

Accounting for the Impact of Management Scenarios on *Typha Domingensis* (Cattail) in an Everglades Wetland

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Abstract The coupled regional simulation model, and the transport and reaction simulation engine were recently adapted to simulate ecology, specifically *Typha domingensis* (Cattail) dynamics in the Everglades. While Cattail is a native Everglades species, it has become invasive over the years due to an altered habitat over the last few decades, taking over historically *Cladium jamaicense* (Sawgrass) areas. Two models of different levels of algorithmic complexity were developed in previous studies, and are used here to determine the impact of various management decisions on the average Cattail density within Water Conservation Area 2A in the Everglades. A Global Uncertainty and Sensitivity Analysis was conducted to test the importance of these management scenarios, as well as the effectiveness of using zonal statistics. Management scenarios included high, medium and low initial water depths, soil

phosphorus concentrations, initial Cattail and Sawgrass densities, as well as annually alternating water depths and soil phosphorus concentrations, and a steadily decreasing soil phosphorus concentration. Analysis suggests that zonal statistics are good indicators of regional trends, and that high soil phosphorus concentration is a pre-requisite for expansive Cattail growth. It is a complex task to manage Cattail expansion in this region, requiring the close management and monitoring of water depth and soil phosphorus concentration, and possibly other factors not considered in the model complexities. However, this modeling framework with user-definable complexities and management scenarios, can be considered a useful tool in analyzing many more alternatives, which could be used to aid management decisions in the future.

Keywords *Typha domingensis* (Cattail) · Regional simulation model · Transport and reaction simulation engine · Management scenarios · Trend analysis · Global uncertainty and sensitivity analysis

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Abbreviations

RSM	Regional Simulation Model
RTE	coupled RSM TARSE model applied towards Ecology
TARSE	Transport and Reaction Simulation Engine
SFWMD	South Florida Water Management District
SFWMM	South Florida Water Management Model
WCA2A	Water Conservation Area 2A
HSE	Hydrologic Simulation Engine
GUSA	Global Uncertainty and Sensitivity Analysis
CERP	Comprehensive Everglades Restoration Plan
USACE	United States Army Corps of Engineers
SIS	Sequential Indicator Simulation
DM	Delta Mean

CATGF	Cattail Growth Factor
SAWGF	Sawgrass Growth Factor
DepthMgmt	Depth Management scenario
PMgmt	Phosphorus Management scenario

Introduction

The Everglades wetland ecosystem of south Florida, USA, is an intensely managed system, and has been for some time. As early as the 1850's with the Swamp and Overflow Act (Glennon 2002), and again in 1948 with the Central (CE) and South Florida Project, the Everglades were channelized in order to aid in flood protection and provide arable land for agriculture (Gunderson et al. 2001). Today, almost all the water in south Florida passes through at least one canal before entering the surrounding ocean (Layzer 2006). This had a negative impact on the environment, with wetland areas being reduced by up to 50 %, and wildlife species becoming threatened. Certain bird populations have been reduced by 90 %, and other species such as *Trichechus manatus latirostris* (Florida manatee), *Puma concolor coryii* (Florida panther), *Ammodramus maritimus mirabilis* (Cape Sable seaside sparrow), and *Tantilla oolitica* (rim rock crowned snake), are at risk of extinction (Brown et al. 2006).

The comprehensive everglades restoration plan (CERP) was approved with the Water Resources Development Act of 2000 with the express goal of some of the Everglades' former extent and ecosystem functioning (USACE 2010a). The main focus of CERP has focused on improved water and water quality management; the assumption is that if the quantity and quality are adequate, the ecology will follow suit. There is, however, an increasing concentration on the ecological impacts of various management decisions, and these efforts center on improving species diversity and protecting existing habitats (USACE 2010b).

In addition to the changes in hydrology, continuous mining, agriculture and urbanization activities have resulted in invasive and exotic plants becoming established in place of the original vegetation, altering habitats and often forming mono-crop stands (single species environment) (Odum et al. 2000). One of these species in particular, *Typha domingensis* (Cattail), has been labeled as an indicator species, or species of concern. Cattail is a native Everglades monocotyledonous vegetation species, typically occurring as sparse complements alongside *Cladium jamaicense* (Sawgrass) stands. They have become invasive, and in the 1980s, the area covered by Cattail stands in Water Conservation Area 2A (WCA2A) doubled, expanding southward into the Sawgrass marshes (Willard 2010).

Their distribution is now used to determine the effectiveness of various water management decisions.

Fitz et al. (2011) notes that models allow us to evaluate different scenarios of management decisions before the more costly task of their implementation. There is a vast amount of literature on the use of models for managing ecological systems. A few such general examples include Chen et al. (2010), Zheng et al. (2011), and Lieske and Bender (2009). More specific examples related to the Everglades include the Across Trophic Level System Simulation (Gross 1996) model and the Everglades Landscape Model (Fitz and Trimble 2006). Another modeling effort by Wu et al. (1997) used Markov chain probabilities to model Cattail in the Everglades, while Tarboton et al. (2004) developed a set of habitat suitability indices for evaluating water management alternatives in the Everglades.

The recently coupled RSM/TARSE (SFWMD 2008a; Jawitz et al. 2008) model was used by Lagerwall et al. (2012) to quantitatively and deterministically model ecology. The ecological implementation of this coupled model (henceforth RTE) was used to model Cattail density dynamics across WCA2A. Model complexity, uncertainty, and sensitivity are important factors to consider in any model development (Ascough et al. 2008; Krysanova et al. 2007; Messina et al. 2008). The complexity/uncertainty/sensitivity trilemma mentioned by Muller et al. (2011) was addressed for this model through a global uncertainty and sensitivity analysis (GUSA) with an added component of spatial uncertainty, very much like that conducted by Zajac (2010). The results of this GUSA can be found in Lagerwall et al. (2014).

The objective of this paper is to evaluate the impact of various management scenarios as they relate to the Cattail density distribution throughout WCA2A, in the Southern Florida Everglades. This is achieved through applying a GUSA to the management scenarios, as well as a close observation of density trends due to various specific scenarios.

Materials and Methods

In the previous two studies by Lagerwall et al. (2012) and Lagerwall et al. (2014), five different levels of increasing complexity were used to simulate Cattail growth. When matching historical data in Lagerwall et al. (2012), the Levels 4 and 5 complexities were determined to be the best match (most accurate), with only slightly elevated minimums, with all other statistics and trends matching the data well. After conducting a GUSA on the five levels of complexity in Lagerwall et al. (2014), it was determined that the Level 4 complexity provided a reduced uncertainty for an

insignificant change in sensitivity from the other three levels of complexity (L3, L2, and L5), which implies an increase in model precision, without any risk of over-parameterization. Based on these previous results it can be concluded that the most relevant model (of the five tested), the one which balances complexity, uncertainty and sensitivity, is the Level 4 complexity, which includes parameters for water depth, soil phosphorus concentration, and Sawgrass density interaction. The Level 5 complexity could be deemed the next most relevant model algorithm, and possibly the more realistic (between L4 and L5) in terms of the included feed-back mechanism. As the most relevant models tested, this paper then will only consider the Levels 4 and 5 complexities to determine the importance of various management scenarios in controlling the spread of Cattail. According to the Sobol sensitivities in Lagerwall et al. (2014), the model was most sensitive to the water depth and soil phosphorus concentration parameters, which is consistent with literature of Newman et al. (1998) and Urban et al. (1993). These parameters will be discussed in more detail in the following two sections.

Hydrology Management Scenarios

Hydrology is one of the main factors influencing Cattail distribution (Newman et al. 1998). The hydrology of WCA2A is controlled primarily by the operation of control points along the S10A, S10C, S10D, S10E, and L35-B canals (seen in Fig. 1). The mesh and associated Hydrologic Simulation Engine (HSE) model setup files were developed and provided by the South Florida Water Management District. An overview of the HSE setup for WCA2A, which provides the hydrological operating conditions, can be found in SFWMD (2008c). Because it is a highly controlled wetland, and water depth is a factor that can be relatively well managed, the water depth was used as a model input parameter. Due to the fact that the model will simulate alternative future scenarios, normal time series data cannot be used. Water depth is therefore set as a uniform value across the WCA2A region. Scenarios involving the control of depth include a high, medium, and low (or dry) water depth. The optimum growing depth for Cattail has been documented as 24–96 cm (Grace 1989). A high water depth can be considered to be 3 m, a medium depth 0.5 m, and a low (dry) depth 0 m (Lagerwall et al. 2014). Another management scenario includes an annual alternation among high and dry water levels.

Soil Phosphorus Management Scenarios

A gradient of soil phosphorus exists along WCA2A, with a high concentration near the inlets at the north, and a low concentration at the outlets in the south. This soil

phosphorus gradient has been widely documented and studied (DeBusk et al. 1994). Soil phosphorus concentration is the second most important external factor affecting the distribution of Cattail (Urban et al. 1993), and is another factor that can be managed. Changing soil phosphorus distributions in WCA2A are noted by Grunwald et al. (2004) and Grunwald et al. (2008), and is largely affected by incoming (upstream) water which is high in phosphorus. As Rutchev et al. (2008) has noted, this incoming water phosphorus can be controlled through the use of best management practices. For the purpose of simulation in this paper, soil phosphorus will be applied uniformly across the domain in high, medium, and low concentrations. The uniform distribution is not wholly realistic, but will suffice to prove the impact of increasing, decreasing, or altering levels of concentration on the current distribution and dynamics of the Cattail. High concentration is 1500 mg/kg, medium concentration is 600 mg/kg, and low concentration is the desired 0 mg/kg. Other management scenarios include an annual alternation among high and low soil phosphorus concentrations, as well as a linearly decreasing concentration from the high (1500 mg/kg), and decreasing at a constant 3 % (45 mg/kg) per annum.

With the two alternating water depth and soil phosphorus management scenarios, the alternations are set to occur at the same time, with a high water depth related to a high soil phosphorus concentration. A final set of management scenarios was to include an out-of-sync combination of these alternating variables, where a high water depth corresponds with a low soil phosphorus concentration.

Global Uncertainty and Sensitivity Analysis (GUSA)

A GUSA was used for its ability to consider every possible combination of management options, initial conditions, spatial impact and timing. It was decided that the variance-based method of Sobol (2001) would be used to conduct the GUSA in order to maintain consistency with Lagerwall et al. (2014). Also, the Sobol method is one of the few methods that can use discrete input distributions, as was necessary when using alternate initial density values in Lagerwall et al. (2014), and is necessary here for realizing alternate management scenarios as well. A succinct overview of the Sobol method is provided by Lilburne & Tarantola (2009). The process involves reducing the probability distribution function (PDF) of the model output (uncertainty), created by PDF's of the model input parameters, into sensitivities of specific model input parameters. There were six input parameters used in this analysis: The Cattail Growth Factor (CATGF), Sawgrass Growth Factor (SAWGF), Cattail (initial densities), Sawgrass (initial densities), Depth Management scenarios (DepthMgmt), and the Phosphorus Management scenarios (PMgmt), as seen in

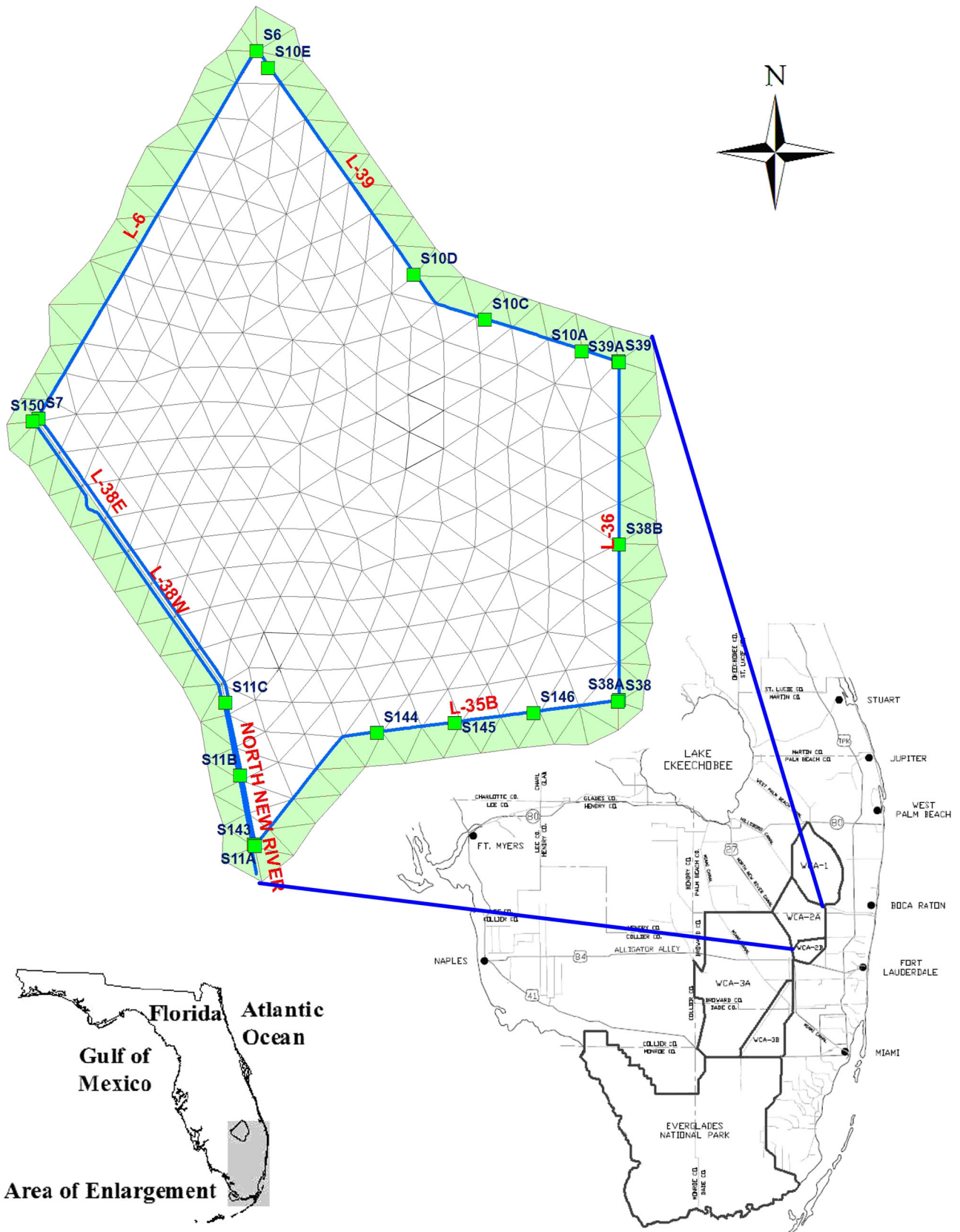


Fig. 1 Test site, Water Conservation Area 2A (WCA2A), in the northern Everglades. *Green squares* represent inlet and outlet control structures; *blue lines* represent canals. *Triangles* represent the mesh

used for simulation, with *green triangles* representing the border cells used in the central difference method (color figure online)

Table 1 Probability distributions of model input factors used in global uncertainty and sensitivity analysis

Parameter definition	Symbol	Distribution	Units
Cattail Initial Densities	Cattail	D (1–250)	SIS maps
Cattail growth factor	CATGF	T (1.0E-6, 1.0E-7, 1.0E-9)	g/g.s
Regional water depth	Depth	D (0.3, 1.5)	m
Regional soil phosphorus concentration	Phosphorus	D (1, 6)	mg/kg
Sawgrass initial densities	Sawgrass	U (0, 1958)	g/m ²
Sawgrass growth factor	SAWGF	T (1.0E-6, 1.0E-7, 1.0E-9)	g/g.s

D = Discrete, T = Triangular, U = Uniform distribution

Table 1. The parameter distributions are labeled either D, for a discrete distribution, U, for a uniform distribution, and T, for a triangular distribution. For example, the discrete distribution will sample each of the 1–250 maps of the Cattail Initial Densities (Cattail) parameter. The uniform distribution will sample uniformly across the range from 0 to 1958 for the Sawgrass Initial Densities (Sawgrass) parameter. The triangular distribution is similar to a Gaussian distribution, and is sampled accordingly, with the apex at 1.0E-7, and the minimum and maximum at 1.0E-6 and 1.0E-9, respectively for the CATGF. The initial Cattail density maps were the same as those used previously in Lagerwall et al. (2014), obtained through a Sequential Indicator Simulation (SIS) using ground-truthed points for the 2003 vegetation map. This prompted the use of “SIS maps” as units for the Cattail Initial Densities parameter in Table 1. The units of g/g.s for the growth factors relate to the growth rate as a function of biomass, and is detailed in Lagerwall et al. (2012), with methodology used by Jawitz et al. (2008), and a logistic function detailed by Keen and Spain (1992). For this analysis a total of 14336 separate simulations were required. The program SIMLAB (Saltelli et al. 2004) was used to perform the GUSA, and compare the parameter input file to the compiled output statistics.

Representative Statistic

The Delta Mean (DM) density, or change in mean density is a scalar statistic that was used previously in Lagerwall et al. (2014). This DM statistic was used for the GUSA to measure the change in the regional mean density. The DM statistic was also used in a zonal analysis, where DM was calculated for three zones of historically high, medium, and low Cattail densities respectively, as well as for the entire WCA2A region. The typically high density, northeast (NE) zone covered cells 175 through 180. The more medium density, CE zone covered cells 280 through 283. While the low density, Southwest (SW) zone covered cells 376 through 380. These zones and respective cell numbers can be seen in Fig. 2.

Time Series Analysis

A time series of regional mean density was created for a select number of management scenarios in order to gain greater insight into the GUSA results and the system dynamics in general. The CATGF was set at 6.7×10^{-9} g/g.s, after the calibrated values obtained by Lagerwall et al. (2012). Instead of a single distribution of initial Sawgrass densities, it was decided to use three levels representing uniformly high (1500 g/m²), medium (900 g/m²), and low (300 g/m²) densities, respectively. The decreasing soil phosphorus concentration management scenario involved a decrease in concentration of 3 % (of the initial High concentration) per annum over the 30-year period, for a total decrease of 90 %. A summary of the management distributions, associated levels, and scenarios can be found in Tables 2, 3, and 4, respectively. The management scenarios in Table 4 are repeated for medium (management scenarios 22–42) and high (management scenarios 43–63) initial Sawgrass density. The complete version of Table 4 can be seen in Figs. 6 and 7, which are used for analyzing the difference between the Level 4 and Level 5 complexity models’ response to the various management scenarios.

Results

The uncertainty plots for the regional and zonal model output frequency distribution of Level 4 can be found in Fig. 3. The bimodal distribution from the GUSA in Lagerwall et al. (2014) is greatly reduced, and could be said to be a tri-modal or even pent-modal distribution. The difference in this distribution is due solely to the management scenarios used, and the reduced range of the associated parameter values. These distributions can be further compared using their 95 % confidence intervals, and these are plotted in Fig. 4. As can be seen from Figs. 3 and 4, the distributions for the Region, NE, CE, and SW zones are all similar, and the regional uncertainty statistic is a good average indicator of the other zonal uncertainty statistics. As

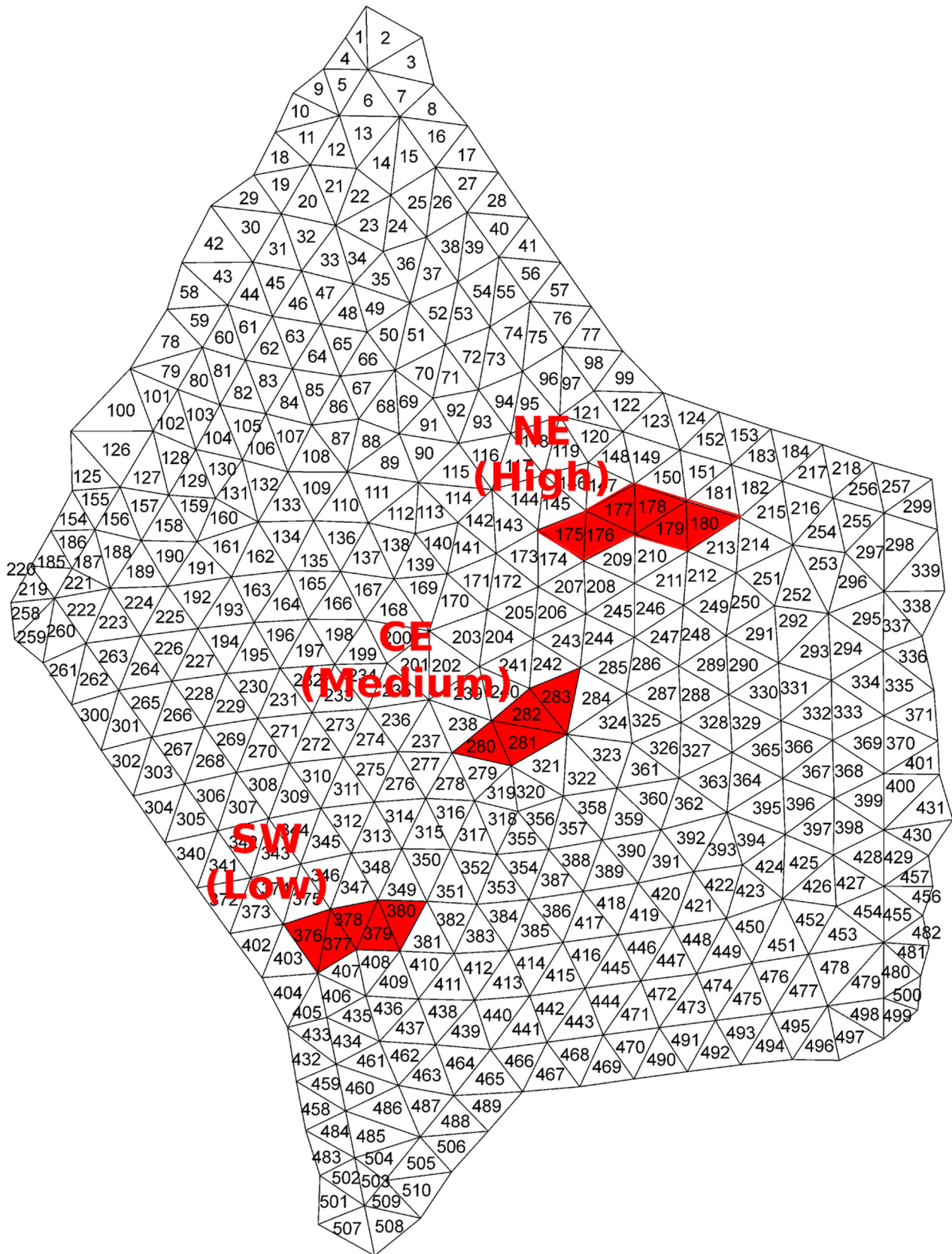


Fig. 2 Water Conservation Area 2A (WCA2A) triangular mesh, with numbered cells, and NE, CE, and SW zones (color figure online)

a result, only the regional distribution for Level 5 is displayed in Fig. 3.

The model sensitivities to the input parameters, both first order and total order, are plotted in Fig. 5. As with the uncertainty distributions, the regional sensitivities are fairly representative of the zonal sensitivities. Upon further consideration of these plots, there are some minor distinctions between the Levels 4 and 5 sensitivities. The Sawgrass initial density decreases for Level 5 in both the first order and total order sensitivities, while the Cattail initial density increases for Level 5 in both plots. The SAWGF has a reduced sensitivity for Level 5 in the first order sensitivities, with an increase in the CATGF total order sensitivity for Level 5. The depth factor is still dominant in the first order sensitivities, although the depth and soil phosphorus factors are much reduced in the total order sensitivities when compared to the GUSA in Lagerwall et al. (2014). Overall, the differences are slight, but they do hint at the increased importance of initial densities of both Cattail and Sawgrass and their respective growth factors on the sensitivities of the Level 5 complexity model when compared to the Level 4 complexity model.

The following management time series plots correspond to the management scenarios illustrated in Table 4 for low initial Sawgrass density, and which is repeated for medium (management scenario 22–42) and high (management scenario 43–63) initial Sawgrass densities. Those trends with a

regional mean density ending over 400 g/m² were considered to have an expansive Cattail growth, while those with a final regional mean Cattail density below 200 g/m², or with level trends below 400 g/m², were considered to have a decreasing or static Cattail growth. For Level 4, these results were compiled into a table in Fig. 6. The time series representing expansive growth are circled in red

Table 2 Management distributions for soil phosphorus, depth and Sawgrass parameters

Distribution	Depth	Phosphorus	Sawgrass
1	High	High	High
2	Medium	Medium	Medium
3	Low	Low	Low
4	Even years high	Even years high	
5	Even years low	Even years low	
6	n/a	Decreasing (Max -3 % p.a.)	

Table 4 Example of management scenarios used for time series analysis

Management scenario	Depth	Soil phosphorus concentration	Sawgrass initial density
1	High	High	Low
2	Low	Low	Low
3	High	Low	Low
4	Low	High	Low
5	Medium	High	Low
6	Medium	Medium	Low
7	Medium	Low	Low
8	High	Medium	Low
9	Low	Medium	Low
10 (Alternating in sync)	Even high	Even High	Low
11 (Alternating out of sync)	Even low	Even High	Low
12	High	Linearly decreasing	Low
13	Medium	Linearly decreasing	Low
14	Low	Linearly decreasing	Low
15	Even High	Linearly decreasing	Low
16	High	Even high	Low
17	Medium	Even high	Low
18	Low	Even high	Low
19	Even high	High	Low
20	Even high	Medium	Low
21	Even high	Low	Low

This table repeats for medium (management scenario 22–42) and high (management scenario 43–63) initial Sawgrass densities

Table 3 Values associated with management scenario parameters

Level	Depth (m)	Soil phosphorus concentration (mg/kg)	Sawgrass initial density (g/m ²)
High	3	1500	1500
Medium	0.5	600	900
Low	0	0	300
Alternating (Even high or even low)	3 and 0	1500 and 0	na
Linearly decreasing	na	1500–150	na

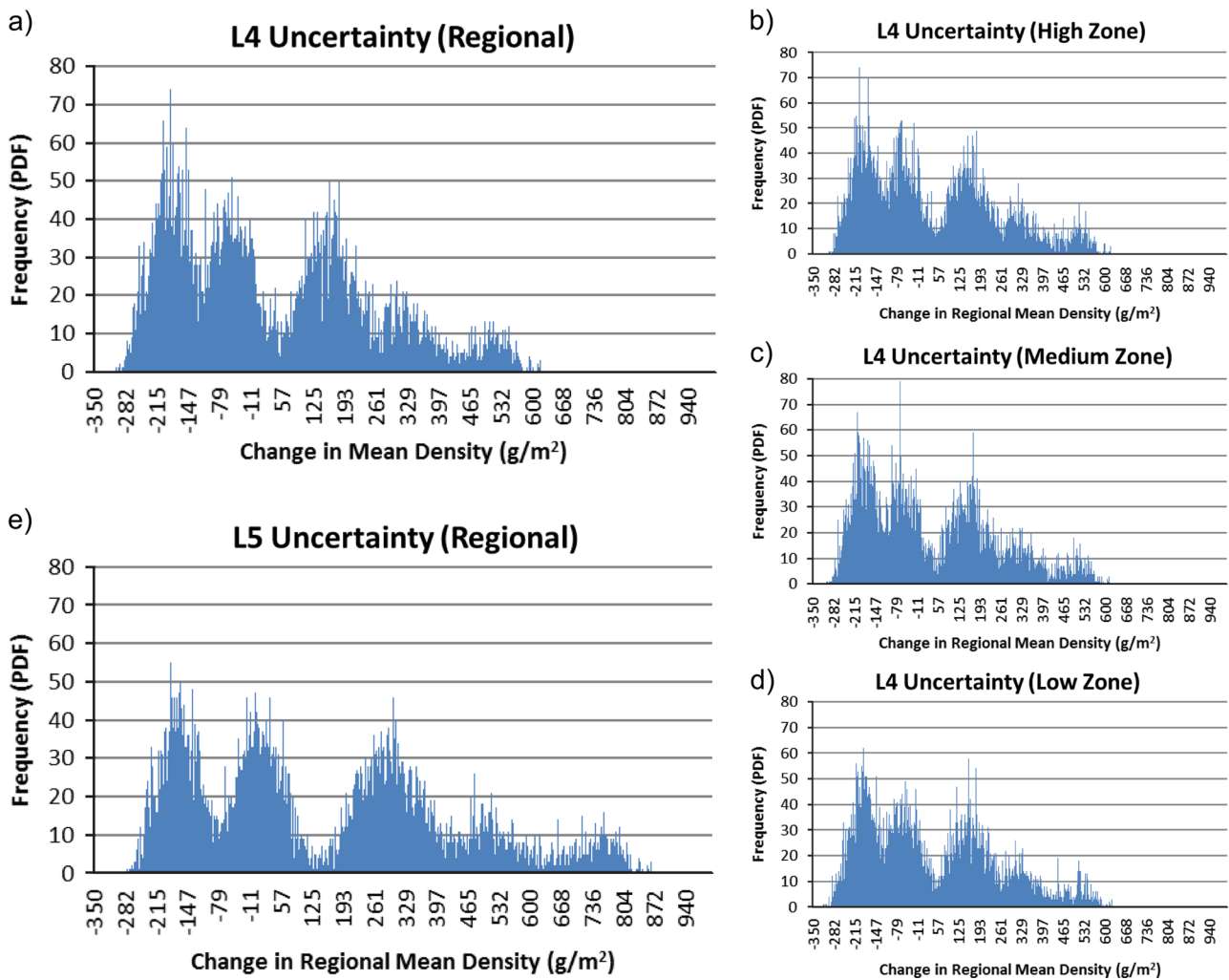


Fig. 3 Model uncertainty plots in frequency format for Level 4. **a** Regional. **b** North East/High Zone. **c** Central/Medium Zone. **d** Southwest/Low Zone, and Level 5 **(e)** Regional (color figure online)

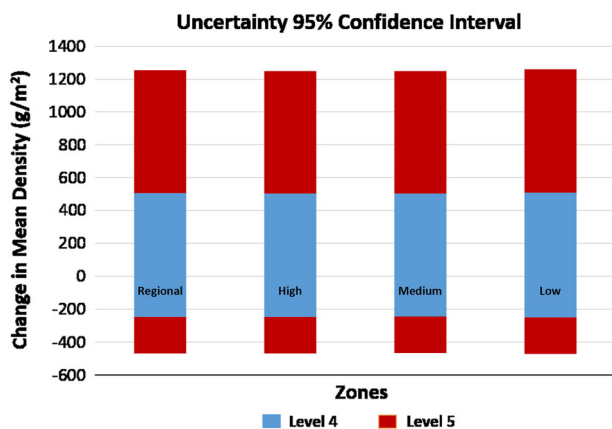


Fig. 4 Model 95 % confidence interval, for the entire Region, as well as the High/Northeast, Medium/CE, and Low/SW zones, for both Level 4 and 5 model complexities, respectively (color figure online)

dashes, while the time series representing a decreasing trend are circled in solid blue in Fig. 6. The common trend between the expansive growth plots for Level 4 is a high soil phosphorus concentration.

For Level 5, the results were compiled into a table in Fig. 7, with those representing expansive growth being circled in red dashes, while the time series representing a decreasing trend being circled in solid blue. The only common immediately noticeable trend between the expansive growth time series for Level 5 is a high soil phosphorus concentration where there are also high initial Sawgrass densities. For lower initial Sawgrass densities, the Level 5 complexity model tends to dominate across a range of combinations of depth and soil phosphorus concentrations. In other words, when the initial Sawgrass density is high, a high soil phosphorus concentration is required for Cattails to become established.

There are no management scenarios that result in the regional mean density dropping close to zero, and this would be due to the elevated minimum density predictions

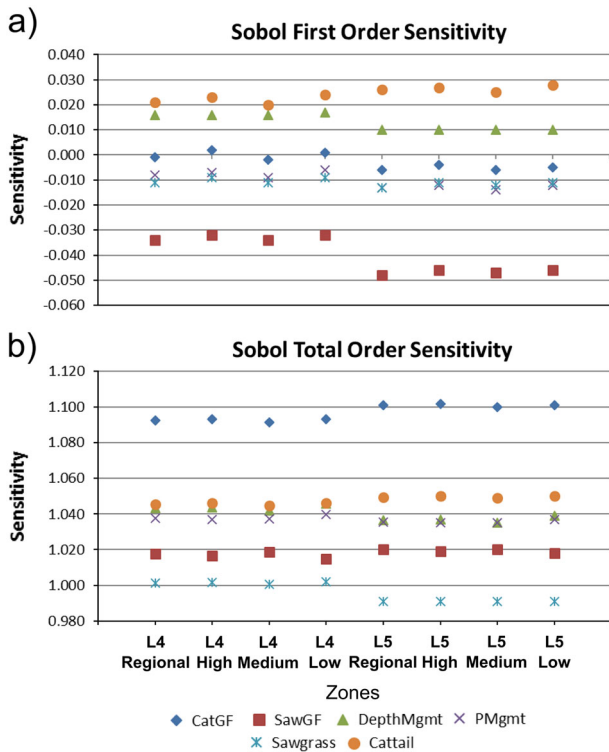


Fig. 5 Model sensitivity for first order (a) and total order; (b) of parameters CATGF, SAWGF, DepthM, PhosphorusM, Sawgrass, and Cattail, for the entire Region as well as the High/Northeast, Medium/CEentral, and Low/SW zones, for Levels 4 and 5, respectively (color figure online)

of the Levels 4 and 5 model complexities, previously noted by Lagerwall et al. (2012). In looking for management solutions that reduce, or at least do not increase regional Cattail densities, one can consider those scenarios circled by solid blue lines in Figs. 6 and 7, respectively. The common theme was a low soil phosphorus concentration. Or, in the case of a low initial Sawgrass density, typically representative of areas currently dominated by Cattail, a depth above the medium level of 0.5 m (See Table 3) and a linearly decreasing soil phosphorus concentration were the primary causes of a decreasing Cattail density trend. Specifically, management scenarios 12 and 13 in this case, which represent combinations of high and medium depth, with a low initial Sawgrass concentration, and a linearly decreasing soil phosphorus concentration. These plots level off after about half the simulation period, which equates to roughly 15 years, and a threshold soil phosphorus concentration of roughly 750 mg/kg.

Discussion and Conclusion

A GUSA was conducted to test the importance of various management scenarios using the Levels 4 and 5 complexity models, as well as the effectiveness of using regional/zonal statistics. Management scenarios included high, medium, and low initial water depths, and soil phosphorus concentrations, as well as annually alternating (in sync and out of sync, high-low) water depths and soil phosphorus concentrations, and a steadily decreasing soil phosphorus

Management Scenario	Depth	Phosphorus	Sawgrass	Management Scenario	Depth	Phosphorus	Sawgrass	Management Scenario	Depth	Phosphorus	Sawgrass
1	High	High	Low	22	High	High	Medium	43	High	High	High
2	Low	Low	Low	23	Low	Low	Medium	44	Low	Low	High
3	High	Low	Low	24	High	Low	Medium	45	High	Low	High
4	Low	High	Low	25	Low	High	Medium	46	Low	High	High
5	Medium	High	Low	26	Medium	High	Medium	47	Medium	High	High
6	Medium	Medium	Low	27	Medium	Medium	Medium	48	Medium	Medium	High
7	Medium	Low	Low	28	Medium	Low	Medium	49	Medium	Low	High
8	High	Medium	Low	29	High	Medium	Medium	50	High	Medium	High
9	Low	Medium	Low	30	Low	Medium	Medium	51	Low	Medium	High
10 (Alt. in)	E.H.	E.H.	Low	31 (Alt. in)	E.H.	E.H.	Medium	52 (Alt. in)	E.H.	E.H.	High
11 (Alt. out)	E.L.	E.H.	Low	32 (Alt. out)	E.L.	E.H.	Medium	53 (Alt. out)	E.L.	E.H.	High
12	High	Ln.Dec.	Low	33	High	Lin.Dec.	Medium	54	High	Lin.Dec.	High
13	Medium	Lin.Dec.	Low	34	Medium	Lin.Dec.	Medium	55	Medium	Lin.Dec.	High
14	Low	Lin.Dec.	Low	35	Low	Lin.Dec.	Medium	56	Low	Lin.Dec.	High
15	Even High	Lin.Dec.	Low	36	E.H.	Lin.Dec.	Medium	57	E.H.	Lin.Dec.	High
16	High	E.H. (Alt.)	Low	37	High	E.H. (Alt.)	Medium	58	High	E.H. (Alt.)	High
17	Medium	E.H. (Alt.)	Low	38	Medium	E.H. (Alt.)	Medium	59	Medium	E.H. (Alt.)	High
18	Low	E.H. (Alt.)	Low	39	Low	E.H. (Alt.)	Medium	60	Low	E.H. (Alt.)	High
19	E.H. (Alt.)	High	Low	40	E.H. (Alt.)	High	Medium	61	E.H. (Alt.)	High	High
20	E.H. (Alt.)	Medium	Low	41	E.H. (Alt.)	Medium	Medium	62	E.H. (Alt.)	Medium	High
21	E.H. (Alt.)	Low	Low	42	E.H. (Alt.)	Low	Medium	63	E.H. (Alt.)	Low	High

E. = Even Alt. = Alternating H. = High L. = Low Lin.Dec. = Linearly Decreasing in = in sync out = out of sync

Expansive Growth (circled in red dashes) Decreasing Growth (circled in solid blue)

Fig. 6 Level 4 table of management scenarios for Cattail growth. Those scenarios considered expansive growth are circled in red dashes, while those considered decreasing growth are circled in solid blue (color figure online)

Management Scenario	Depth	Phosphorus	Sawgrass	Management Scenario	Depth	Phosphorus	Sawgrass	Management Scenario	Depth	Phosphorus	Sawgrass
1	High	High	Low	22	High	High	Medium	43	High	High	High
2	Low	Low	Low	23	Low	Low	Medium	44	Low	Low	High
3	High	Low	Low	24	High	Low	Medium	45	High	Low	High
4	Low	High	Low	25	Low	High	Medium	46	Low	High	High
5	Medium	High	Low	26	Medium	High	Medium	47	Medium	High	High
6	Medium	Medium	Low	27	Medium	Medium	Medium	48	Medium	Medium	High
7	Medium	Low	Low	28	Medium	Low	Medium	49	Medium	Low	High
8	High	Medium	Low	29	High	Medium	Medium	50	High	Medium	High
9	Low	Medium	Low	30	Low	Medium	Medium	51	Low	Medium	High
10 (Alt. in)	E.H.	E.H.	Low	31 (Alt. in)	E.H.	E.H.	Medium	52 (Alt. in)	E.H.	E.H.	High
11 (Alt. out)	E.L.	E.H.	Low	32 (Alt. out)	E.L.	E.H.	Medium	53 (Alt. out)	E.L.	E.H.	High
12	High	Lin.Dec.	Low	33	High	Lin.Dec.	Medium	54	High	Lin.Dec.	High
13	Medium	Lin.Dec.	Low	34	Medium	Lin.Dec.	Medium	55	Medium	Lin.Dec.	High
14	Low	Lin.Dec.	Low	35	Low	Lin.Dec.	Medium	56	Low	Lin.Dec.	High
15	Even	High	Low	36	E.H.	Lin.Dec.	Medium	57	E.H.	Lin.Dec.	High
16	High	E.H. (Alt.)	Low	37	High	E.H. (Alt.)	Medium	58	High	E.H. (Alt.)	High
17	Medium	E.H. (Alt.)	Low	38	Medium	E.H. (Alt.)	Medium	59	Medium	E.H. (Alt.)	High
18	Low	E.H. (Alt.)	Low	39	Low	E.H. (Alt.)	Medium	60	Low	E.H. (Alt.)	High
19	E.H. (Alt.)	High	Low	40	E.H. (Alt.)	High	Medium	61	E.H. (Alt.)	High	High
20	E.H. (Alt.)	Medium	Low	41	E.H. (Alt.)	Medium	Medium	62	E.H. (Alt.)	Medium	High
21	E.H. (Alt.)	Low	Low	42	E.H. (Alt.)	Low	Medium	63	E.H. (Alt.)	Low	High

E. = Even Alt. = Alternating H. = High L. = Low Lin.Dec.= Linearly Decreasing in = in sync out = out of sync

Expansive Growth (circled in red dashes) **Decreasing Growth** (circled in solid blue)

Fig. 7 Level 5 table of management scenarios for Cattail growth. Those scenarios considered expansive growth are circled in red dashes, while those considered decreasing growth are circled in solid blue (color figure online)

concentration. A selection of these scenarios, with initial Sawgrass densities set as high, medium or low, were plotted over time (30 years) to gain further insight of possible management practices and their expected results.

From the GUSA, it can be concluded that a regional analysis is an acceptable representation of the various zones within that region. Or, that the statistics for a zonal analysis can be used as a fair representation of the region (using the current Levels 4 and 5 complexity models). This is important for data collection and mapping programs to ensure the most accurate data representation possible. Again, depth is a highly influential factor when considering management scenarios, with initial densities of Cattail and Sawgrass also coming into play.

From the management time series analysis, the high soil phosphorus requirement for expansive growth is consistent with literature, Newman et al. (1998) and Miao & Sklar (1998), with the depth and initial Sawgrass parameters accounting for the observed variation of these plots. The lack of significantly decreasing trends is possibly due to the averaging-out of the three influencing parameters, as they are calculated in the Levels 4 and 5 complexity models. After analyzing the decreasing trends, with final densities either below the 200 g/m² mark or a level trend below the 400 g/m² mark, the implicit threshold soil phosphorus concentration of roughly 750 mg/kg is of importance because when it is combined with a relatively high depth (>= 0.5 m), the Cattail densities can be relatively well managed. It is possible to find other trends, specifically referring to the Level 4 management scenarios 3, 6, 7, 8, 16,

17, 20, 21, which do not match the decreasing growth qualifications, but which have visibly lower densities (< 400 g/m²), and less aggressive trends, than other management scenarios. This is significant because when one considers the interplay of depth, soil phosphorus and Sawgrass, it is not necessary to reduce soil phosphorus completely, provided depth is relatively high (at least for certain periods). These last statements require a caveat in that the values provided do not necessarily reflect the real world threshold values. They illustrate only that there exist thresholds of soil phosphorus and water depth which, when managed, can be used to control the Cattail population. It must also be noted that using a significantly increased water depth to control Cattail will also result in the undesirable killing of other vegetative species, including Sawgrass.

It must be noted that due to the structure of the Level 4 complexity, provided that there is a long enough simulation period, the Sawgrass density will achieve its maximum value (due to it being based on a purely logistic function), as well as its maximum impact on the Cattail density. This is not seen as a major problem in short-term simulation periods as in Lagerwall et al. (2012), but it can become a major bias in longer term simulations as in Lagerwall et al. (2014) and here. For this reason, a Level 5 complexity model with its feed-back effect, despite its higher uncertainty, would be considered the most applicable model for management purposes due to its more realistic structure.

The initial results from this analysis are positive and confirm trends found in literature Newman et al. (1998) and Miao & Sklar (1998). It is a complex task to manage the

Cattail expansion in this region, requiring the close management and monitoring of water depth and soil phosphorus concentration, and possibly other factors not considered in these model complexities. However, this modeling framework with user-definable complexities and management scenarios, can be considered a useful tool in analyzing many more alternatives, which could be used to aid management decisions in the future.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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Authors' contributions GL conducted the majority of the research, Global Uncertainty and Sensitivity Analysis, and writing of the paper. GK provided ecological modeling expertise, general guidance, paper writing, and review contributions. RMC provided invaluable guidance with the statistics, running the distributed model on the high performance computing cluster, and ensured that the general logic of the paper was maintained. NW provided RSM and WCA2A expertise, supplied raw vegetation maps, and provided critical review on model design. All authors read and approved the final manuscript.

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