale and repeated chemical treatments on flora and fauna inhabiting the Carolina willow community and what are the short- and long-term changes in the food web, reproductive behavior and capacity, etc.
- What is the comparative evapotranspiration rate in willow and other marsh plant communities during dry periods when the water table is below the soil? How does this impact groundwater levels and local water availability?
- When Carolina willow is removed from a wetland, what plant communities replace them and/or how long does it take for the willow community to recover? Is the new community a flammable plant community that will allow the use of fire to prevent recolonization of willow?
- What is the effect of Carolina willow on nutrient uptake and/or enrichment of the water column and soils? Can it be used as an effective bioremediation agent?
- How quickly does willow expand via vegetative growth? How does nutrient enrichment and uptake effect the clonal growth and expansion of willow?
- What are the effects of fire intensity and fire season on willows in different developmental stages, especially seedlings and saplings?
- Can we identify rapid survey techniques (other than mapping willows as adults) that will allow us to determine willow invasion at stages where it is vulnerable to management by hydrology, fire, grazing, etc.?

CONCLUSIONS

Carolina willow is a quintessential pioneer species, quickly responding to conditions that promote its establishment, growth and proliferation. Like many willow species, the most important conditions for young Carolina willow, when they are most susceptible to mortality, are hydrology and light availability. Moist soil conditions in areas with plenty of sunlight promote seed germination and growth, allowing seedlings and saplings to quickly out-grow gradually rising water levels and competing vegetation. In addition, nutrient-rich organic soils and symbiotic nitrogen-fixing organisms can support rapid growth. However, drought conditions, especially on non-organic soils with limited capacity to retain water, can quickly lead to the mortality of willow seedlings and saplings. Fast-rising water levels that cause extended inundation and excessive shading by surrounding vegetation are also factors that will quickly kill seedlings and small individuals. Other major factors that may effect the survival and growth of young Carolina willow are fire and herbivory. Specifically, the absence of fire and cattle grazing, contribute to the persistence of small willows.

Once mature, Carolina willow becomes less susceptible to the impacts of flooding, drought, competition, fire, and herbivory. Morphological traits, such as adventitious roots along the stem, enable adult willows to withstand extended periods of high water, while deep roots in the soil allow adult willows to tap groundwater during extended periods of drought. As willows become taller, their canopies extend beyond the reach of most vertebrate herbivores, such as deer and cattle. Eventually, willows shade out plants in the understory reducing fuel loads that are necessary to carry fire. In addition, the high water-holding capacity of mature willows make them practically inflammable, and when subjected to fire, they are merely pruned and can show invigorated growth afterwards.

The competitive traits of Carolina willow and the modification of hydrology on many SJRWMD lands has resulted in the encroachment of willow into historically herbaceous-dominated wetlands. Mature willow communities harbor a diverse assemblage of flora and fauna which is comparable to, and in some cases, greater than that found in other plant communities occurring in the wetland. However, the propensity of willow to replace and eliminate other plant communities on a broad scale may result in the loss of rare fauna or flora that occur in those other communities and may reduce the overall mosaic of habitat diversity in the wetland landscape. When Carolina willow dominates the landscape, it changes the hydrologic balance by transpiring more water than the herbaceous plant communities that it replaces. This can result in a lower water table that promotes the proliferation of deeply-rooted species and may facilitate the development of hardwood swamp communities. Consequently, willow management may be necessary to preserve herbaceous marsh communities.

Managers have a number of tools for controlling Carolina willow that have variable efficacy depending on site conditions. Fire can negatively impact Carolina willow, provided that it is applied when willows are at a young and vulnerable stage of development. Mechanical removal of Carolina willow can be successful when paired with hydrologic events that overtop or inundate chopped plants. However, accessibility on organic soils is limited to dry conditions and the long-lasting impacts of heavy equipment on organic soils is of special concern. Some chemical treatments have proven to be successful in removing and reducing the cover of mature willow stands. The efficacy of a number of chemical treatments are currently being investigated.

Where Carolina willow has been removed by these treatments, managers need to address the reasons why the invasion initially occurred and change those conditions to prevent recolonization. A combination of these treatments (e.g. chemical treatment followed by burning and subsequent flooding) can be used synergistically to control willow invasion. However, hydrologic manipulation, either to reduce germination on exposed soil or to flood mechanically- and/or chemically-treated willows, may prove to be one of the biggest challenges for managers that work on large-scale wetlands.

There is still much District staff don't know about Carolina willow or the ramifications of different treatment options. While some mechanical and chemical treatments have lead to the restoration of herbaceous marsh, the long-term effects of willow removal have not been extensively studied. In order to make informed management decisions, more investigations need to be conducted on the ecosystem services provided by willow and the attendant costs and benefits of removing willow, controlling its spread, or allowing succession to an alternate or climax community.

If management actions include willow removal, managers should prioritize areas for treatment depending on: 1) the goals they wish to achieve, 2) known or suspected indirect impacts of removal, and 3) the probability of success based on the age of the willow and site conditions. Management techniques should be applied with an end goal in mind and with full knowledge of the site conditions that will best achieve that goal. Finally, managers should consider the necessity of using more than one technique, or repeated applications of those techniques, to reach the desired goal.

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APPENDIX A - SCIENTIFIC AND COMMON NAMES FOR WILLOW SPECIES

Authorities for nomenclature are: Florida *Salix* species – Institute for Systematic Botany, USF at http://florida.plantatlas.usf.edu/. United States *Salix* species – USDA Plant Profiles at http://plants.usda.gov/core/profile?symbol=SALIX. Other species – http://www.treenames.net/ti/salix/salix_willow_names_index.html

Scientific Name	**Common Name**
S. alba	White willow
S. alba var. sanguinea	*S. alba var. sanguinea*
S. amygdaloides	Peachleaf willow
S. artica	Artic willow
S. babylonica	Weeping willow
S. ballii	Ball's willow
S. bebbiana	Bebb willow
S. caprea	Goat willow
S. caroliniana	Carolina willow
S. cinerea	Large grey willow
S. dasyclados	*S. dasyclados*
S. discolor	Pussy willow
S. elaeagnus	Elaeagnus willow
S. eriocephala	Missouri River willow
S. floridana	Florida willow
S. geyeriana	Geyer willow
S. glauca	Greyleaf willow
S. gooddingii	Goodding's willow
S. humboldtiana	Humbolt's willow
S. humilis	Prairie willow
S. integra	Dappled willow
S. interior	Sandbar willow
S. laevigata	Red willow
S. lucida	Shining willow
S. miyabeana	S. miyabeana
S. monticola	Park willow
S. myrsinifolia	Myrsine-leaved willow
S. nigra	Black willow
S. petiolaris	Meadow willow
S. pulchra	Tealeaf willow
S. purpurea	Purple Osier willow
S. richardsonii	Richardson's willow
S. rubens	*S. rubens*
S. sachalinensis	Japanese fantail willow

Scientific Name	**Common Name**
S. sericea	Silky willow
S. sitchensis	Sitka willow
S. subfragilis	Almond leaf willow
S. viminalis	Basket willow

APPENDIX B – RESPONSES FROM OTHER AGENCIES AND ORGANIZATIONS ABOUT CAROLINA WILLOW TREATMENTS

Responses to inquiry concerning management of Carolina willow posted on the Florida Exotic Pest Plant Council's (FLEPPC) listserv in 2015.

In 2015, the Florida Exotic Pest Plant Council's (FLEPPC) listserv was contacted requesting information from land managers from around the state of Florida and the southeast U.S. regarding the control of the Carolina willow. In particular, information was requested about herbicide and mechanical treatment efforts and successes/failures.

In addition, a number of land managers throughout Florida were contacted directly and asked if they had any experience controlling willow.

Following are short descriptions of the responses received and the point of contact, in no particular order.

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1. Jonathan Taylor, Restoration Program Manager
Everglades National Park
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In 2014, we started to treat Carolina willow (willow), in the Hole-in-the-Donut (HID) wetland mitigation project in Everglades National Park. This is a new management goal. Willow was not perceived as a nuisance previously. This effort was started at the request of both the Army Corps of Engineers and Florida Department of Environmental Protection. Both agencies that permit the project and evaluate the project's performance as an off-site wetland mitigation project.

Thus far our best success has come from using Garlon 4 (10%). We achieve near 100% success. We have applied this using both basal bark and cut stump applications. Basal Bark applications are perceptively more successful, but the difference is slight and would not deter us from using the cut stump application method. However, we are limited to using this herbicide during the dry season.

To allow year round treatment, we experimented with Renovate at rates between 3-6%. We applied this using cut stump applications during the wet season when there was varying depths of water (< 1 foot). This was not successful. Within 4-6 weeks we saw re-sprouting from the base of the trees.

We have recently tried again during the dry season, using Element 3 at a rate of 19%. We applied using cut stump application. Preliminary observations are that there is re-sprouting occurring. We will do a final evaluation in mid June.

Our management goal is to utilize prescribed fire to maintain sites that have been cleared of willow. Our understanding of how best to apply prescribed fire is only now being developed. We have used prescribed fire with some success in the HID only since 2010. Our observations of using prescribed fire on willow is that mature willow plants are top killed. The mature plants re-sprout within 4-5 weeks. Our observations are that there is a tendency for the plants to be more multi stemmed post fire. (This has implications for follow up chemical treatments).

It is our observation that seedlings, small or juvenile plants (< 2-3 feet) may be killed and prevented from colonizing. The likely hood of this increases if you have a prescribed fire that is hot, or that can maintain some residency time. For us, it is difficult to accomplish either of these goals due to the nature of the fuels we have in the HID.

We are considering timing chemical treatments using Garlon 4 with basal bark applications within 2-3 months post fire. This may be more efficient. However, we have not yet done this.

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2. Casey J. Beavers, Environmental Specialist
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Division of Water Resource Management
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One summer, I was treating Carolina willow in a forested wetland. I treated it with Habitat solution (label rate). It would fry it good. Then the willow would come back the following year. The hydrologic conditions were just right for it. And then I noticed that the young trees underneath it were doing just fine. And I read studies saying that the willow could be kind of a nurse crop for young wetland trees. And that is what has happened. The trees have now overtopped the willow, and the willow is diminishing. I currently have a marsh that is starting to have a lot of willow. I don’t think I’ll even try to spray it. My plan is to put it on a regular burn cycle. I saw a study that said the only way to keep it down is regular burning. I hope to have it on a 3-year burn rotation.

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3. Rob Rossmanith, Park Biologist

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Robin.Rossmanith@dep.state.fl.us

I'm in the beginning stages of experimenting with willow control with herbicides.

Mostly, when we've added fire (and it's dry) I've seen that the fire will kill the willows back, opening the understory for sawgrass, *Pontederia*, etc. That's the most work we've done in terms of acreage.

I did a small plot with foliar application of 3% glyphosate after the first green up in the spring and it worked pretty well, as long as you had 90% coverage.

The plan is to restore hydrology in a 800ish acre area and then over time do some aerial applications of glyphosate to thin the willow and then continue to burn to get rid of the biomass.

On a small scale it seems to be working, but we haven't scaled it up.

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4. Kelly McPherson
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We have chemically treated Carolina willow along a levee system in attempts to knock it back two times now. Our treatments have been paired with mulching and repeated mowing and the fight continues.

The initial treatment was with triclopyr in the fall of 2012. The willows got browned out, but many re-sprouted from the stems or root collars within a year of treatment.

They were mulched to the ground in 2013. They re-sprouted from root collars again and were sprayed a second time in late summer last year again with triclopyr 2% solution.

Some of the treated stems were subsequently flooded - those seem to be dead. We mow side slopes to water's edge or as far as the machine can reach one time per year. So the treated stems have been mowed once again last fall.

We still have willow along the levee. Its density is lower now and the 1 time per year mowings will hopefully keep it at bay. I would say triclopyr doesn't work that well.

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5. Michael A. Yustin
Project Manager
Engineering Department
Martin County Board of County Commissioners
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I am currently working on a mechanical removal project that includes exotic vegetation and a large monoculture of Carolina Willow. I have no documentation of long-term project success because we are still in the removal process.

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6. Jason Lauritsen
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We've been working on treatment of willow within Audubon's Corkscrew Swamp Sanctuary and similarly are trying a variety of methods to identify the best approach to reclaim herbaceous marsh.

Late spring (May) of 2013. Mechanical treatment of 4 small patches of willow using a gyro-trac skid vehicle with a forestry cutter head). Organic soils under three of the four patches was in excess of 6 inches deep, the 4th patch was less than 3 inches of organic soil. Heavy rains fell within 10 days of mechanical treatment (grinding to a mulch) inundating all four treatment areas. Very little regrowth occurred on the plots and no chemical treatment was used. Diverse herbaceous native plant communities established from the seed bank. We intended to burn this year but were not able to.

Late Spring (May 2014). Mechanical treatment of 2 patches totaling approximately 10 acres. Aerial herbicide application of approximately 60 acres. The first mechanical treatment area done this year came back with thick regrowth from the roots. The second, which has a longer deeper hydropattern and was treated close to rainy season, did not show regrowth.

Eleven months following the aerial treatment, a ground visit showed primarily native species coming from beneath the willows. Nearest a canal/ditch there was a considerable amount of invasive exotic Peruvian primrosewillow, the farther into the plot, the less Peruvian primrosewillow and more natives. However, there was only one sedge identified, most of the species being broadleaf. This was an older willow stand, and perhaps had a much different seed bank as a result. This area remains inundated with water much longer than historic conditions due to off-site influences. We are working to find a solution to the water problem, but until we find one, we will likely have a difficult time adding fire to the management.

We've done additional mechanical treatment this season, and will modify our aerial treatment to target areas with higher probability of a grass/sedge seed bank and closer to historic hydrology to facilitate addition of fire.

Cost, treatment window and organic soil depth are all factors limiting our ability to rely solely on a gyro-trac, which has yielded superior results thus far.

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7. Hillary Cherry
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Weeds Of National Significance Coordinator
Pests and Weeds Team
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I work with a program called Weeds of National Significance (WoNS) here in Australia and willows are considered a WoNS here. We have done considerable work on gathering management information and resources for stakeholders, and most of this is contained on the willows WoNS webpage:

http://www.weeds.org.au/WoNS/willows/

There may be some tools here that can assist in your willow mgmt. quest…….especially the Best Practice Guide, which is full of great info for a range of willow types. Feel free to add or reference any materials when putting together your mgmt. compendium.

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8. Marsha Ward, District Biologist
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Wildlife and Habitat Management
Florida Fish and Wildlife Conservation Commission
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Here is a short summary of the willow treatment we did last fall. I've copied two other FWC staff (Beachum and Kathleen) who may also be able to help you with your request. If you need additional details on the Everglades treatment, please let me know.

The FWC treated woody species – coastal plain willow (*Salix caroliniana*) and wax myrtle (*Myrica cerifera*) – in the Water Conservation Area 3A North portion of the Everglades and Francis S. Taylor Wildlife Management Area in September 2014. Timing was scheduled to ensure standing water in the marsh and that wading/marsh bird nesting would be complete. There were three 200-acre treatment plots and three 25-acre untreated control plots treated via aerial herbicide application:

- Plot 1: 96 oz. glyphosate/acre + 30 oz. MSO/acre (10 gallon mix/acre)
- Plot 2: 80 oz. glyphosate + 24 oz. imazapyr/acre + 30 oz. MSO/acre (10 gallon mix/acre)
- Plot 3: 32 oz. imazapyr/acre + 30 oz. MSO/acre (10 gallon mix/acre)

Eight months post-treatment the following results were noted from a helicopter visual survey:

- Plot 1: glyphosate-only appeared ineffective against willow (100% alive)
- Plot 2: glyphosate + imazapyr appeared very effective against willow (<10% alive)
- Plot 3: imazapyr-only also appeared very effective against willow (<5% alive)

All three plots showed signs of damage to non-woody emergent plant species, including: cattail (*Typha* sp.), which is generally considered undesirable; and sawgrass (*Cladium jamaicense*), which is highly desirable in our marsh community. Other desirable emergent plant species, such as duck potato (*Sagittaria lancifolia*), were either unaffected or recovered relatively quickly in all three plots. Ground assessments will occur once water levels permit. The onset of the rainy season is expected to initiate some plant recovery since marsh plant growth is more vigorous during this time. There is a second aerial herbicide treatment planned for a nearby location to examine whether we can reduce non-target damage while still controlling undesirable woody vegetation. This treatment will compare the 80 oz. glyphosate + 24 oz. imazapyr treatment (Plot 2 above) with a lower rate of imazapyr (96 oz.

glyphosate + 16 oz. imazapyr). Two 300-acre plots are scheduled to be aerially sprayed in September 2015.

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9. Beacham Furse
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Jessica Griffith and Kathleen Smith treated 1,093 acres of willow in coordination with Joe Bozzo @ CREW WEA last fall. FWC treated 592 acres using 80 oz. glyphosate/24 oz. imazapyr (16 oz. MSO Concentrate) and 376 acres using 96 oz. glyphosate/16 oz. imazapyr (16 oz. MSO Concentrate). Jessica can provide you with the monitoring data she and Kathleen have collected. Joe can provide the herbicides and treatment rates the SFWMD used on their 125-acre treatment area.

Jessica and Kathleen treated an additional 330 acres of willow using a mix of 96 oz. glyphosate/16 oz. imazapyr (16 oz. SUNRISE [a MSO adjuvant]) @ CREW WEA in May 2015 (they were happier with the 96:16 rate than the 80:24 rate). Jessica and Collier County staff treated 175 acres of willow using a mix of 96 oz. glyphosate/16 oz. imazapyr (16 oz. SUNRISE) @ Pepper Ranch in May 2015.

Megan Keserauskis and Ed Hayes also treated willow within Blue Springs State Park in fall 2014. Megan and Ed will provide the treatment rates and acreages and Jessica or Megan can provide the monitoring data for this treatment.

In addition to the two 300-acre treatments described below by Marsha in WCA 3A North planned for fall 2015, we are also planning to treat 100 acres of willow, myrtle, and red maple within Holey Land WMA in fall 2015 using either the 96:16 or 80:24 mix and, depending on funding, also conduct selective mechanical treatment of woody vegetation within Holey Land in either fall/winter 2015-16 (FY 15/16) or fall/winter 2016-17 (see attached 2015/16 AHRE funding application; the herbicide work is currently funded for 15/16, but not the mechanical work).

See Appendix C for detailed response from Kathleen Smith

10. LeRoy Rodgers
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SFWMD Willow Management Experience

Corkscrew Marsh Willow Treatments

Corkscrew marsh is a 5,000-acre sawgrass/herbaceous marsh located in Collier County. The South Florida Water Management District treated large (15-20') dense willows with glyphosate and surfactant using helicopter applications between 2008 and 2011. All treatments were in July, August or September. Areas treated in 2008 and 2009 were retreated in 2011. Treatments were effective in killing the large willows that intercepted the herbicide but it's likely that willows that did not come in contact with the herbicide survived the initial treatment.

Peruvian primrosewillow, cattails and some Carolina willow have colonized the 2008 and 2009 treatments. Very little if any improvement of graminoid cover has been observed following those treatments so far. We plan on retreating the areas that have been infested with Peruvian primrosewillow and cattail later this summer (2015) using FWC AHRE grant funding.

We treated 1195 acres of large willows in 2014 (August/September) with glyphosate:Imazapyr combinations in the following ratios 96:16, 80:24 and 120:64 with a helicopter using FWC AHRE grant funding. Initial results indicate that each combination was effective in killing willows. We are monitoring the results with aerial photographs and have left 3 areas untreated to serve as control units.

We treated what we believe is our final stand of large willows (330 acres) in May 2015 using a glyphosate:Imazapyr ratio of 96:16.

One of the problems that we have encountered is that the large dead willow stems become rigid following death which makes airboat travel more hazardous especially when you have a forest of them.

11. Joe Bozzo
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Willow management in STA's

The District has treated Carolina willow with both aerial and ground herbicide applications throughout the STAs. We have used both 1 and 2 gal rates of triclopyr and imazapyr/glyphosate mixes and found imazapyr and glyphosate to provide the most effective kill and long-term control. Variable levels of post-treatment re-sprouting usually occurs (observed as long as four years after an aerial treatment in STA 5/6), but prompt re-treatment of new growth typically provides a thorough kill. I don't have definitive data to show it but aerial herbicide treatments tend to be more effective than ground treatments.

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12. Lou Toth
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Aerial imazamox applications in Water Conservation Areas.

During ongoing field evaluations on the efficacy of imazamox (Clearcast) for control of cattail, District staff have noted that Carolina willow is NOT effectively controlled at 32 oz/ac when aerially applied. Defoliation typically occurs, but complete recovery is seen within 6 months. This rate is well below the maximum labeled rate and we have no experience with imazamox above 32 oz/ac.

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13. Bruce V. Jaggers
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Paynes Prairie treated some woody species including willow with glyphosate and 2,4-D and then another treatment with imazapyr (see attached summary). They liked results from imazapyr better (3 pints/acre with 1% DLZ).

The contractor was Coastal Air out of Panama City.

We did an initial application in mid June 2012, Glyphosate and 2,4-D (I have to get back to my office to get you the rates), 10 gallons solution per acre, that had okay, but somewhat spotty kill overall.

We did a follow-up application in mid June 2013, re-treated some of the June 2012 areas, and did initial treatment on some additional areas, including the one patch of willows south of the

boardwalk on the east side of Hwy 441. 3 pints imazapyr per acre, 20 gallons solution per acre.

For both years, the adjuvant was Helena Chemical DLZ (Droplet Landing Zone), 1% solution.

The target species were a mix of native and non-native hardwoods invading the prairie basin,

including Chinese tallow, Carolina willow, Peruvian primrosewillow, red maple, persimmon, water oak, saltbush, and others.

Overall the imazapyr seems to have performed much better than the glyphosate/2,4-D mix.

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I am sending Andi's restoration plan for the Prairie basin between I-75 and US 441 which was modified to include the management zones west of I-75. I am also sending an herbicide recipe from what must have been the second application. I am still trying to track down the actual contracts/scope of work for each aerial application. Martin Jacob is Andi's temporary replacement, and he was able to provide the attached documents.

As far as I know, there is not a formal monitoring plan for the project, but Andi may have set something up.

Paynes Prairie Preserve State Park

Basin Marsh Restoration 10- Year Plan – Management Zones PP-5 and PP-6

2013-2023

Prepared by: **Andrea Christman**, Park Biologist, Paynes Prairie Preserve State Park 3/20/13, rev 8/5/14. **andrea.christman@dep.state.fl.us**

The dominant natural community in the preserve is the 13,000-acre basin marsh community within the Paynes Prairie basin. As a National Natural Landmark, the Paynes Prairie basin is a critical area for restoration and improvement actions. The basin marsh tracts (management zones) have the highest priority for active resource management, including treatment with prescribed fire. A combination of factors has contributed to the ongoing encroachment of hardwoods into the basin marsh community at Paynes Prairie Preserve State Park. Ditching, diking and water diversions have created an ongoing water deficit that reduces the frequency and intensity of flooding events. The lack of flooding, combined with the difficulty in applying prescribed fire due to increased urbanization and the presence of two federal highways, has allowed woody vegetation to expand. Hardwood species have become established as scattered trees and shrubs and as dense tree islands. Coastal plain willow is encroaching upon and replacing the herbaceous vegetation along dikes and berms in some areas of the basin marsh (Figure 1). This woody shrub is changing the natural community structure and species composition of the basin marsh.

Hardwood trees and shrubs have encroached into the basin marsh in management zones PP-5 and PP-6, and the close proximity of Interstate 75 and US Highway 441 makes it extremely difficult to use prescribed fire to control the vegetation (Figure 2). For these two zones, there is no prevailing wind direction that will allow the application of prescribed fire without unacceptable smoke impacts on either US Highway 441, or Interstate 75. A priority management objective is to improve the condition of the basin marsh and restore its naturally open, treeless condition. Management strategies that include mechanical and chemical treatments, and which provide for retention and promotion of desirable native species in these zones, are now being prioritized for the restoration of these zones.

Primary species to be treated include:

coastal plain willow (*Salix caroliniana*)
persimmon (*Diospyros virginiana*)
sweetgum (*Liquidamber styraciflua*)

red maple (*Acer rubrum*)
water oak (*Quercus nigra*)
Chinese tallow (*Triadica sebifera*)
buttonbush (*Cephalanthus occidentalus*)
Peruvian primrosewillow (*Ludwigia peruviana)*
wax myrtle (*Myrica cerifera*)

Restoration of the basin marsh, is included in the Florida Fish and Wildlife Conservation Commission Aquatic Plant Control Permit number SR-12-47 (expiration date 5/16/2015), which authorizes both chemical and mechanical treatment of the basin marsh for control of hardwood encroachment by native and non-native species.

Figure 1: Aerial view of management zones PP-5 and PP-6, looking south. Management zone PP-6 is in foreground, management zone PP-5 in background (February 2012).

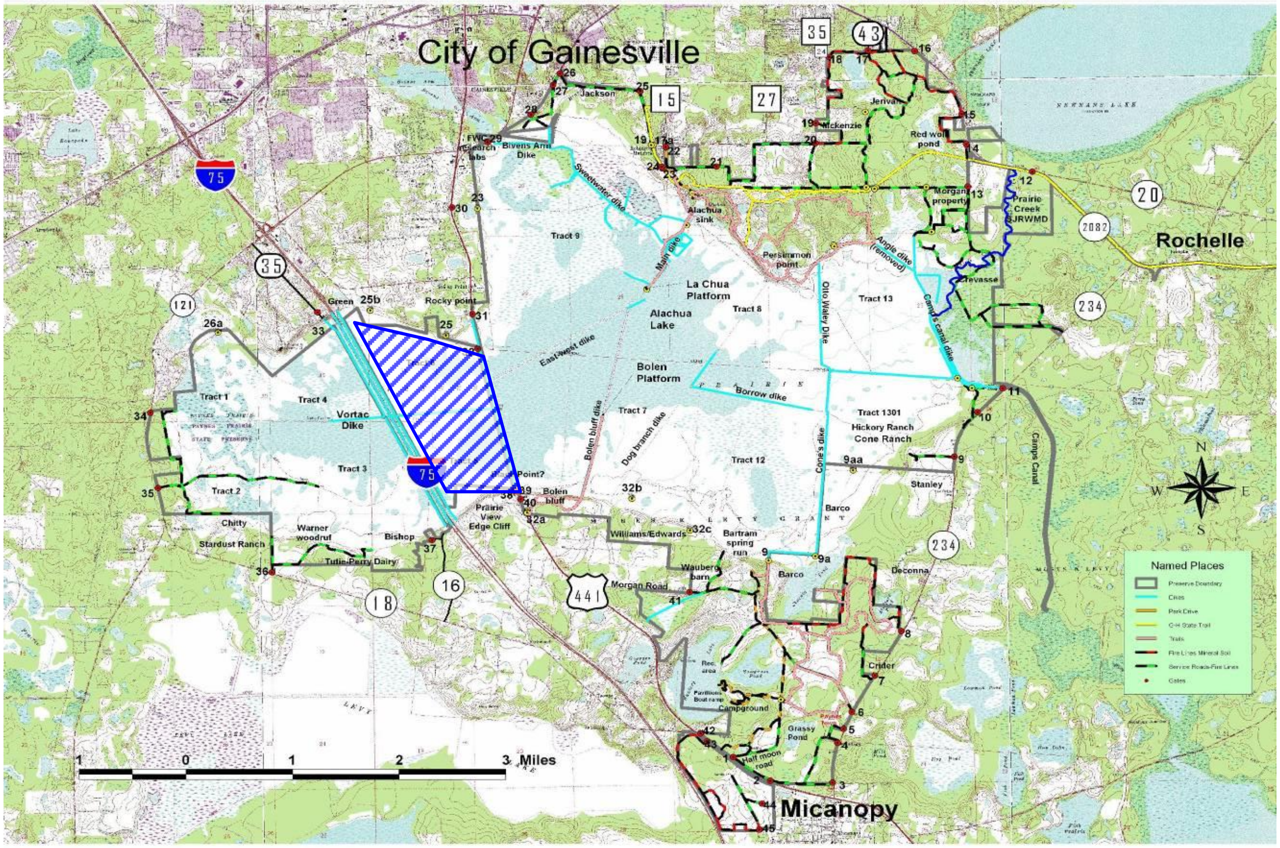

Figure 2: Zones PP-5 and PP-6 are within blue hash-marks. Preserve boundary indicated with grey boundary line.

Restoration was initiated in 2010/11 with contractual mowing of the margin of the basin marsh at the north end of PP-6 and the south end of PP-5. In 2012, an aerial herbicide application was conducted on 330 acres of the basin marsh to begin controlling Chinese tallow, coastal plain willow, and other invading native hardwoods (Figure 3). This initial treatment applied a tank mixture of aquatic labeled glyphosate and 2,4-D with a drift control agent at a rate of 10 gallons per acre. Based on results of the 2012 treatment and consultation with other land managers conducting similar restoration activities, a 2013 follow-up aerial treatment utilized a 20 gallon per acre application including 3 pints per acre of aquatic labeled imazapyr with a drift control agent. A series of additional ground and aerial herbicide applications targeting the encroaching native and non-native hardwood trees and shrubs will be conducted each year. A combination of ongoing mechanical treatment utilizing mowing, bush hogging, tree-cutting, and other similar treatments is planned for periods when the basin is dry enough to allow heavy equipment access. Future treatments will be scheduled and designed based on the results of previous treatments. By adopting an adaptive management strategy, the park can base future actions on past results. The 2013 Draft Unit Management Plan for the preserve has set a goal of a minimum of 400 acres of basin marsh to receive restoration and improvement treatments during the plan period. A similar restoration process involving aerial treatment of invading non-native and native hardwoods was initiated in Management Zones 1, 3, and 4 on the west side of Interstate 75 in July 2014. The 2014 treatment utilized the same methodology as the 2013 treatment.

On-site meetings have been held with staff from the St. Johns River Water Management District to compare restoration techniques and results in similar habitats. Park staff will continue to cooperate with other agencies that maintain easements within or have title to portions of the Paynes Prairie basin marsh, including the Florida Department of Transportation, City of Gainesville, Alachua County, Gainesville Regional Utilities, and Progress Energy.

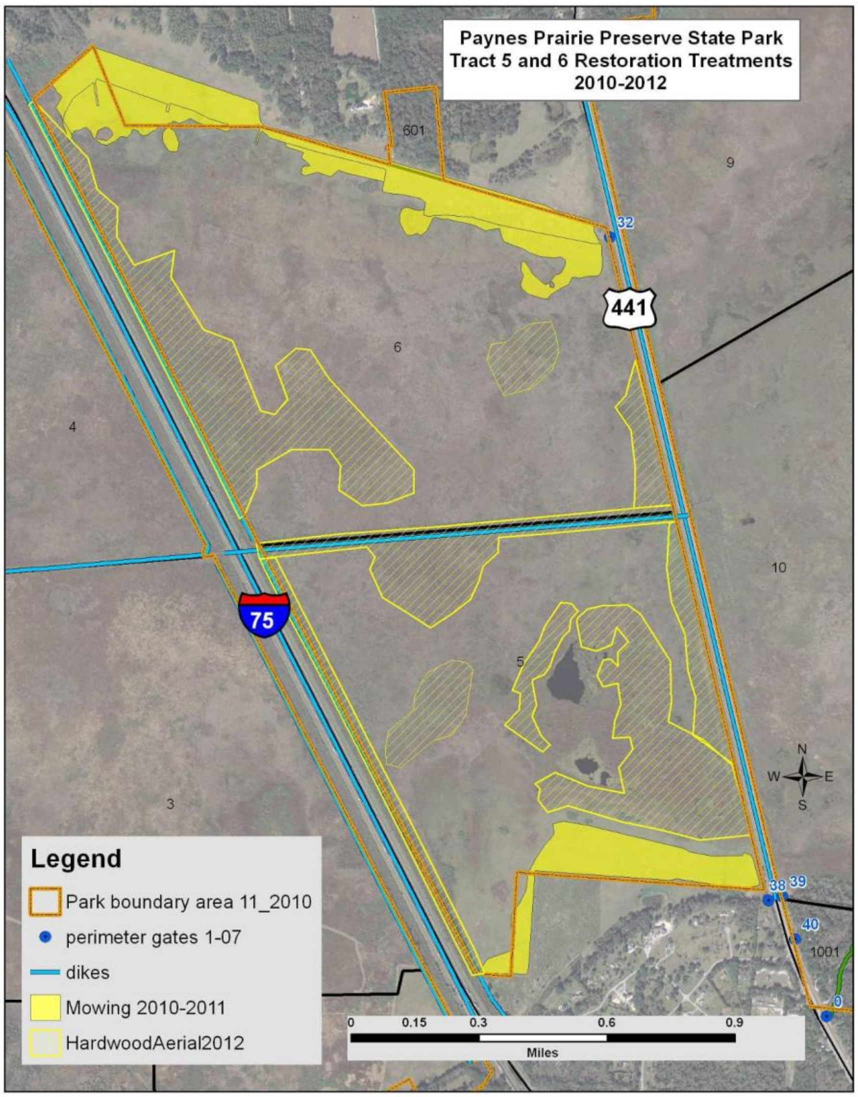

Figure 3: Restoration treatments conducted in zones PP-5 and PP-6 in 2010 and 201

2014 Paynes Prairie Preserve State Park - Aerial Hardwood Control Project

Treatment Acreage = 345

Application Rate = 20 gallons per acre

Prescription

3 pints of imazapyr (Alligare Ecomazapyr) per acre

1% by volume DLZ (Droplet Landing Zone, adjuvant)

		Quantity Mixed		
	1 gallon	20 gallons	100 gallons	250 gallons
Ecomazapyr	2.4 ounces	3 pints or 48 ounces	15 pints or 1 gallon and 7 pints (112 ounces)	4 gallons and 88 ounces
DLZ	1.28 ounces	0.2 gallon or 25.6 ounces	1 gallon	2.5 gallons
Area treated		1 acres	5 acres	12.5 acres

APPENDIX C - RESPONSE ON MANAGEMENT OF CAROLINA WILLOW IN THE CORKSCREW REGIONAL ECOSYSTEM WATERSHED WILDLIFE AND ENVIRONMENTAL AREA (CREW WEA) MARSH RESTORATION PROJECT, COLLIER COUNTY, FL

Prepared by: **Kathleen Smith** and Jean McCollom
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July 07, 2016
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CREW Management Area and Wildlife and Environmental Area began *Salix* treatments in 2007 and have continued those intermittently until the present. The below information should be viewed as preliminary. Evaluations of the treated areas have been minimal. Aerial georeferenced photos were taken in 2014 and 2015. In the fall of 2015, one replication of 0.20 miles of qualitative vegetation surveys was attempted in each treatment and control unit using airboats. The below narrative summarizes the preliminary results of the qualitative vegetation surveys. Additional vegetation surveys are planned for the fall of 2016. Long-term regeneration of herbaceous material using these techniques is unknown. Our goal with these treatments is to test a variety of treatments to see what is effective. Our ultimate goal is to minimize *Salix* encroachment and maximize retention of desirable freshwater marsh vegetation, i.e. killing *Salix* is only part of the goal. Protecting the desirable plants and seedbank as much as possible are important factors in long-term management of the marsh, and therefore an important part of the evaluation of our treatments.

Summary of Treatments

The attached table provides a summary of the aerial and ground herbicide treatments conducted on the CREW WEA's 5,000-acre Corkscrew Marsh since 2007. Limited information exists from the 2007-2011 treatments due to changes in staff at the CREW Management Area, but more recent treatments are described below.

In September 2013, FWC and the South Florida Water Management District (SFWMD) began working with FWC's Aquatic Habitat Restoration/Enhancement Section (AHREs). We designed and conducted an experiment of 3 different aerial herbicide treatments on *Salix* spp. in the Corkscrew Marsh. Three different treatment plots and 3 different control plots (approximately 100 acres adjacent to each treatment plot) were established. The treatment plot rates and herbicide consisted of 96:16 oz/ac (377 ac), 80:24 oz/ac (727 ac), and 120:64 oz/ac (125 ac) glyphosate:imazapyr. All of the 2014 treatments were applied in August/September after the wading bird nesting season and with standing water present in the marsh.

In addition, in May 2015, we used the 96:16 glyphosate:imazapyr rate (our most conservative rate) to treat an additional 320 ac of *Salix*. With the timing of this treatment, we could accurately compare the effects of the aerial herbicide treatments between the dry and wet seasons.

Finally, in September 2015, imazamox (Clearcast) was used to treat the northern area of the CREW marsh for *Typha* spp. and to a lesser extent, non-native *Ludwigia peruviana*. The treatment of these two species seems to be relatively effective, and now we are looking to burn the *Typha* to additionally stress the unwanted vegetation.

Summary of Results

Vegetation surveys of the 2014 96:16 wet season treatment revealed the following abundances: occasional *Salix*, rare *Typha*, and no *Cladium*. There was very little (roughly 5%) plant cover present after one growing season. *Cladium* is common in the adjoining control plot, but in our minimal sampling it was not present in the treated unit after one growing season.

Vegetation surveys of the 80:24 also revealed abundant *Salix*, no *Typha*, and no *Cladium*. The 120:64 treatment contained occasional *Salix*, abundant *Typha*, and no *Cladium*. In addition, there was no *Pontederia* spp. (pickerel weed) or *Sagittaria lancifolia* (lanceleaf arrowhead) in the 120:64 treatment. These species were abundant and occasional in the 80:24 treatment, respectively and occasional and not present in the 96:16 treatment. *Cladium* appears to be the most sensitive of our primary wetland plants at CREW. It is too early to tell if the *Cladium* will regenerate or what combination of herbaceous species will regrow in these areas.

The area treated during the May 2015 dry-season (no standing water in treated area) needs to be revisited for additional evaluation before determining the effectiveness of the *Salix* reduction. The limited observations that we have conducted revealed a substantial impact of the herbicide on the *Cladium* (observed as rare in our vegetation surveys). We attribute most of this non-target collateral damage to the lack of water in the marsh during the time of treatment. But other factors, such as windy conditions and lower density of willow (allowing more herbicide to contact non-target herbaceous material) than the 2014 treatment areas, could have also had an impact on the amount of *Cladium* killed. As a result of this treatment, *Salix* is best treated during the wet season with standing water present to prevent collateral damage to non-target herbaceous species and their seedbank.

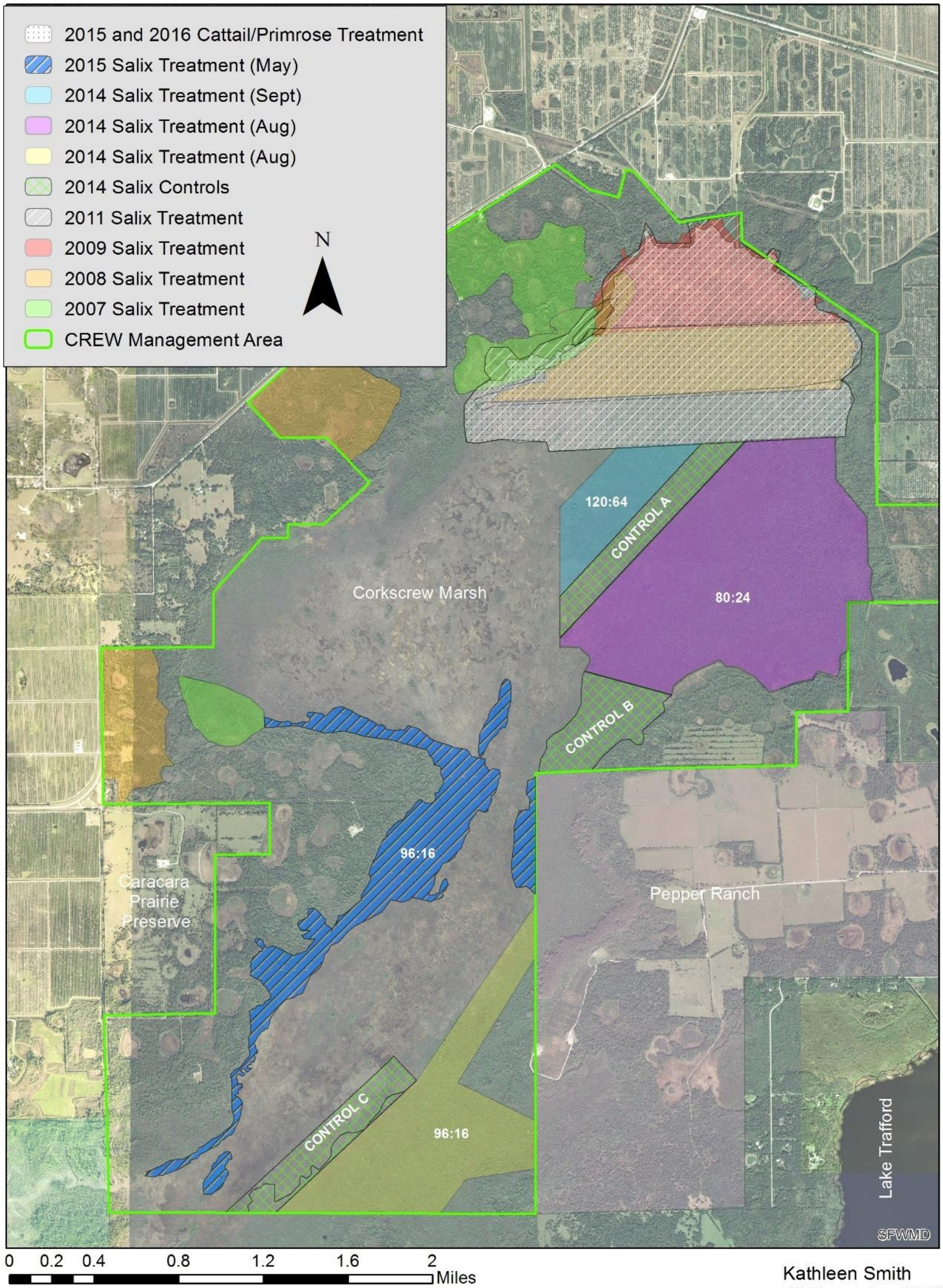
Earlier treatments of *Salix* in the Corkscrew Marsh (2007-2011) had not included imazapyr, and there is no information on *Salix* mortality post-treatment. But *Salix* has regenerated and *Typha* appears abundant in portions of this area. Therefore, we are optimistic that imazapyr in combination with glyphosate will more effectively control *Salix*.

Future Project Ideas in Corkscrew Marsh

Future management and research ideas for the Corkscrew Marsh include research on the re-treatment of emerging *Salix* within the treatment areas (comparing the use of herbicide and the use of fire to control *Salix* recruitment) and aggressively treating *Typha* in the 2007-2011 treatment areas. With the treatment of *Salix* and *Typha*, we hope to increase the abundance of graminoids and increase the amount of burnable vegetation in the marsh. By introducing fire back into the marsh, we can likely decrease the persistence of *Salix*. CREW managers and biologists may also consider planting *Cladium* in the Corkscrew Marsh to help regenerate native, desirable herbaceous vegetation once the necessary *Salix* encroachment has been inhibited. In the future, prescribed fire and selective treatment of *Salix* would be used to shape and maintain the desirable vegetation in the marsh post-treatment.

In addition, research on the water quality of the Corkscrew Marsh and how that may impact the emergence of *Typha* spp. is needed. Discharges from nearby citrus groves may be affecting the water quality and quantity of the Corkscrew Marsh.

2016 CREW Marsh Herbicide/Fire Treatment Project Area



Kathleen Smith
10 December 2015

Appendix C. Summary of Carolina willow management at the Corkscrew Marsh Restoration project in Collier County (2007-2015)

CREW WEA'S CORKSCREW MARSH HERBICIDE TREATMENT SUMMARY (as of 14 July 2016)									RESULTS OF VEGETATION SURVEYS (Oct/Nov 2015)										
SPECIES	DENSITY	TREAT-MENT MONTH	TREAT-MENT YEAR	MAP COLOR†	ACRES	TREAT-MENT	RATE (oz/ac)	CHEMICAL	*SALIX*	*TYPHA*	*CLADIUM*	TOTAL SPECIES	# DESIRABLE SPECIES	# UNDESIRABLE SPECIES	# GRASSES & SEDGES	WATER DEPTH (ft) START	WATER DEPTH (ft) END	ORGANIC DEPTH (ft) START	ORGANIC DEPTH (ft) END
SALIX SPP.	MED	May	2015	BLUE /HATCH _WEST	292	AERIAL	96-16	IMAZAPYR/ GLYPHO	Needs additional surveying						3	1.5	1.3	2.7	3.4
SALIX SPP.	MED	May	2015	BLUE /HATCH _EAST	28	AERIAL	96-16	IMAZAPYR/ GLYPHO	Needs additional surveying										
SALIX SPP.	HIGH	Sep	2014	TEAL	125	AERIAL	120-64	IMAZAPYR/ GLYPHO	Occasional	Abundant	Not Found	9	1	8	1	1	NAS	5 +	NAS
SALIX SPP.	HIGH	Aug	2014	PURPLE	727	AERIAL	80-24	IMAZAPYR/ GLYPHO	Abundant	Not Found	Not Found	22	17	5	4	0.9	1.3	3.3	3.9
SALIX SPP.	HIGH	Aug	2014	LIGHT YELLOW /GREEN	377	AERIAL	96-16	IMAZAPYR/ GLYPHO	Occasional	Rare	Not Found	23	14	9	7	2.3	1.6	4	3.6
SALIX SPP.	MED	6-Mar	2011	YELLOW /HATCH	323	AERIAL	TBD	GLYPHO	Abundant	Abundant	Not Found	28	17	11	7	1.5	1.5	5 +	5 +
SALIX SPP.	MED	16-Jun	2011	CLEAR /HATCH	324	AERIAL	TBD	GLYPHO	Abundant	Common	Not Found	24	14	10	5	1.4	NAS	4.3 +	NAS
SALIX SPP.	MED	17-Jun	2011	RED /HATCH	248	AERIAL	TBD	GLYPHO	Not Found	Abundant (Monoculture)	Not Found	1	0	1	1	NAS	NAS	NAS	NAS
SALIX SPP.	MED	Aug	2009	RED	248	AERIAL	TBD	GLYPHO	Same unit as 2009 above										
SALIX SPP.	HIGH	15-Sep	2008	YELLOW	326	AERIAL	TBD	TBD	Same unit 2008 above										
SALIX SPP.	HIGH	Jul	2007	GREEN_ NORTH	114	BASAL/ FOLIAR	TBD	TRIC/ GLYPH	Occasional	Common	Common	46	35	11	13	0.2	1.1	0.6	1.3
SALIX SPP.	HIGH	Aug	2007	GREEN_ SOUTH	56	BASAL/ FOLIAR	TBD	TRIC/ GLYPH	Not yet surveyed										
CONTROL A	N/A	Aug	2014	GREEN /HATCH	101	CONTROL	N/A	N/A	Abundant	Not Found	Abundant	25	19	6	1	0.9	0.8	4.3	2.9
CONTROL B	N/A	Aug	2014	GREEN /HATCH	98	CONTROL	N/A	N/A	Unable to access by airboat										
CONTROL C	N/A	Aug	2014	GREEN /HATCH	100	CONTROL	N/A	N/A	Common	Rare	Common	27	20	7	2	1.3	1	3.9	2

*NAS - needs additional surveying

† - See Appendix B map