Baseline Soil Conditions in C-139 Flow Equalization Basin, Stormwater Treatment Area-1W Expansion #2, and A-2 Stormwater Treatment Area

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Prepared by
Odi Villapando and Ryan Goebel

Stormwater Treatment Section
Applied Sciences Bureau
South Florida Water Management District
3301 Gun Club Road
West Palm Beach, FL 33406

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ACRONYMS, ABBREVIATIONS, AND UNITS OF MEASUREMENT

°C	degrees Celsius
α	significance level
µg/L	microgram(s) per liter
A-2 STA	A-2 Stormwater Treatment Area
Al	aluminum
C	carbon
C-139 FEB	C-139 Flow Equalization Basin
Ca	calcium
CEPP	Central Everglades Planning Project
CERP	Comprehensive Everglades Restoration Plan
cfs	cubic foot (feet) per second
cm	centimeter(s)
CO_2	carbon dioxide
EAA	Everglades Agricultural Area
EAV	emergent aquatic vegetation
Exp	Expansion
Expansion #2	Stormwater Treatment Area 1W Expansion #2
Fe	iron
FEB	flow equalization basin
g P/m^2	gram(s) phosphorus per square meter
g/cm^3	gram(s) per cubic centimeter
g/kg	gram(s) per kilogram
g/m^2	gram(s) per square meter
GPS	global positioning system
ha	hectare(s)
ISP	initially stored phosphorus
K	potassium
kg/ac	kilogram(s) per acre
Max	Maximum
Mg	magnesium
mg/kg	milligram(s) per kilogram
Min	Minimum

N	nitrogen
P	phosphorus
PVC	polyvinyl chloride
S	sulfur
SAV	submerged aquatic vegetation
SEM	Standard Error around the Mean
SFWMD	South Florida Water Management District
STA	stormwater treatment area
t	metric ton(s)
TC	total carbon
TN	total nitrogen
TP	total phosphorus
WCA	Water Conservation Area
WQBEL	water quality-based effluent limit

INTRODUCTION

The Everglades Stormwater Treatment Areas (STAs) are a large network of constructed wetlands that are an integral component of the state and federal efforts to restore the Everglades ecosystem. They were constructed in over 25,000 hectares (ha) of south Florida lands to remove phosphorus (P) from stormwater runoff (Armstrong et al. 2023) primarily from the Everglades Agricultural Area (EAA), the C-51 W Basin, and the C-139 Basin, and when capacity exists, releases from Lake Okeechobee, before discharging south to the Everglades Protection Area (**Figure 1**). The Everglades STAs are a requirement of the Everglades Forever Act, which governs the state of Florida's obligation to achieve compliance with Everglades water quality standards. Because these STAs discharge to the Everglades and are mandated to meet the water quality-based effluent limit (WQBEL), it is imperative to monitor and evaluate their performance.

Soils play a crucial role in the ability of the STAs to remove and store P from runoff water in the short-term and long-term through various processes (Reddy and DeLaune 2008). Short-term storage involves initial sorption of P to soil particles and mineral surfaces, plant and microbial uptake, and particulate settling. Long-term storage occurs through the accumulation of organic matter and sediments, forming peat and soil layers that effectively sequester phosphorus. To evaluate the effect of soils on P removal performance of these constructed wetlands, baseline soil conditions prior to operation should be properly documented. Baseline data serves as a historical record against which changes in physical, chemical, and biological function of an STA can be measured. Understanding the initial conditions of the soils for new facilities (STAs and flow equalization basins [FEBs]) is essential for evaluating changes in treatment performance and for designing effective remediation plans needed to help improve performance.

OBJECTIVES

The overall goal of this soil sampling and characterization effort was to document the baseline soil conditions in three new facilities: C-139 FEB, STA-1W Expansion #2, and A-2 STA (**Figure 1**) prior to inundation to use as reference for future sampling efforts should we need to explain their treatment performance over time. Our specific objectives were to (1) determine the basic physical and chemical properties of the soils in each treatment facility; (2) measure the spatial distribution of major nutrients namely, carbon (C), nitrogen (N), and P in the soils; (4) estimate the initial amount of P stored in the soils; and (4) provide insights into the short-term and long-term P storage capacities of each facility based on their initial soil characteristics.

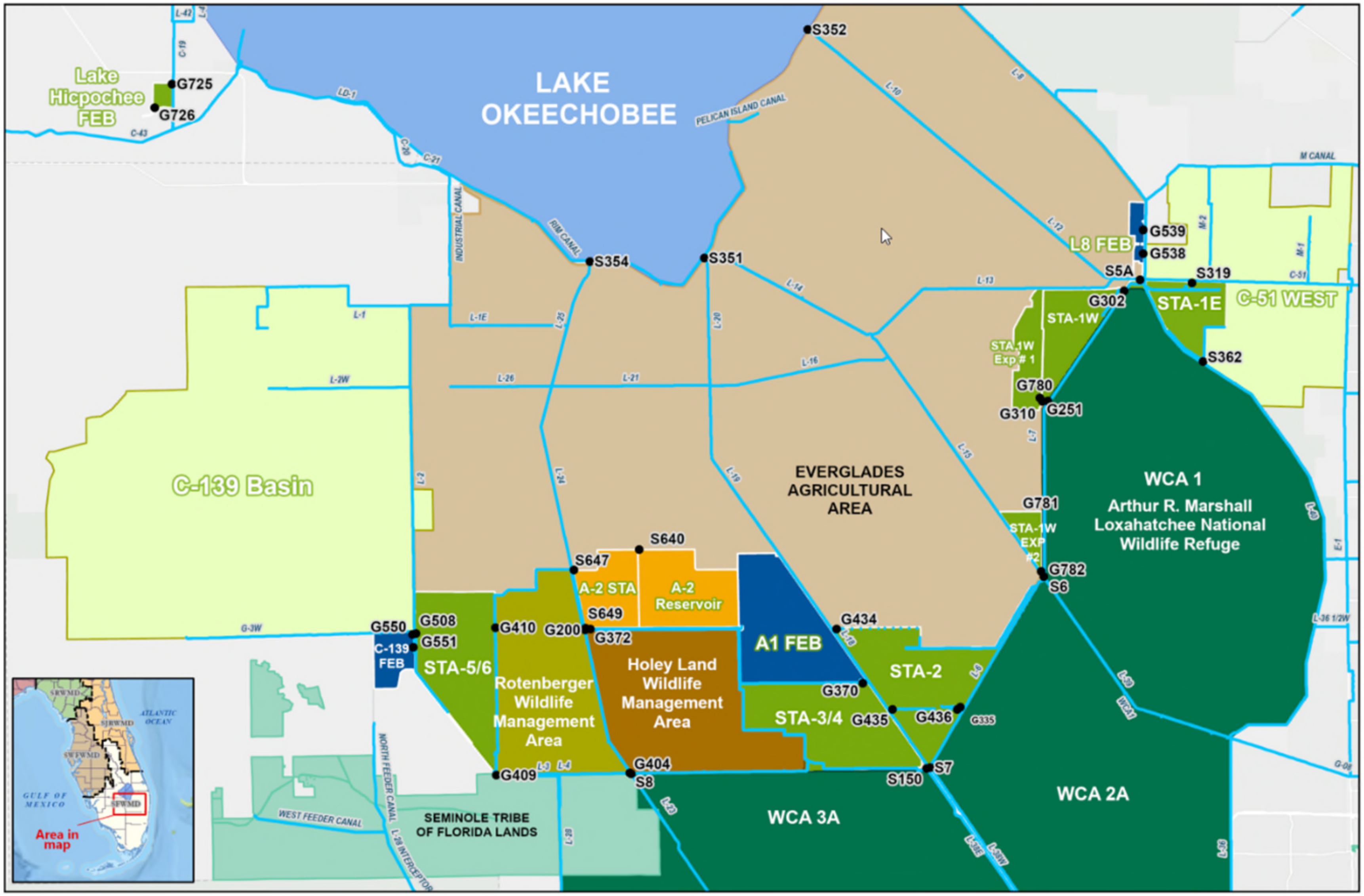

Figure 1. Locations of the Everglades STAs, A-2 STA, and FEBs in relation to Lake Okeechobee and Water Conservation Areas (WCAs) in south Florida. (Note: EXP – Expansion.)

MATERIALS AND METHODS

PROJECT SITES

C-139 FEB

The C-139 Flow Equalization Basin (C-139 FEB) is located south of the Deer Fence Canal and west of STA-5/6 Flow-ways 3 and 4 in south-central Hendry County. It is a 2,800-acre shallow impoundment designed to store approximately 11,000 acre-feet of water at a maximum operating depth of four feet (**Figure 2**). The C-139 FEB will capture and store stormwater runoff primarily from the C-139 Basin, which subsequently will be sent to STA-5/6 at steady rates to optimize performance and help achieve the WQBEL. The project includes a 690-cubic feet per second (cfs) pump station (G-550), and a gated outflow structure (G-551) located on the eastern levee. The inflow pump station brings water from the Deer Fence Canal (L-3 Canal), and discharges it directly into the C-139 FEB. The outflow structure sends water from the FEB to STA-5/6 through the L-3 Canal. The C-139 FEB will also be used to assist in maintaining minimum water levels to reduce the frequency of dry-out conditions within STA-5/6, which will help improve and sustain outflow TP concentrations that meet the WQBEL. Construction of the C-139 FEB was completed in 2024.

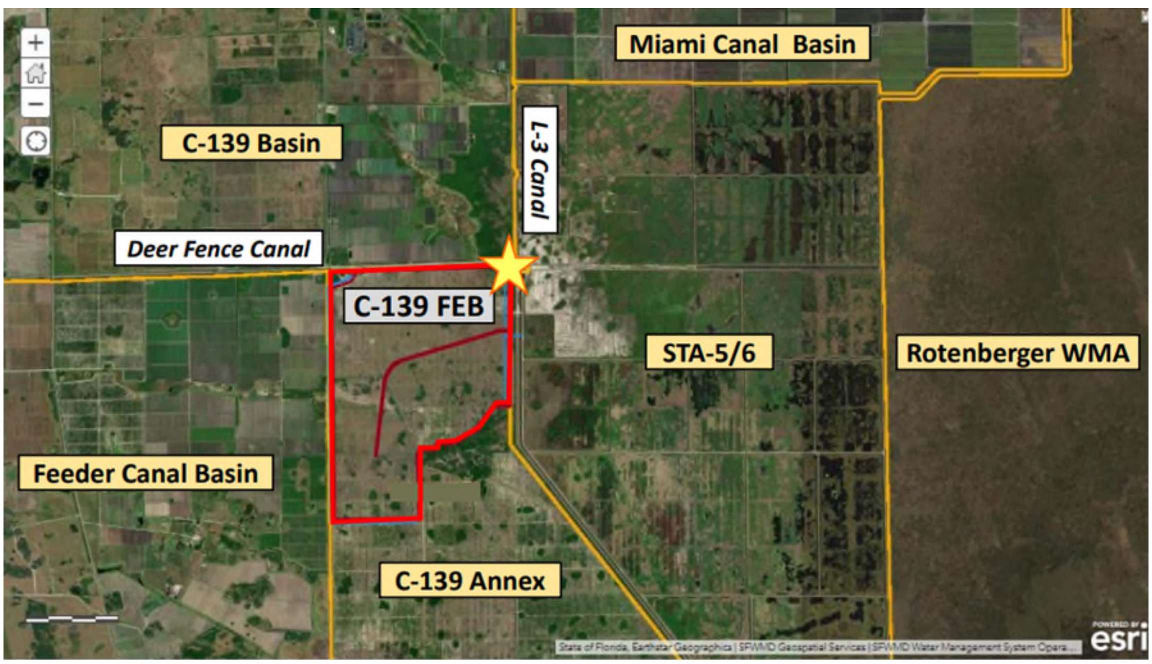

Figure 2. Location of C-139 FEB in relation to STA-5/6 and the surrounding basins. (Note: WMA – Wildlife Management Area.)

STA-1W Expansion #2

STA-1W Expansion #2 (Expansion #2) is located within Palm Beach County immediately west of the Arthur R. Marshall Loxahatchee National Wildlife Refuge or Water Conservation Area (WCA) 1 (**Figure 3**). Expansion #2 is a component of the Restoration Strategies projects identified to work in conjunction with the existing Everglades STAs to meet the WQBEL. This project provides an additional 1,867 acres of effective treatment area within 2,185 acres of land located north of pump station S-6. The landscape within the limits of Expansion #2 consists of an unfarmed remnant Everglades wetland (Snail Farm), and a previously farmed area known as the Sunset Farm (SFWMD 2020). This project contains two 500-cfs inflow pump stations (G-780 and G-781) and one 625-cfs outflow pump station (G-782). A concrete lined canal parallel to the L-7 Canal provides hydraulic connection between the existing STA-1W and Expansion #2. This Expansion #2 receives pre-treated water from STA-1W and uses emergent aquatic vegetation (EAV) and submerged aquatic vegetation (SAV) similar to existing EAV/SAV cells within STA-1W to remove P. This project was fully constructed in 2024.

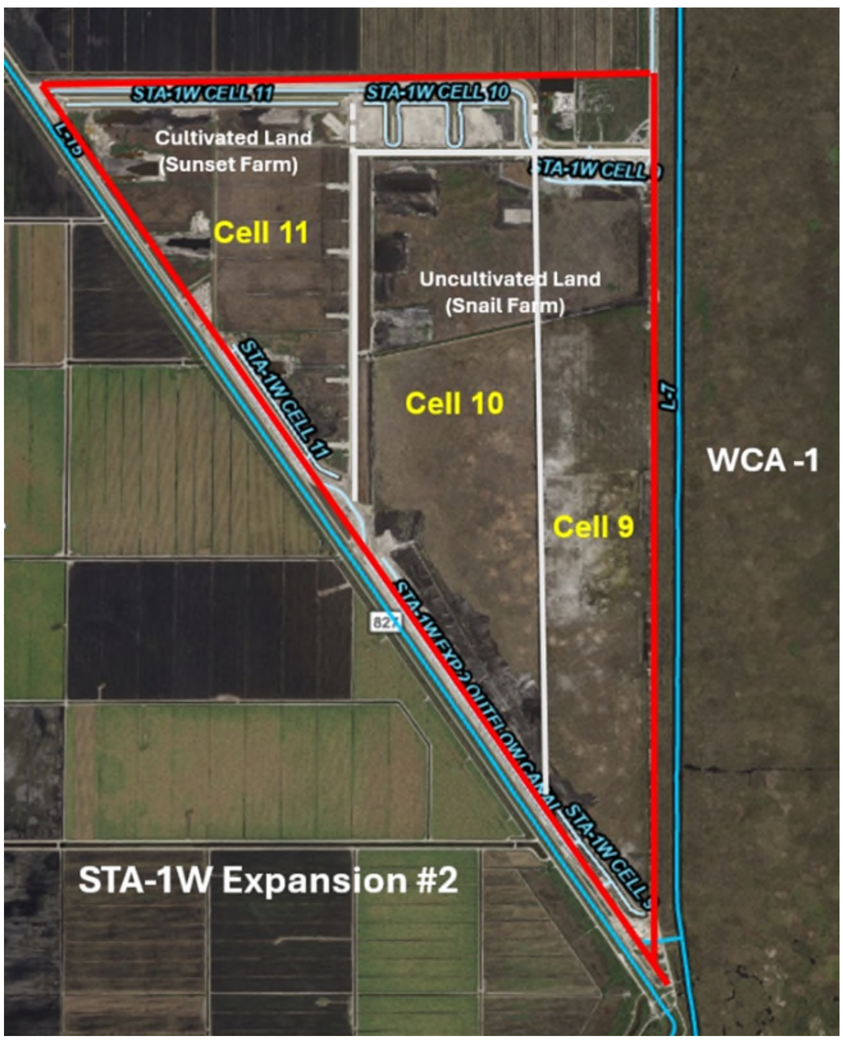

Figure 3. Location of STA-1W Expansion #2 in Palm Beach County.

A-2 STA

The A-2 Stormwater Treatment Area (A-2 STA) is located between the North New River and Miami Canal in southern Palm Beach County immediately west of the A-2 Reservoir and A-1 FEB (**Figure 4**). It is part of the Central Everglades Planning Project (CEPP) and the larger Comprehensive Everglades Restoration Plan (CERP). It is a 6,500-acre treatment wetland that will treat runoff water primarily from the Miami Canal, and from the A-2 Reservoir once operational. The A-2 Reservoir and STA will help improve the quantity, quality, timing, and distribution of water flows to the central Everglades, WCA-3A, and Everglades National Park. A-2 STA construction included the creation of inflow, outflow, and seepage canals, as well as a 3,000-cfs spillway (S-647), pump stations (S-648 and S-640), a discharge structure (S-649), and multiple gated culverts. This project also must meet the WQBEL. Construction of A-2 STA was substantially completed in 2024.

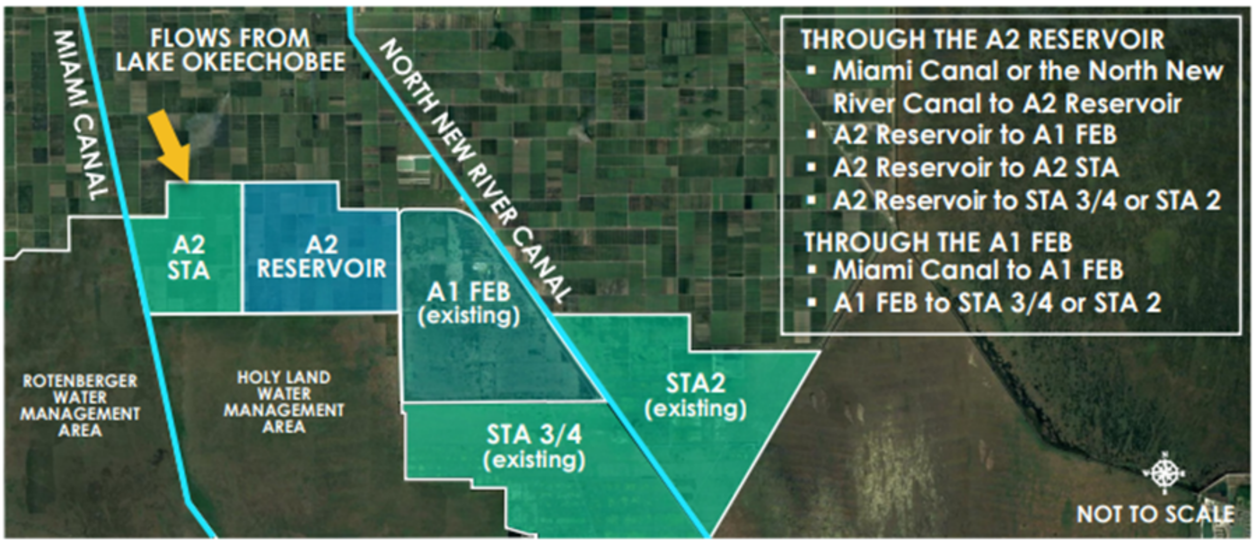

Figure 4. Location of A-2 STA in Palm Beach County.

SOIL SAMPLING AND ANALYSIS

The centroid of a 100-acre x 100-acre georeferenced grid system was used to establish sampling sites. This technique ensures that the sampling sites were equally spaced. Thirty, 18, and 66 sampling sites were established within C-139 FEB, STA-1W Expansion #2, and A-2 STA, respectively (**Figure 5**). The latitude and longitude coordinates associated with each sampling site were used to navigate to each location in the field using a global positioning satellite (GPS)-enabled device. Samples were collected between December 2023 and May 2024 and followed the procedures and requirements detailed in the *Standard Operating Procedure for Field Soil Sampling (Push Core)* (SFWMD RSSP-FLD-SOP-00005-02). A 5-centimeter (cm) diameter stainless steel corer (with a retaining plastic cylinder) was driven into the soil profile to collect intact soil cores. The cores were transported on ice in coolers to a cold room at the S5A Laboratory where they were later sectioned into 0-10 cm and 10-30 cm depth increments and qualitatively described for color, texture, and presence of nonsoil materials. Samples were cleaned of any vegetative parts, rocks, and shells and then sent to the South Florida Water Management District (SFWMD) Laboratory for analyses. All analyses done at the laboratory were performed according to standard methods outlined in the *Chemistry Laboratory Quality Manual* (SFWMD 2023). Bulk density was measured using the core method, by collecting a known volume of soil using a polyvinyl chloride (PVC) ring pressed into the soil and determining the weight after drying (Blake 1965). Bulk density in grams per cubic centimeter (g/cm^3) is calculated by dividing the mass of solids by the volume of soil.

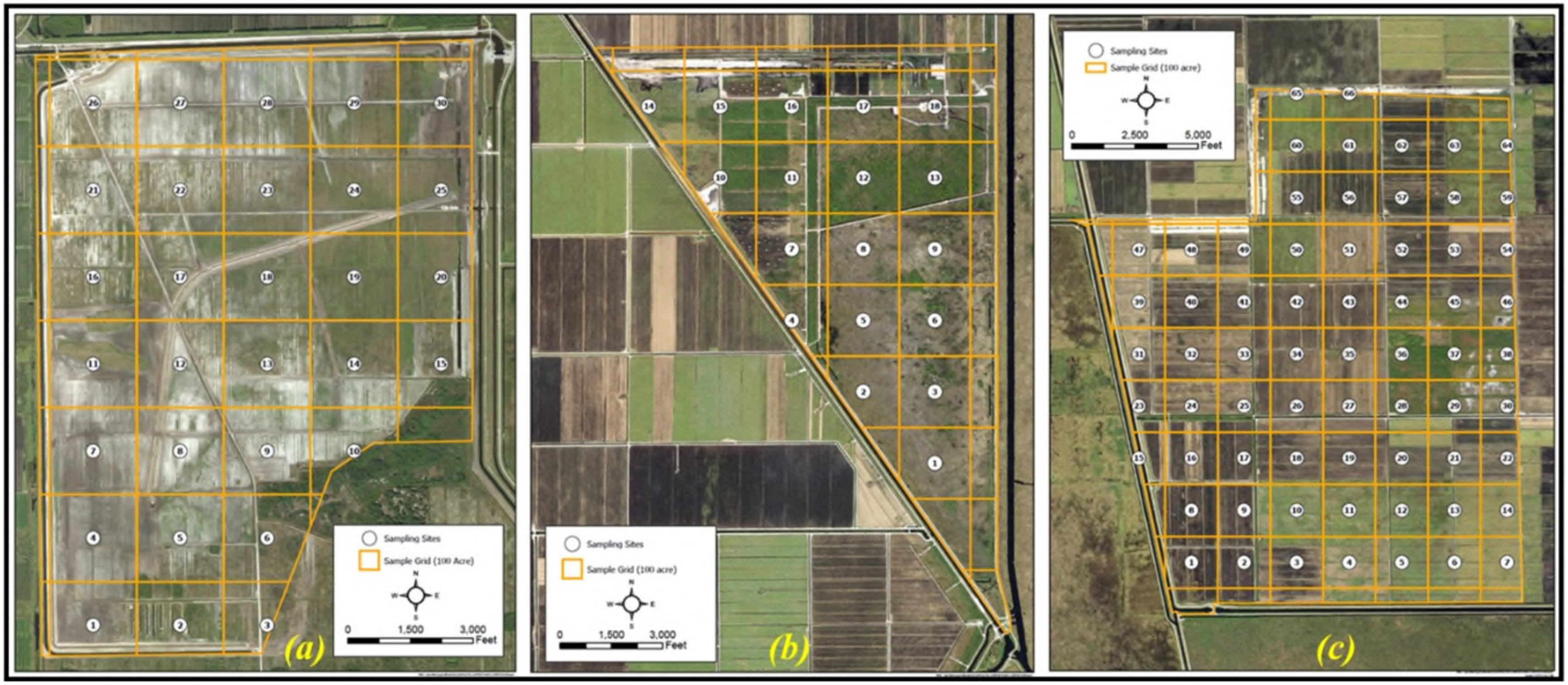

Figure 5. Soil sampling stations in (a) C-139 FEB, (b) STA-1W Expansion #2, and (c) A-2 STA established using georeferenced grid system.

Soil pH was measured from a 1:2 soil to water ratio, where one part of soil is mixed with 2 parts of reagent grade water (SFWMD-LAB-SOP-1640-003). The ash content of the soils was determined by ignition to a constant weight at 550 ± 50 degrees Celsius (° C). The weight of the residue after ignition divided by the fresh weight of the sample is the ash content (SFWMD-LAB-SOP-1620-002), which was converted to percent organic matter by subtracting percent ash content from one hundred (ASTM 2007). Total phosphorus (TP) was measured by first subjecting the sample to dry ashing procedure to convert all organic phosphates to inorganic phosphates, followed by hot acid extraction to extract and convert inorganic phosphates into reactive phosphate, and then measuring the released phosphate colorimetrically (SFWMD-LAB-SOP-3210-002). Total carbon (TC) and total nitrogen (TN) were measured by the dry combustion method, which involves oxidizing the sample in a high temperature environment, converting carbon to carbon dioxide (CO_2) and nitrogen to nitrogen oxides, which are then measured by Fisher Flash 2000 Combustion NC Soil Analyzer (SFWMD-LAB-SOP-3200-002). The analysis of sulfur (S), calcium (Ca), magnesium (Mg), potassium (K), iron (Fe), and aluminum (Al) in the soils was done by digesting a dry sample in nitric acid and hydrogen peroxide, followed by additional reflux with hydrochloric acid. The concentration of each element in the extract was then measured by Inductively Coupled Plasma Spectroscopy (SFWMD-LAB-SOP-2220-004).

INITIALLY STORED PHOSPHORUS

The amount of initially stored P (ISP) in the top 30 cm of the soils was estimated using **Equation 1**:

$$ISP = \frac{TP \times BD \times d}{100} \quad \textbf{(1)}$$

where TP is the concentration of phosphorus in the soil in milligrams per kilogram (mg/kg), BD is the soil bulk density in grams per cubic centimeter (g/cm^3), and d is the soil depth in centimeters (cm), 10 and 20 cm for 0-10 and 10-30 cm sampling depths, respectively.

DATA ANALYSIS

Prior to analysis, raw data were screened for outliers. Measurement values greater than the 99th percentile for a given site and soil depth were identified as outliers and removed from further statistical analysis (Julian and Hill 2012). The screening identified 79 outliers out of 2,736 data points collected across twelve parameters, three project sites, and two sample depths.

Summary statistics were generated for each analyte, by soil depth and project site. As virtually all data sets deviated from normality, significant differences between soil depths (0-10 cm vs. 10-30 cm) were established using Kruskal Wallis/Wilcoxon's test, a non-parametric pairwise comparison procedure based on rank sums. All statistical analyses were done using JMP® Software 17 (JMP 2025).

Spatial maps of the major nutrients C, N, and P were generated using ArcGIS Pro (ESRI 2024) to examine their distribution across space within each project site. The maps were created using kriging, a method of geostatistical interpolation that assumes spatial correlation between sample points to predict values at unmeasured locations. The spatial maps were created by estimating values based on the spatial structure of the data, incorporating the concept that proximity implies similarity. The kriging results were converted to a raster to cover the area of analysis and symbolized using 10 equal intervals.

RESULTS AND DISCUSSION

SOIL DESCRIPTIONS

C-139 FEB

The soils in south-central Hendry County belong to Immokalee-Basinger-Myakka Association (Soil Survey Staff 1991). These soils predominantly belong to the Spodosol soil order, which is characterized by sandy textures, high infiltration rates, and poor internal drainage due to low permeability of the spodic horizon, also referred to as a “hardpan”, typically found within one meter of the surface. P retention capacities are generally very low for the surface and subsurface horizons but high for the spodic horizon that is rich in organic matter complexed with Fe and Al (Villapando 2001). Minor soils in the area belong to Malabar, Holopaw, Riviera, Pineda, Delray, and Chobee soil series (Soil Survey Staff 1991). While native or improved pasture accounts for the majority of land use in the Immokalee-Basinger-Myakka association, the C-139 FEB was formerly a citrus grove.

The soils inside the C-139 FEB generally consist of dark to very dark gray fine sands in the surface layer and light gray to dark brown sands in the subsurface layer. The soils have a weak fine granular structure and are friable. Many fine to medium roots and rhizomes are present in the majority of samples (**Figure 6**).

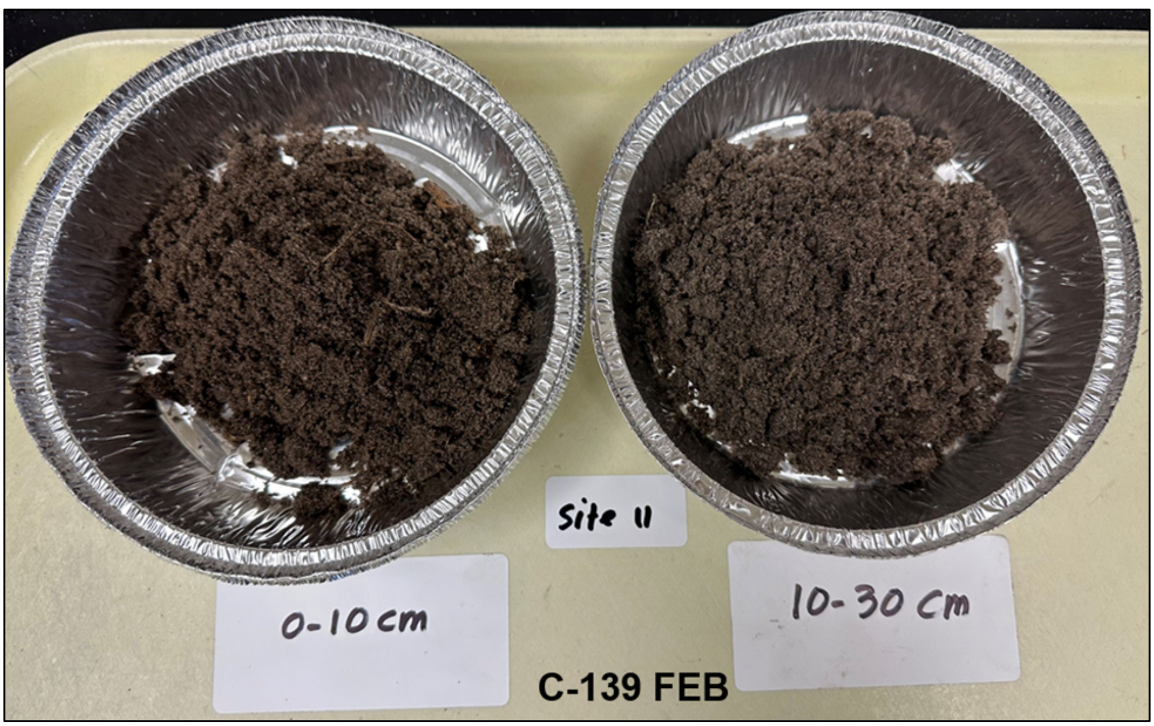

Figure 6. General appearance of representative soils collected in C-139 FEB.

STA-1W Expansion #2

The surface soil of STA-1W Expansion #2 is predominantly muck, which is typical of Histosols in the EAA. The soil profile also includes peat and marl below the muck layer. These soils belong to Terra Ceia muck, Pahokee muck, and Torry muck series that are nearly level, very poorly drained organic soils used mainly for growing sugarcane. Other soils within the EAA basin include Dania muck, Lauderhill muck, and Okeechobee muck (Soil Survey Staff 1978). Expansion #2 was partially built on undeveloped agricultural property. Portions of the project were used for sugarcane production (Cell 11) where farming stopped in 2017. A large portion of the property (Cells 9 and 10) consisted of freshwater marsh (**Figure 3**).

The soil in the top 10-cm layer within the limits of Expansion #2 consists of black muck with moderate medium granular structure, friable, and with some shell and rock fragments and fine roots. The soil in the bottom 10-30 cm layer is very dark brown muck with moderate medium structure, also friable, and with larger rock fragments and fine roots throughout (**Figure 7**). The cores were moist due to wet conditions during sampling.

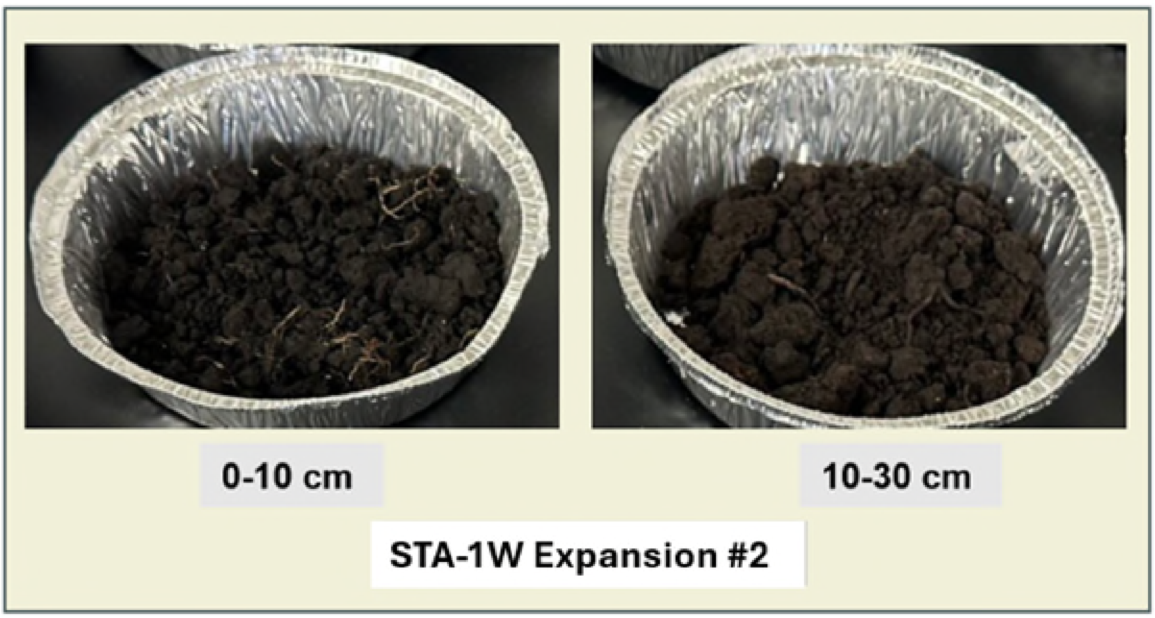

Figure 7. General appearance of representative soils within STA-1W Expansion #2.

A-2 STA

The soils in A-2 STA are similar to the organic soils (Histosols) in STA-1W Expansion #2. They are characterized by a very dark color, often black or dark brown, due to the high content of decomposed organic material and are poorly drained. The main soil series within the EAA are Torry muck, Terra Ceia muck, Pahokee muck, Lauderhill muck, Dania muck, and Okeechobee muck (Soil Survey Staff 1978). The A-2 STA was formerly a sugarcane field.

Soils within the A-2 STA footprint consist of black material, rich in organic matter with medium to coarse fragments of calcitic material and some roots in the top 10 cm and are friable. The soils within the 10-30 cm depth are predominantly organic, very dark brown in color, and with calcitic clay material and limestone fragments (**Figure 8**).

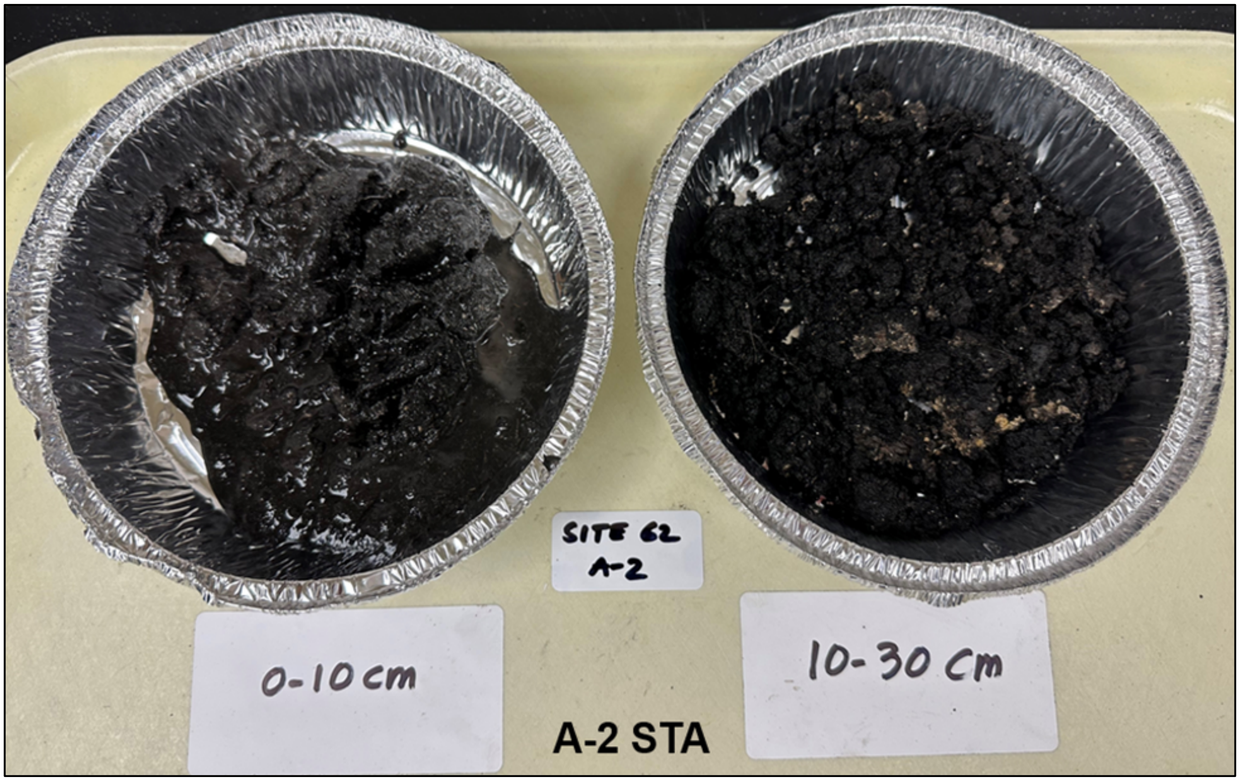

Figure 8. General appearance of representative soils collected in A-2 STA.

SOIL PHYSICO-CHEMICAL CHARACTERISTICS

C-139 FEB

The soils inside the FEB are sandy mineral soils, with low organic matter content and therefore, low capacity to retain nutrients especially in the surface layer. Soil pH varied from very acidic to slightly basic with a mean pH of 6.26 and 6.13 in the 0-10 and 10-30 cm soil depths, respectively (**Table 1**). Organic matter content was low with mean values of 1.62 and 1.65% in the top and underlying soil, respectively. The high bulk densities (>1.50 g/cm^3, mean) indicate the highly mineral nature of the soils. The elemental concentrations of macronutrients (C, N, P, and S) and metals (Ca, Mg, Al, Fe, and K) are generally low and are typical of concentrations found in mineral soils. Nutrient and metal concentrations are consistently slightly higher in the surface than in the subsurface soil. The differences in median values, however, are not significant between sampling depths (**Table 1**).

Table 1. Comparison of physico-chemical properties of the soils in the surface (0-10 cm) and subsurface (10-30 cm) soil layers of the C-139 FEB. Minimum (Min) and Maximum (Max) are the lowest and highest observed values, respectively. Mean is the average value and SEM is the standard error around the mean. Median is the middle value in the data set, the basis of non-parametric Wilcoxon's pairwise comparisons. For a given parameter, median values for 0-10 cm and 10-30 cm depth increments with the same letter are not significantly different at significant factor (α) = 0.05.

Parameter	Unit	0–10 cm				10–30 cm			
		Min	Max	Mean ± SEM	Median	Min	Max	Mean ± SEM	Median
pH		4.22	7.27	6.26 ± 0.12	6.38 ***a***	4.02	7.63	6.13 ± 0.14	6.20 ***a***
Bulk Density	g/cm^3	1.11	1.65	1.51 ± 0.02	1.55 ***b***	1.29	1.69	1.58 ± 0.02	1.60 ***a***
Organic Matter	%	0.20	8.60	1.62 ± 0.29	1.20 ***a***	0.20	9.60	1.65 ± 0.33	1.20 ***a***
Total P	mg/kg	20	344	69 ± 12	52 ***a***	20	145	56 ± 6	52 ***a***
Total N	%	0.32	0.62	0.47 ± 0.02	0.47 ***a***	0.33	0.60	0.46 ± 0.02	0.47 ***a***
Total C	%	0.36	1.81	0.79 ± 0.06	0.70 ***a***	0.33	1.85	0.75 ± 0.08	0.58 ***a***
Total S	mg/kg	93	118	102 ± 1	99 ***a***	93	134	102 ± 2	99 ***a***
Total Ca	mg/kg	138	1,634	498 ± 75	365 ***a***	121	1,488	427 ± 69	251 ***a***
Total Mg	mg/kg	93	118	102 ± 1	100 ***a***	93	112	100 ± 1	99 ***a***
Total K	mg/kg	56	70	61 ± 1	59 ***a***	56	71	60 ± 1	60 ***a***
Total Fe	mg/kg	62	564	149 ± 21	117 ***a***	38	398	123 ± 15	104 ***a***
Total Al	mg/kg	83	2,770	575 ± 117	259 ***a***	38	3,429	524 ± 144	252 ***a***

TP concentrations in the FEB ranged from 20 to 344 mg/kg and from 20 to 145 mg/kg in the 0-10 cm and 10-30 cm soil depths, respectively (**Table 1**). These values are distributed similarly across the FEB with higher concentrations observed in the southern section of the FEB for both soil depths (**Figure 9**). Mean TP values of 69 mg/kg in the upper 10 cm of the soil and 56 mg/kg in the 10-30 cm soil depth are much lower compared to the average concentration of P in mineral soils that is typically around 500 to 800 mg/kg of dry soil with most surface soils containing a TP content averaging around 600 mg/kg (He et al. 2021).

TC content in the soil was generally low throughout most of the FEB with majority of the values falling in the low range of < 7.9 grams per kilogram (g/kg) for both soil depths (**Figure 10**). The isolated pockets of C containing material (16.5 to 17.8 g/kg) in the northwestern portion of the FEB are consistent with the very dark gray/brown color of soils in this area and are indicative of wetter areas in the FEB where organic matter decomposes at slower rates.

TN concentrations in the FEB ranged from 0.32 to 0.62% (3.2 to 6.2 g/kg) in the surface layer and from 0.33 to 0.60% (3.3 to 6.0 g/kg) in the subsurface layer. While the TN values are similar for both soil depths, their spatial distribution across the FEB is different. TN concentrations are somewhat evenly distributed in the top 10 cm with slightly higher TN concentrations along the eastern side of the FEB. The distribution of TN concentrations in the 10-30 cm is not even or consistent, with areas of high and low concentrations (**Figure 11**).

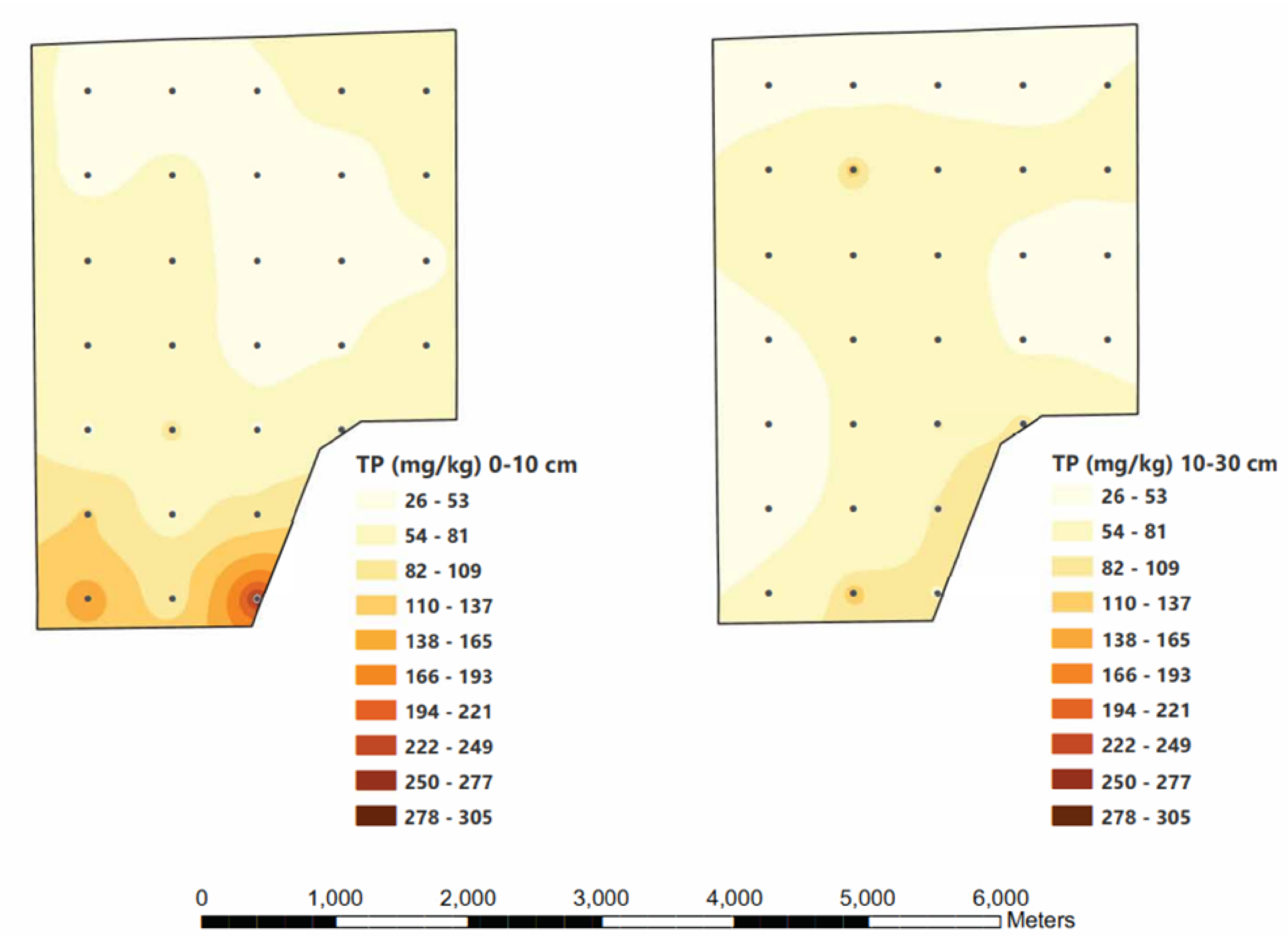

Figure 9. Spatial distribution of TP concentrations in the 0-10 and 10-30 cm soil layers within the C-139 FEB. The dots on the map represent sampling locations.

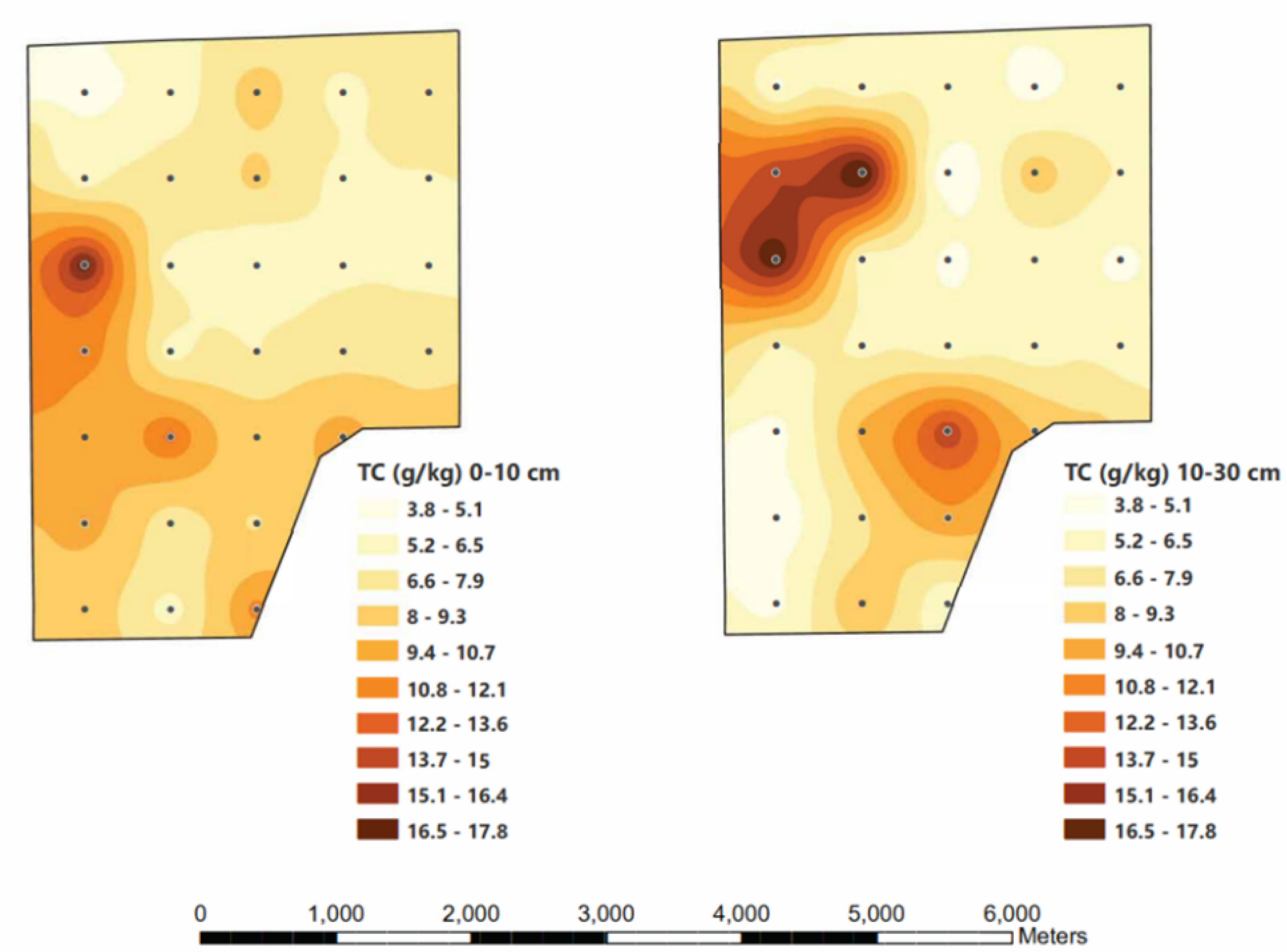

Figure 10. Spatial distribution of TC concentrations in the 0-10 and 10-30 cm soil layers within the C-139 FEB. The dots on the map represent sampling locations.

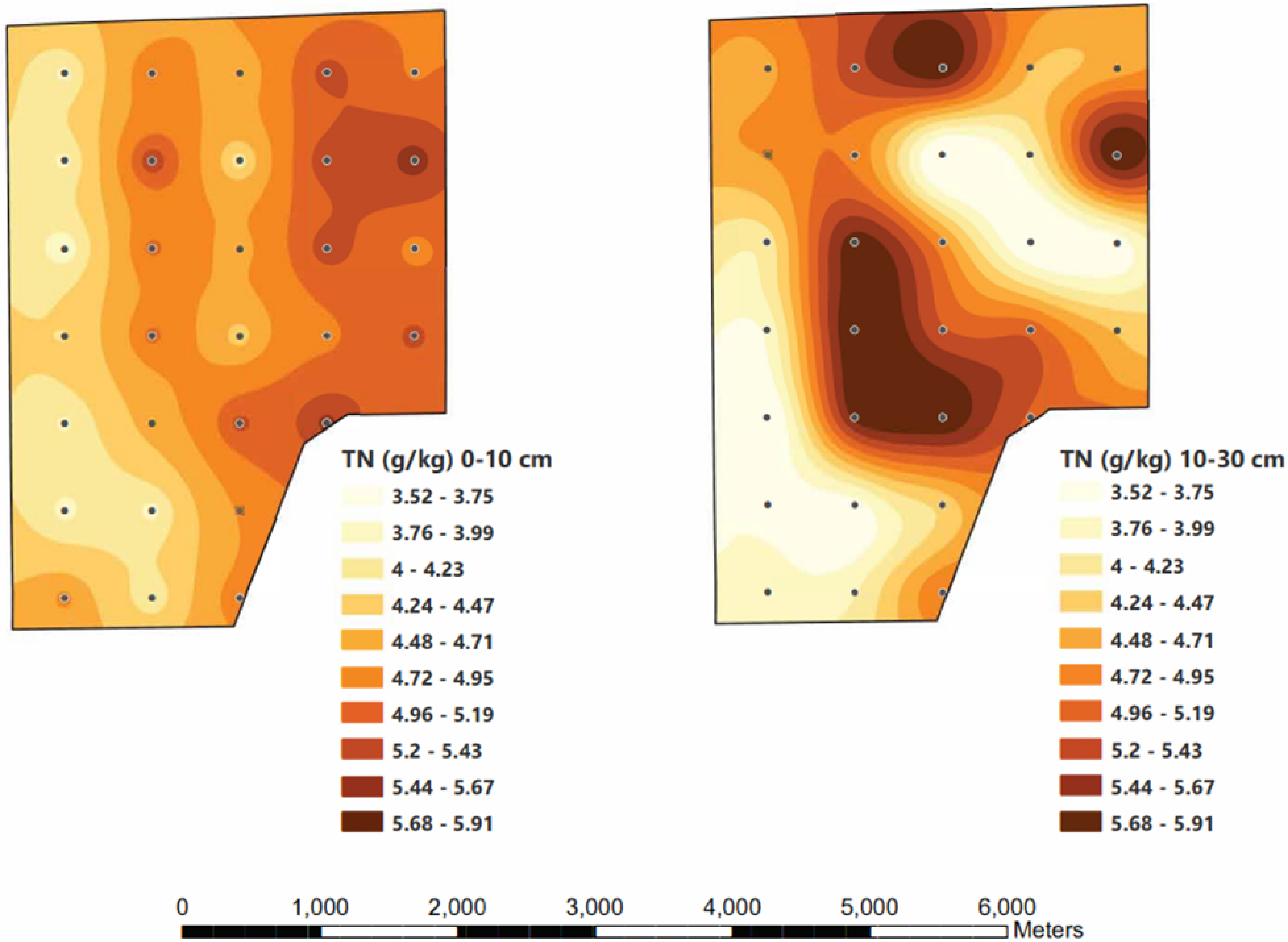

Figure 10. Spatial distribution of TN concentrations in the 0-10 and 10-30 cm soil layers within the C-139 FEB. The dots on the map represent sampling locations.

STA-1W Expansion #2

The organic soils of STA-1W Expansion #2 belong to Histosols soil order, which are characterized by high pH, high organic matter content, and low bulk density. Soil pH ranged from 7.23 to 7.88 (mean of 7.65) in the top 10 cm and from 6.91 to 7.82 (mean of 7.47) in the 10-30 cm depth (**Table 2**). While some Florida soils are acidic, the organic soils in South Florida can have a high pH due to the influence of underlying calcareous bedrock. On average, organic matter accounted for 74 and 80% of the soils in 0-10 cm and 10-30 cm depth, respectively. Due to high proportion of organic matter, the soils in Expansion #2 have low bulk densities, averaging 0.41 g/cm^3 in the 0-10 cm depth and 0.35 g/cm^3 in the 10-30 cm depth.

TP concentrations in the soils vary widely, from 224 to 944 mg/kg in the 0-10 cm depth and from 186 to 703 mg/kg in the 10-30 cm depth. The spatial distribution of TP concentrations is consistent with the natural landscape within the limits of Expansion #2. In the previously farmed area known as the Sunset Farm, TP concentrations in the top 10 cm are much higher compared to TP concentrations across the area represented by unfarmed remnant Everglades (**Figures 3** and **12**). TP concentrations in the 10-30 cm are lower and are distributed similarly as TP concentrations in the surface layer. Mean TP values of 538 and 331 mg/kg in the surface and subsurface soil layers, respectively are lower than 750 to 1,000 mg P/kg reported for soils in the EAA (McCray et al. 2019).

TC content, which is predominantly organic ranged from 29 to 50% (290 to 500 g/kg) in the topsoil and from 27 to 53% (270 to 530 g/kg) in the subsoil with respective mean values of 42% (420 g/kg) and 45% (450 g/kg). Organic soils in south Florida typically contain a high percentage of organic C, with some areas reaching levels over 50%. The distribution of TP data over space is somewhat patchy, with areas of high concentrations in the section of Expansion #2 that was unfarmed compared to slightly lower concentrations across the section of Expansion #2 that was previously farmed (**Figure 13**). Farming can disrupt soil structure, exposing previously protected organic matter to decomposition and oxidation, releasing C into the atmosphere as CO_2. The spatial distributions of TC in the soils are similar for both the topsoil and subsoil.

The ranges of TN concentrations in the soils are similar for both depths and are within the average 2 to 4% (20 to 40 g/kg) TN reported for similar soils in the EAA (McCray et al. 2019). The distribution patterns of TN data are strikingly similar to how TC data were distributed in both the topsoil and subsoil (**Figure 14**). In wetland soils, there is a generally positive correlation between C and N (Villa et al. 2023). This means that as the amount of C in the soil increases, the amount of N also tends to increase, and vice versa. This relationship is influenced by various factors such as wetland type, soil depth, and plant and microbial activity.

Similarly, S concentrations are high, averaging 4,524 mg/kg in the surface and 4,375 mg/kg in the subsurface layer. These high concentrations are attributed to agricultural S use and the oxidation of organic soils in the EAA (McCray et al. 2019). Ca and Mg are the most abundant metallic cations in the soils since these soils were derived from calcium carbonate-rich materials, that are dominated by minerals like calcite, a major component of marl soils. Ca content ranged from 40 to 147 g/kg and from 35 to 137 mg/kg in the 0-10 and 10-30 cm depths, respectively. Median Ca content is higher in the 0-10 cm depth than in 10-30 cm depth, but the difference is not significantly different. Mg content averaged 5.3 g/kg in the 0-10 cm depth, which is slightly higher than mean Mg content of almost 5 g/kg in the 10-30 cm depth. Relative to Ca and Mg contents, Fe, Al, and K contents were lower for both soil depths.

Table 2. Comparison of physico-chemical properties of the soils in the surface (0-10 cm) and subsurface (10-30 cm) soil layers in STA-1W Expansion #2. Minimum (Min) and Maximum (Max) are the lowest and highest observed values, respectively. Mean is the average value and SEM is the standard error around the mean. Median is the middle value in the data set, the basis of non-parametric Wilcoxon's pairwise comparisons. For a given parameter, median values for 0-10 cm and 10-30 cm depth increments with the same letter are not significantly different at a significance level (α) = 0.05.

Parameter	Unit	0-10 cm				10-30 cm			
		Min	Max	Mean ± SEM	Median	Min	Max	Mean ± SEM	Median
pH		7.23	7.88	7.65 ± 0.05	7.71 ***a***	6.91	7.82	7.47 ± 0.07	7.51 ***a***
Bulk Density	g/cm^3	0.15	0.68	0.41 ± 0.04	0.37 ***a***	0.12	0.75	0.35 ± 0.05	0.35 ***a***
Organic Matter	%	46	86	74 ± 3	79 ***b***	48	89	80 ± 3	85 ***a***
Total P	mg/kg	224	944	538 ± 58	541 ***a***	186	703	331 ± 32	301 ***b***
Total N	%	1.30	3.11	2.45 ± 0.15	2.64 ***a***	1.23	2.99	2.48 ± 0.14	2.75 ***a***
Total C	%	29	50	42 ± 2	46 ***a***	27	53	45±2	49 ***a***
Total S	mg/kg	3,104	6,735	4,524 ± 255	4,726 ***a***	2,857	5,682	4,374±211	4,426 ***a***
Total Ca	mg/kg	40,138	147,446	71,795 ± 8,085	57,348 ***a***	34,977	136,571	65,618 ± 8,490	50,019 ***a***
Total Mg	mg/kg	2,741	10,099	5,257 ± 506	4,399 ***a***	3,159	10,074	4,986 ± 519	4,341 ***a***
Total K	mg/kg	176	674	382 ± 36	361 ***a***	139	724	336 ± 46	251 ***a***
Total Fe	mg/kg	1,434	5,010	2,950 ± 254	2,863 ***a***	1,097	5,135	2,665 ± 324	2,088 ***a***
Total Al	mg/kg	1,322	6,557	3,372 ± 380	2,785 ***a***	911	7,358	3,055 ± 510	2,292 ***a***

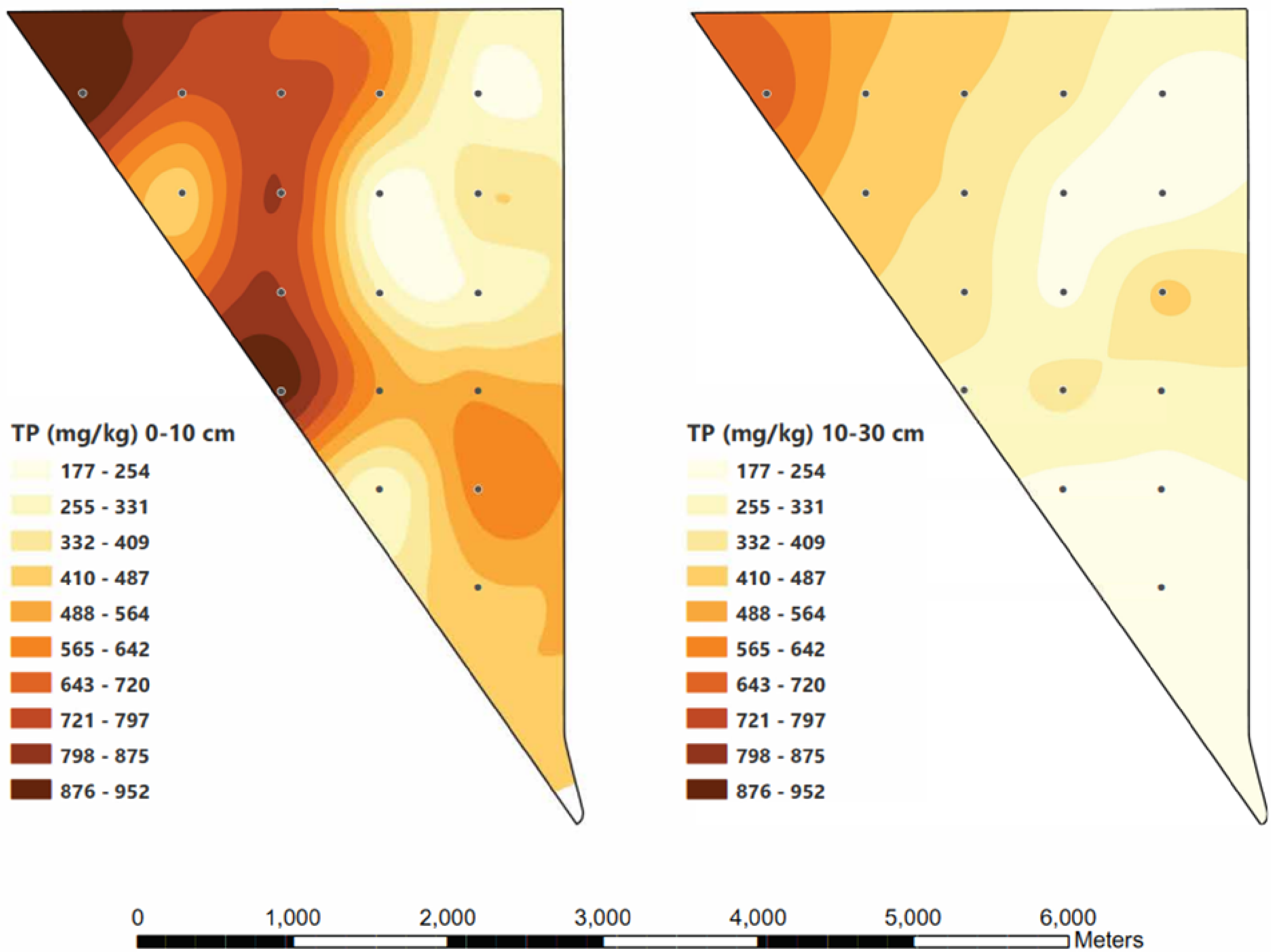

Figure 11. Spatial distribution of TP in the 0-10 cm and 10-30 cm soil layers in STA-1W Expansion #2. The dots on the map represent sampling locations.

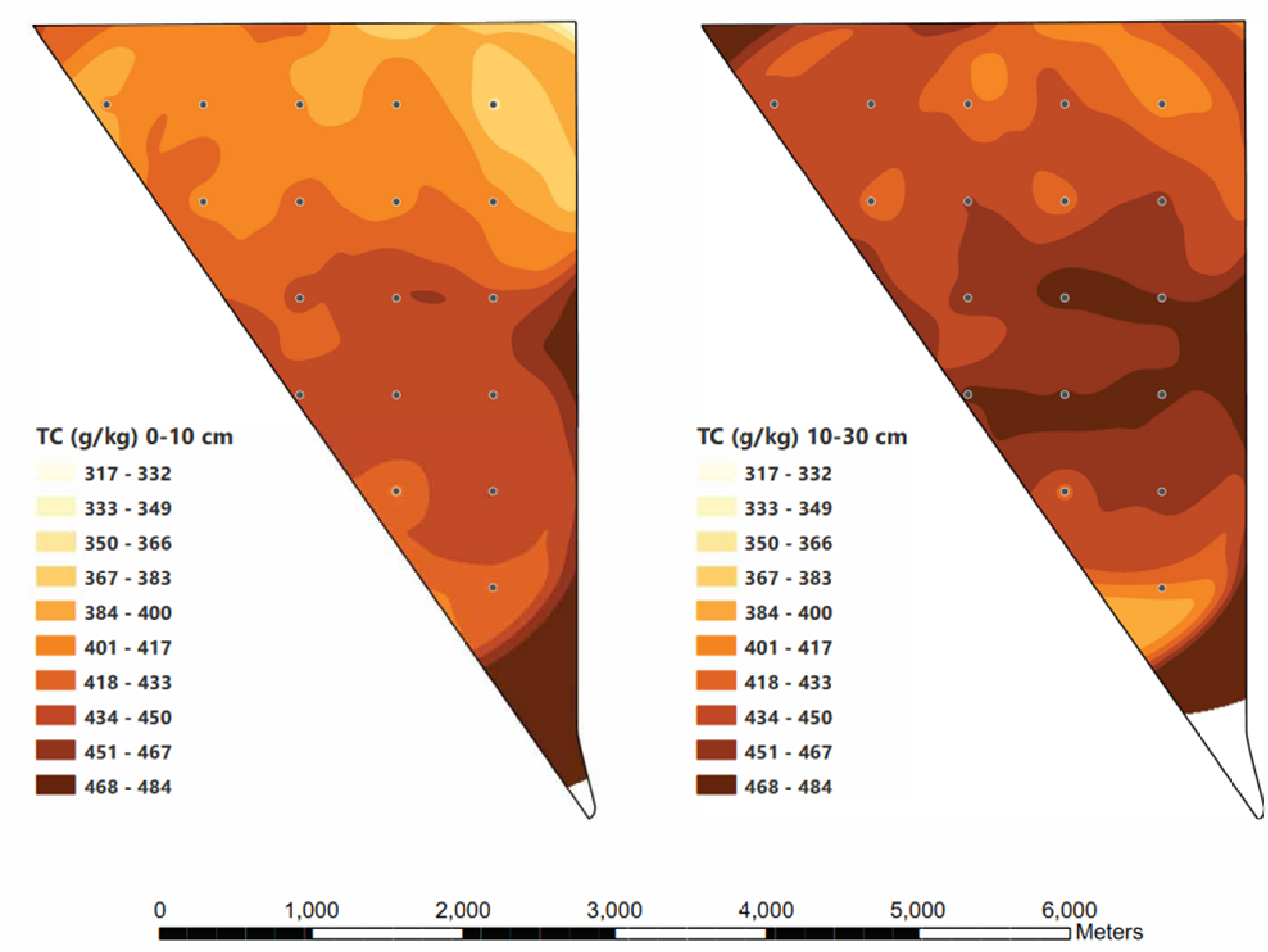

Figure 12. Spatial distribution of TC concentrations in the 0-10 cm and 10-30 cm soil layers in STA-1W Expansion #2. The dots on the map represent sampling locations.

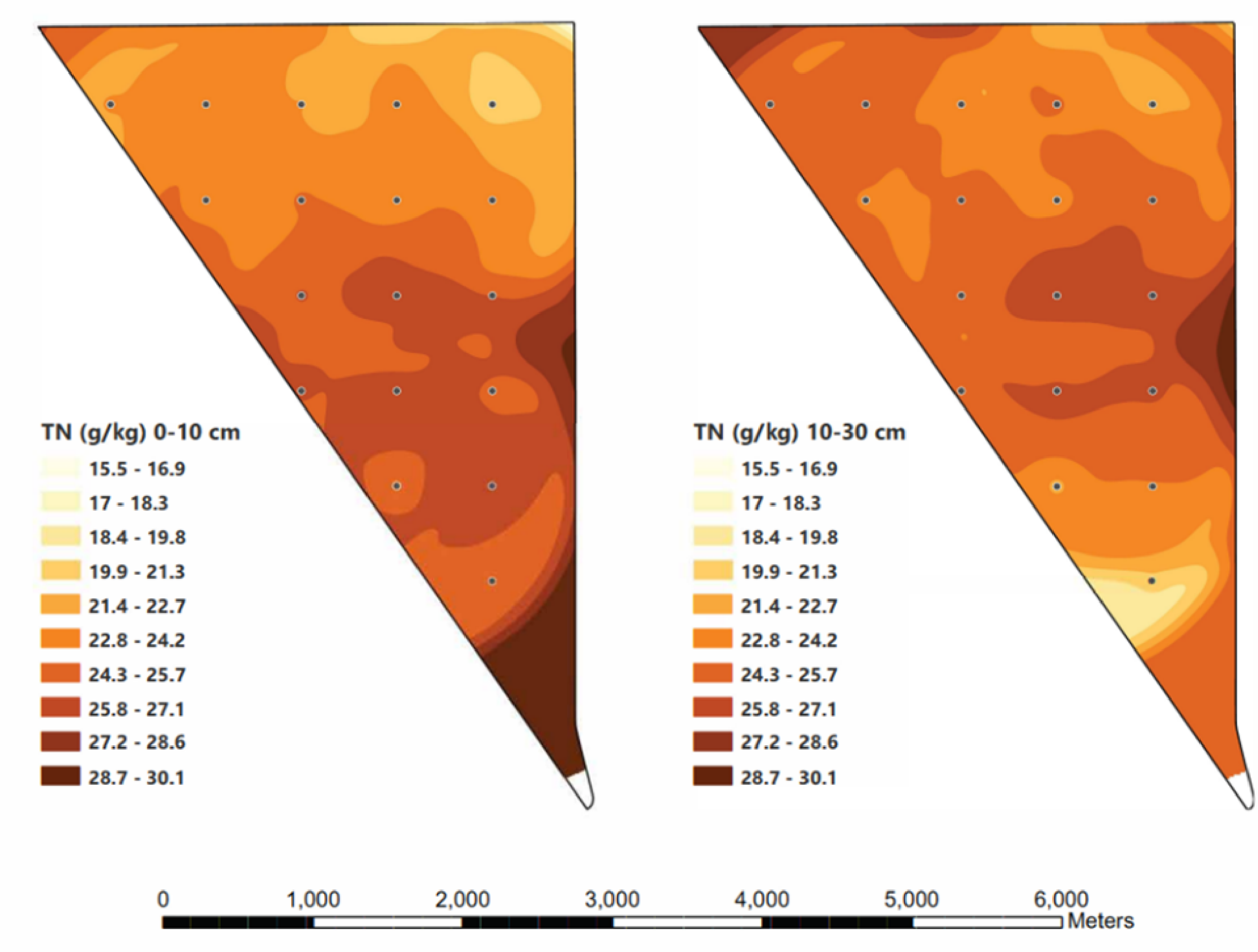

Figure 13. Spatial distribution of TN concentrations in the 0-10 cm and 10-30 cm soil layers in STA-1W Expansion #2. The dots on the map represent sampling locations.

A-2 STA

The soils in the A-2 STA are representative of the organic soils (Histosols) in the EAA. They are characterized by high organic matter content that imparts a black to dark brown color to the soil. The high organic matter content (56% in topsoil; 44% in subsoil) is associated with lower bulk density (**Table 3**). Bulk density averaged 0.57 g/cm^3 in the surface and 0.62 g/cm^3 in the subsurface layer, which are significantly lower than mean bulk density of > 1.50 g/cm^3 reported for mineral soils of the C-139 FEB. Soil pH ranged from slightly acidic to alkaline with a mean pH of 7.38 in the topsoil and 7.53 in the subsoil. Acidic conditions are attributed to decomposing plant organic matter. However, the influence of underlying calcareous bedrock can lead to higher pH, making them alkaline.

TP content ranged from 532 to 1,616 mg/kg in the topsoil and from 136 to 1,492 g/kg in the subsoil. Respective median TP values of 934 and 671 mg/kg are significantly higher than those reported for soils in the STA-1W Expansion #2 and are well within the 100 to 3,000 mg/kg reported for Histosols in the EAA (McCray et al. 2019). The spatial map of TP is somewhat clustered in the topsoil where certain data points are concentrated in the lower northeast section of the STA forming hotspots (**Figure 15**). In the subsoil, the data points are more evenly distributed with a few spots of higher concentrations in the northern section of the STA.

Mean TC concentrations of 33% (330 g/kg) in the topsoil and 27% (270 g/kg) in the subsoil are lower compared to TC concentrations reported for soils in the STA-1W Expansion #2. This is because a significant portion of Expansion #2 was unfarmed while A-2 STA site was used for sugarcane production for many years where original plant material in soils have undergone decomposition. The spatial map of TC concentrations across the site indicates higher concentrations with lower degree of variation in the topsoil than in the subsoil. The distribution pattern is patchy, with areas of high and low concentrations, creating a mosaic-like pattern (**Figure 16**).

TN concentrations in the soils and their distribution pattern across the site are similar to those reported for TC (**Figure 17**). This is because C and N are strongly coupled in wetland ecosystems, influencing each other through a variety of interconnected processes. TN concentrations varied from 0.59 to 2.89% (5.9 to 28.9 g/kg) in the topsoil and from 0.45 to 2.76% (4.5 to 27.6 g/kg) in the subsoil. These are within the range of 0.5 to 3.5% reported for Histosols in the EAA (McCray et al. 2019).

Total S concentrations averaged 3,169 mg/kg in the topsoil and 2,470 mg/kg in the subsoil. The high levels of total S in the soils are a direct result of organic matter mineralization and elemental S application, an agricultural practice to increase availability of micronutrients by decreasing pH of alkaline soils (McCray et al. 2019). Since marl and limestone deposits generally underlie the organic soils used for sugarcane production, Ca levels were very high, with mean values of 70 and 62 g/kg in the topsoil and subsoil, respectively. Compared to Ca, Mg and K levels were relatively low. Fe and Al are present in appreciable amounts. Fe levels averaged 9.7 g/kg in the topsoil and 10.9 g/kg in the subsoil. Respective Al mean values were 11 g/kg and almost 17 g/kg. The high levels of Fe and Al could have originated from the decomposition of wetland plants, the shallow groundwater, and mineral translocation within the soil profile.

Table 3. Comparison of physico-chemical properties of the soils in the surface (0-10 cm) and subsurface (10-30 cm) soil layers of A-2 STA. Minimum (Min) and Maximum (Max) are the lowest and highest observed values, respectively. Mean is the average value and SEM is the standard error around the mean. Median is the middle value in the data set, the basis of non-parametric Wilcoxon's pairwise comparisons. For a given parameter, median values for 0-10 cm and 10-30 cm depth increments with the same letter are not significantly different at significance level (α) = 0.05.

Parameter	Unit	0-10 cm				10-30 cm			
		Min	Max	Mean ± SEM	Median	Min	Max	Mean ± SEM	Median
pH		6.50	7.93	7.38 ± 0.01	7.55 ***b***	6.44	8.09	7.53 ± 0.05	7.65 ***a***
Bulk Density	g/cm^3	0.30	0.82	0.57 ± 0.01	0.58 ***a***	0.33	0.88	0.62 ± 0.02	0.61 ***a***
Organic Matter	%	33	75	56 ± 1	59 ***a***	9	72	44 ± 2	43 ***b***
Total P	mg/kg	532	1,616	962 ± 25	934 ***a***	136	1,492	707 ± 36	671 ***b***
Total N	%	0.59	2.89	2.15 ± 0.05	2.21 ***a***	0.45	2.76	1.80 ± 0.07	1.82 ***b***
Total C	%	6	43	33 ± 1	34 ***a***	0.5	41	27 ± 1	28 ***b***
Total S	mg/kg	1,838	4,493	3,169 ± 63	3,241 ***a***	502	4,439	2,470 ± 114	2,540 ***b***
Total Ca	mg/kg	33,407	154,591	70,030 ± 3,725	58,846 ***a***	11,150	155,171	62,108 ± 4,103	54,785 ***a***
Total Mg	mg/kg	905	4,380	2,508 ± 96	2,344 ***b***	540	8,010	3,209 ± 193	2,670 ***a***
Total K	mg/kg	228	1,005	588 ± 24	555 ***a***	178	1,434	634 ± 31	572 ***a***
Total Fe	mg/kg	5,147	15,402	9,674 ± 278	9,751 ***a***	2,631	24,428	10,890 ± 513	10,013 ***a***
Total Al	mg/kg	3,230	23,088	11,031 ± 558	10,498 ***b***	3,439	46,510	16,856 ± 1,274	12,692 ***a***

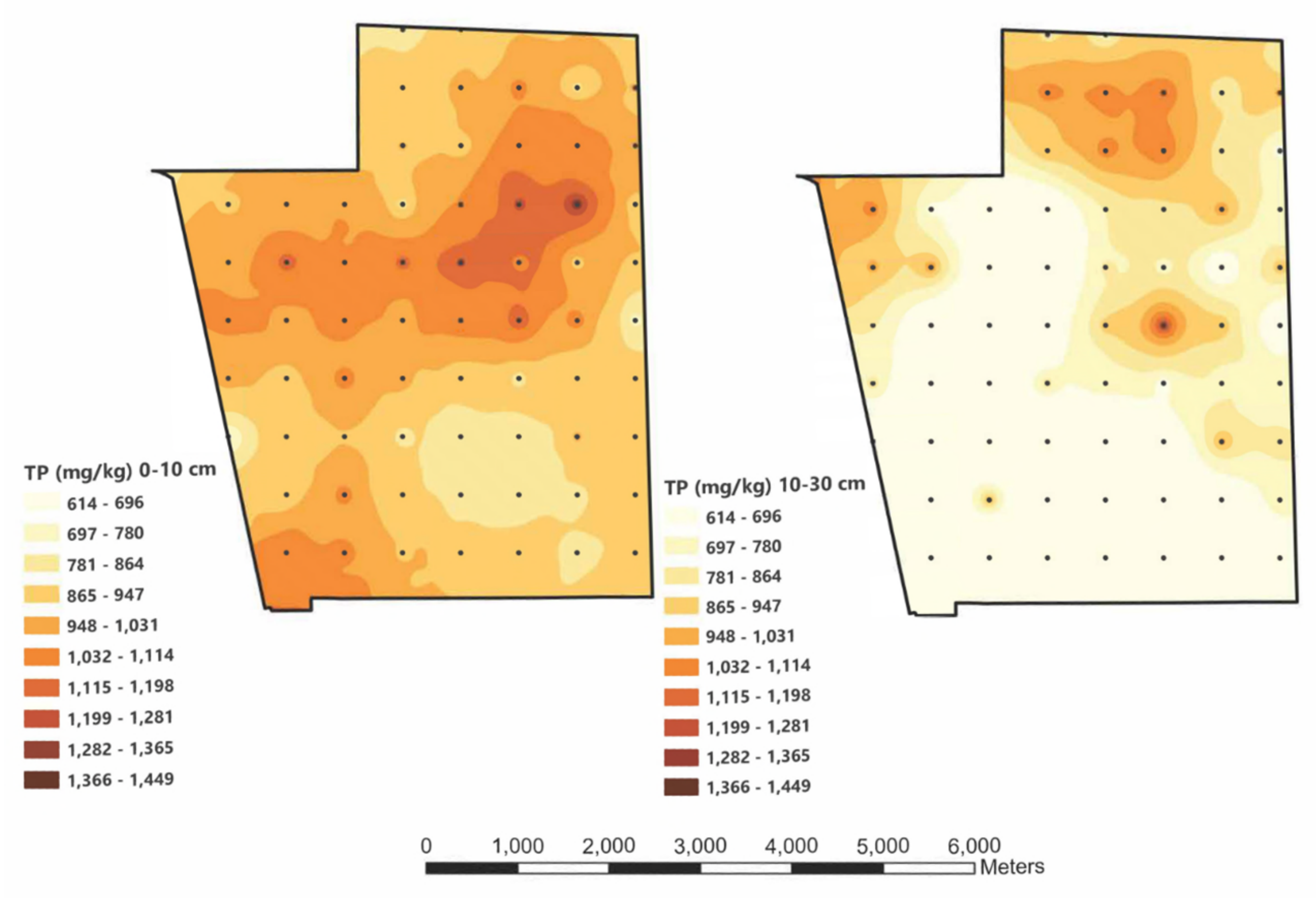

Figure 14. Spatial distribution of TP concentrations in the 0-10 cm and 10-30 cm soil layers in the A-2 STA. The dots on the map represent sampling locations.

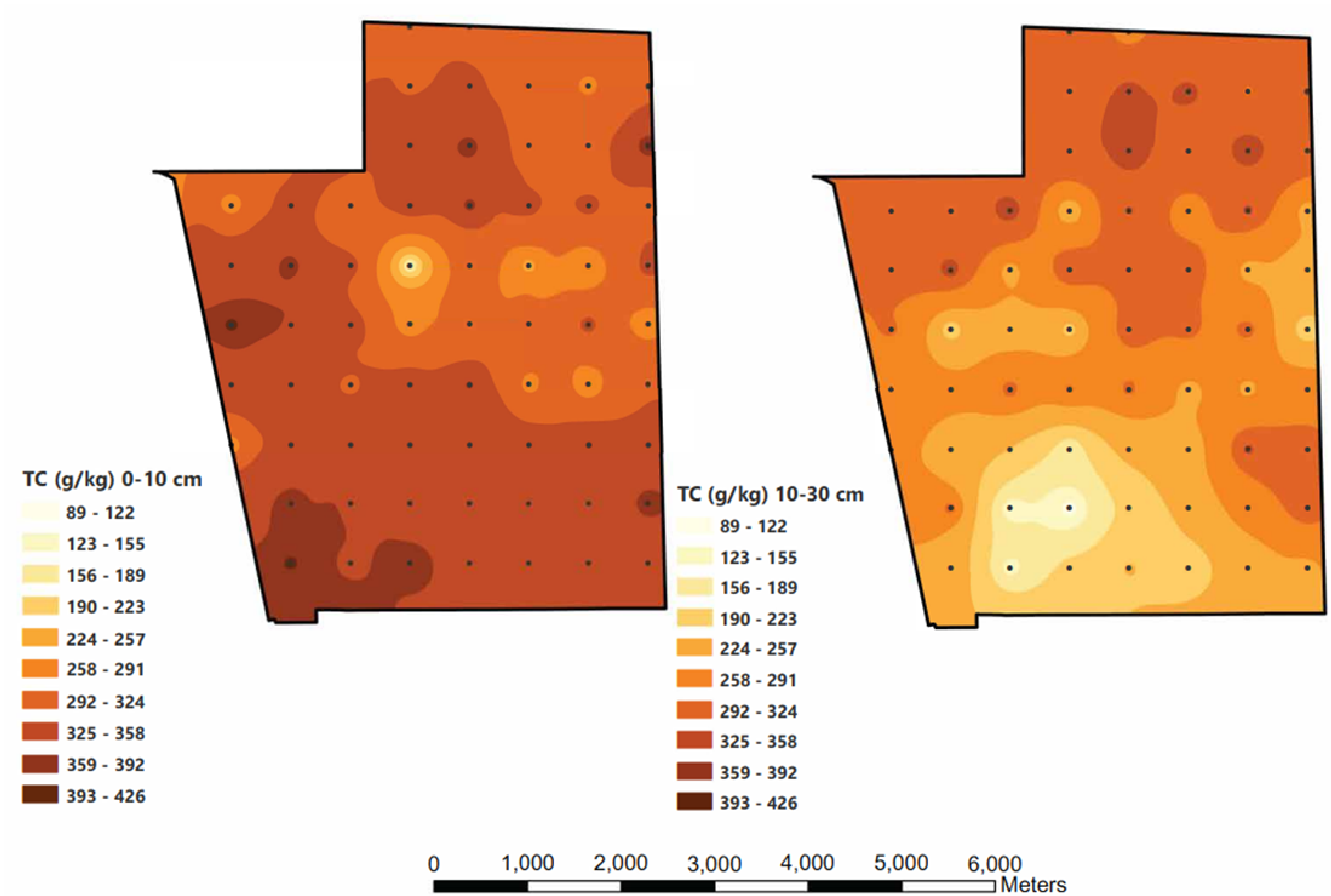

Figure 15. Spatial distribution of TC concentrations in the 0-10 cm and 10-30 cm soil layers in STA-1W Expansion #2. The dots on the map represent sampling locations.

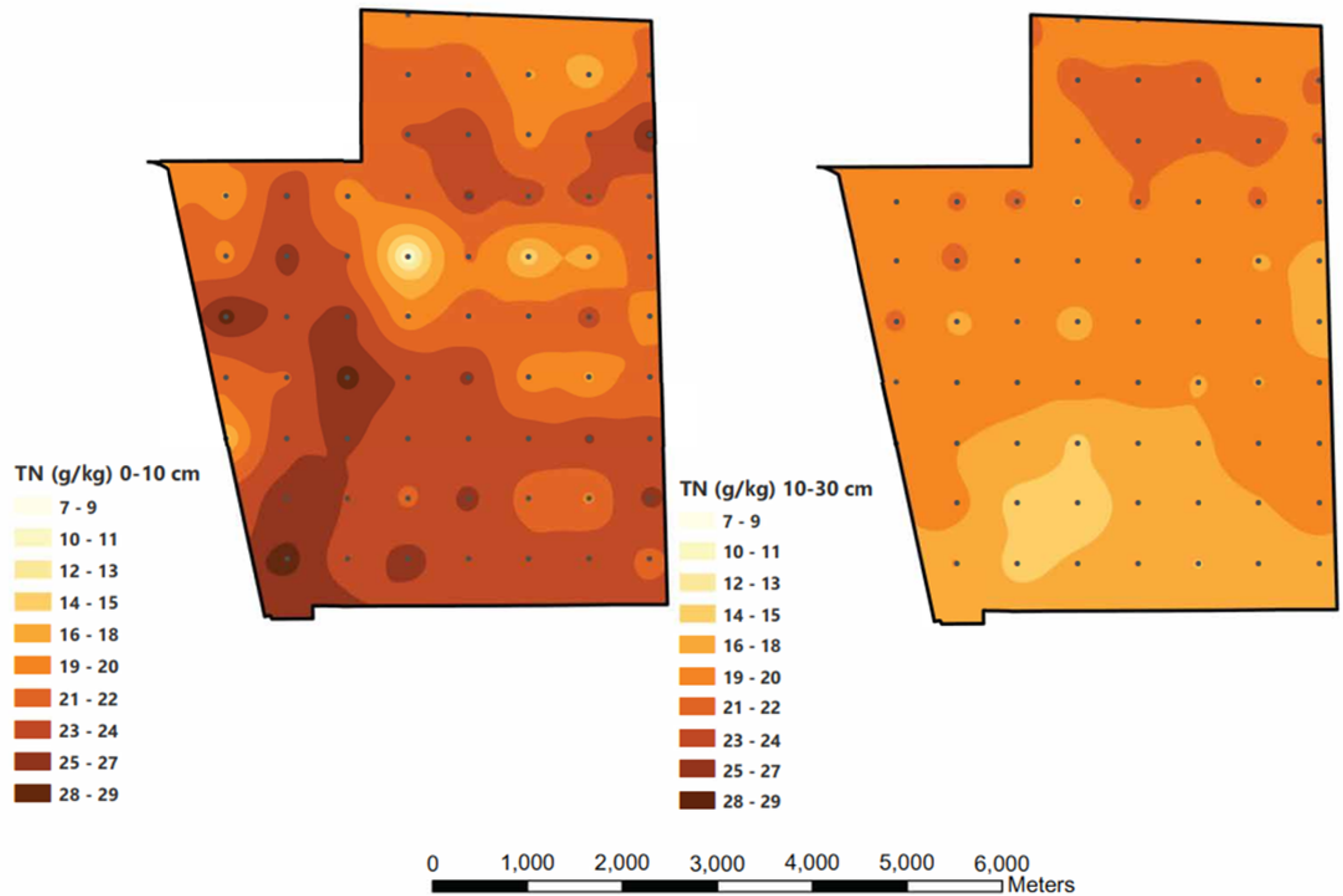

Figure 16. Spatial distribution of TN concentrations in the 0-10 cm and 10-30 cm soil layers in the A-2 STA. The dots on the map represent sampling locations.

BASELINE PHOSPHORUS LEVELS

The initial levels of stored P in the soils varied widely among project sites. The mineral soils of the C-139 FEB contained the lowest amount of P on an areal basis compared to the organic soils of STA-1W Expansion #2 and the A-2 STA. Median TP levels were significantly different among project sites for both sample depths (**Table 4**). Mean TP levels stored within the top 30 cm of soil in the C-139 FEB, STA-1W Expansion #2, and A-2 STA were 28, 48, and 141 grams per square meter (g/m^2), respectively. Initial soil P levels generally differ significantly between mineral and organic soils. The mineral sandy soils of Florida often contain low levels of P especially in the upper horizons because they have limited ability to retain P, thus making them more susceptible to leaching. The low P retention capacity is associated with limited amounts of organic matter content and metallic cations that can bind with P, and rapid drainage that leaches P down through the soil profile. Organic soils tend to be higher in P than mineral soils primarily because they contain a large amount of organic matter that is rich in organic P compounds. Organic matter, particularly its components like humic acids, can form complexes with metals like Fe and Al, preventing the formation of insoluble phosphate compounds that can lock up P in mineral soils (Yang et al. 2019).

Table 4. Calculated mean and median values of initially stored P expressed as grams of P per square meter ($g P/m^2$) in the surface (0-10 cm) and subsurface (10-30 cm) soil layers of the C-139 FEB, STA-1W Expansion #2, and A-2 STA. Mean is the average value and SEM is the standard error around the mean. Median is the middle value in the data set, the basis of non-parametric Wilcoxon's pairwise comparisons. Median values for project sites with the same letter are not significantly different at significance level (α) = 0.05.

Project Site	Treatment Area (acres)	0-10 cm		10-30 cm	
		Mean ± SEM	Median	Mean ± SEM	Median
C-139 FEB	2,800	10.23 ± 1.58	8.40 ***c***	17.98 ± 1.95	15.55 ***b***
STA-1W Expansion #2	1,867	22.15 ± 3.61	15.10 ***b***	25.63 ± 4.29	22.37 ***b***
A-2 STA	6,599	54.85 ± 1.74	52.97 ***a***	85.82 ± 4.87	77.26 ***a***

The mean mass concentrations (g/m^2) in **Table 4** were multiplied by the treatment area to obtain the mass of total P in metric tons (t) over the specified area. TP mass was generally higher in the subsoil (10-30 cm) than in the topsoil (0-10 cm), which is an artefact of the differences in sampling depth more than TP concentration. The highly organic soils of the A-2 STA, the largest of the three facilities and with the highest mean TP concentrations (**Table 4**) by far had the highest amount of P in the soil. While the mineral soils of the C-139 FEB exhibited the lowest TP concentrations, its TP mass in the subsoil was comparable to the organic soils of STA-1W Expansion #2. This can be attributed to the C-139 FEB having a larger treatment area and much higher soil bulk density compared to STA-1W Expansion #2, which compensate for the lower concentrations when calculating the total mass present. The mass of TP in the top 30 cm of the soil in the C-139 FEB, STA-1W Expansion #2, and A-2 STA were 320, 361, and 3,757 t, respectively (**Figure 18**). Per acre basis, these numbers correspond to 114, 193, and 569 kilogram per acre (kg/ac).

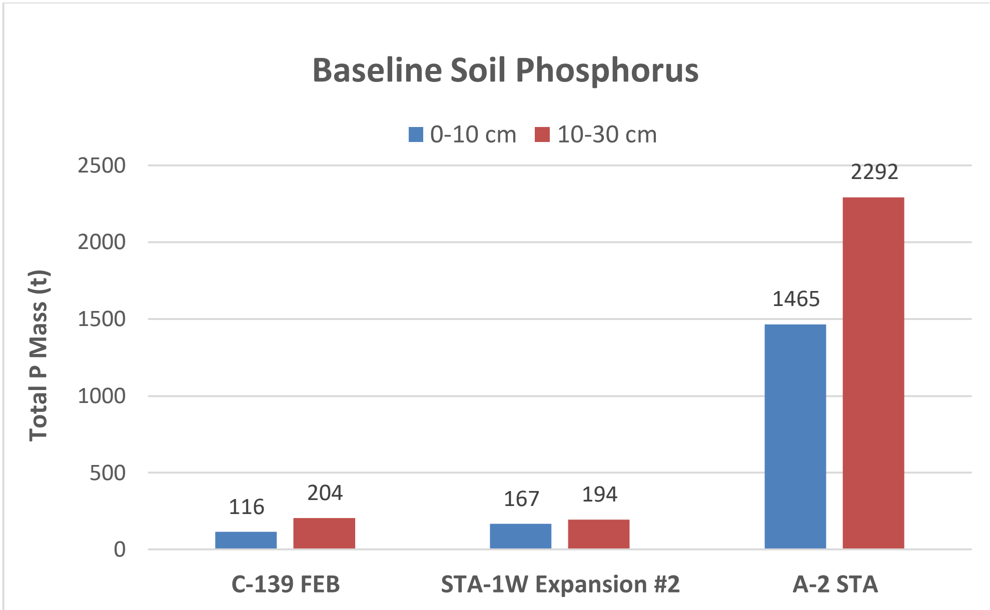

Figure 17. The amounts of P initially present in the top 0-10 cm and 10-30 cm of the soil in the project sites prior to inundation.

Based on existing knowledge, it is expected that a substantial portion of the soil P at the project sites is in organic form. Organic soils typically contain a large percentage of their TP in various organic forms, which are not readily available to plants. However, because TP in this project was not chemically differentiated into its organic and inorganic components, it is not possible to accurately determine the exact percentage of TP in the soil samples that is present as organic P. Differentiating between organic and inorganic P forms would have provided a more precise understanding of the potential P availability and the contribution of the organic P pool at the project sites.

IMPLICATIONS OF BASELINE SOIL P CONDITIONS FOR LONG-TERM FUNCTION OF TREATMENT SYSTEMS

The short-term effectiveness of wetland treatment systems is significantly influenced by the initial amount of P present in the soil. When a treatment facility begins receiving flows, the initial P in the soils undergoes several transformations due to changes in hydrologic conditions and related biogeochemical processes. The nature and extent of these transformations are primarily governed by the concentration of P in the incoming water and the size of labile P pools in the receiving soil. If the soil has a higher concentration of P than the incoming water, a concentration gradient is created at the soil-water interface that will drive the movement of P from the soil (the area of higher concentration) into the water column (area of lower concentration). Thus, for soils with high starting P concentrations, such as the organic soils of the A-2 STA and STA-1W Expansion #2, there could be an initial release of P into the water column. Initial P release from these soils can decrease and stabilize over weeks or months as equilibrium is established between P concentrations in the soil and the water column. Once the initial P release subsides, these wetland treatment systems become efficient at removing P through processes of sedimentation, uptake by vegetation, and chemical binding (sorption/precipitation). While soils generally have a capacity to bind and store P, their binding sites can become saturated with P if loading increases over time. Once saturation is reached, the wetland's ability to retain additional P decreases. However, wetlands do not provide P removal only through sorption processes on existing soils (Kadlec and Wallace 2009). The long-term P removal efficiency depends on the stability of the stored P within the wetland. More stable P pools are less prone to mobilization and release back into the water. The formation of new soils, through peat accretion from decomposing plant matter and detritus is the only long-term sustainable mechanism for P removal and storage in the STAs (Kadlec and Wallace 2009). Maintaining consistently moderate hydraulic and P loads into the STAs and avoiding drying and rewetting cycles are important for ensuring the long-term effectiveness of wetland treatment systems in P removal.

For mineral soils of the C-139 FEB, an initial flush of P upon flooding is not expected given the initially low P concentrations in the soil and the high concentrations of P (> 200 micrograms per liter or µg/L) in the runoff water that this FEB receives from the C-139 Basin. While the C-139 FEB was designed primarily to store water and helps control the flow of water into STA-5/6, it contributes to P removal indirectly through sedimentation/settling and to a lesser extent, incidental biological uptake. This managed flow is important because it helps to prevent dry-out conditions that can negatively impact STA-5/6 performance. By managing water flows and facilitating P removal within the FEB-STA system, the goal is to ultimately achieve and sustain TP concentrations that meet the WQBEL for discharge into the Everglades Protection Area.

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