

Evaluation of biogeochemical changes in channelized and restored portions of a subtropical floodplain

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Abstract

Floodplains are critically important ecosystems that provide a whole suite of ecosystem services including nutrient and carbon sequestration, flood mitigation, water storage, and critical wildlife habitat to name a few. However, human modification of rivers and floodplains through channelization, artificial levee construction, reduction in active floodplain area, and water management can significantly reduce the ecosystem function of river-floodplain systems. In this study, we evaluated the changes in nutrient loading of the Kissimmee River floodplain during the restoration of the river-floodplain system. In addition to time-series loading analysis, we also evaluated soil nutrient concentrations across the lower portion of the Kissimmee River floodplain. During the 44-year nutrient loading time-series, the floodplain remained a nutrient exporter with changes in nutrient loading generally corresponding to both water quality (i.e. point source reductions) and hydrologic restoration activities in the watershed and Kissimmee River floodplain. During the study period, inputs of total phosphorus and total nitrogen loads from upstream either significantly increased or remained the same. In addition to external sources of nutrients, internal sources of nutrients from floodplain soils can also contribute to the total nutrient export from the system. These internal sources could be organic via the decomposition of organic matter or geologic from the original excavation of the canal and/or restoration backfilling. Soil nutrient concentrations vary between vegetative communities and landscape position and could be a significant source of phosphorus to the downstream system which is plagued by eutrophic

conditions. Therefore, as floodplain function in the Kissimmee River continues to be restored and managed, additional effort may be needed to address nutrient inputs and internal legacy nutrients.

Keywords: floodplain restoration, phosphorus, nutrients, loading

Introduction

Floodplains are characteristically dynamic environments located at the aquatic-terrestrial interface governed by climate and flow regimes and balances between lotic and lentic conditions. Floodplains are not homogeneous ecological units but rather a mosaic of distinct hydrologic environments [1]. While the definition of floodplains can vary, the genetic floodplain definition includes hydraulic, hydrologic, and geomorphic features. Nanson and Croke (1992) define the genetic floodplain as “*the largely horizontally-bedded alluvial landform adjacent to a channel, separated from the channel by banks and built of sediment transported by the present flow - regime.*”[2]. Therefore floodplains are defined in terms of hydrology such as inundation frequency and geomorphic terms concerning inundation and depositional history.

River-floodplain systems provide critical habitat for terrestrial and aquatic biota, as well as key ecosystem services including water storage, flood mitigation, carbon sequestration, and nutrient retention to name a few [1–3]. Floodplains perform a diverse array of interconnected physical and ecological functions [1,3,4]. Primarily floodplains attenuate fluxes of water, nutrients, and particulate material such as sediment and organic matter. How these constituents are attenuated depends on the river and floodplain morphology which in turn dictate how things move downstream [4–6]. Therefore changes to floodplain extent, surface water inputs, and climate variables can affect floodplain function.

Human alterations along stream channels, rivers, and within catchments have affected floodplain ecological functions by changing fluvial geomorphic processes, floodplain morphology, and channel-floodplain connectivity. Human alterations include changes to water management; water control feature construction such as dams, levees, canals, and channelization; land clearance with upland erosion; or downstream aggradation can lead to geomorphic changes to a floodplain, disconnection of channels and floodplains, affecting vertical accretion and storage [1,7,8]. These changes cause a cascade of impacts on the natural ecology of floodplains by altering suitable habitats, biodiversity, and nutrient cycling [7,9]. Artificial levees, channelization, and water

management can cause complex changes in river-floodplain connectivity reducing floodplain extent and fundamentally altering the habitat of aquatic and wetland communities [6,10].

A prime example of anthropogenic manipulation of river-floodplain ecosystems (and its restoration) is the Kissimmee River. Historically, the Kissimmee River meandered 161 km from Lake Kissimmee through a 2 – 5 km wide floodplain eventually flowing into Lake Okeechobee. The river was characterized by a low elevation gradient (0.07 m/km) and with a mean main channel velocity of 0.2 – 0.6 m/sec [11,12]. Historically, the floodplain wetlands were characterized by a diverse assemblage of plant communities adapted for long-duration inundation patterns and supported abundant wildlife [10,13]. Long-duration flooding was common in the pre-drainage Kissimmee Basin with little adverse impact on human life and property, however, after severe flooding flood control measures were initiated in the mid to late 1940s in the form of the Central & Southern Flood Control Project. Construction of a flood control canal (C-38) was initiated in the lower Kissimmee Basin in 1962 and completed less than a decade later. The canal bisected the meandering Kissimmee River, eliminating flow in remnant channels and conveying all water formerly in the floodplain to Lake Okeechobee. A series of water control structures were also constructed along the C-38 to control releases of water to and through the basin. The effect of channelization was realized as wetland ecosystems quickly deteriorated, relatively consistent water levels were managed throughout the different pools and seasonal overbank flow was eliminated [12,14,15]. The Kissimmee River restoration project was recently completed (July 2021) and backfilled 35 km of canal, reconstructed ~18 km of river channel, opened up ~64 km of floodplain, and restored ~50 km² of wetlands. Ultimately the river-floodplain physical template has been reconstructed, now changes to water management is needed to complete the hydrologic restoration of the floodplain [16].

An analysis of North American floodplains demonstrated the reduction in net connectivity within the Kissimmee River floodplain with >500 km² of accumulated alternating due to flood control measures [6]. The primary goal of the restoration effort was to restore the ecological integrity of the river-floodplain system by reestablishing the physical and hydrologic form of the river including the seasonal changes in water management to the historic flood and drawdown dynamics. Thereby improving the net connectivity of the Kissimmee River floodplain and re-establishing floodplain processes. The purpose of this paper is to present a long-term study of

nutrient loading to the Kissimmee River floodplain and document the spatial distribution of soil nutrients during a large-scale restoration effort. Our goal was to demonstrate the effect of incremental restoration on floodplain function relative to nutrient loading. We hypothesize that as the restoration of the Kissimmee River floodplain progresses nutrient export from the Kissimmee River will change.

Materials and Methods

Study Area

The Kissimmee River drains approximately 7804 km² of central Florida. The river begins as the outlet of Lake Kissimmee south of Orlando Florida and ends at Lake Okeechobee. Historically the river flowed for approximately 166 km in a low elevation gradient anabranching channel that frequently flooded annually [10]. Historically, the river was a mosaic of wetland and upland vegetation communities with a broad marsh punctuated with live oak hummocks and a channel delineated by a narrow “levee” of willows and wetland shrubs [17]. Post channelization (1972), the channel was 9 m deep and approximately 100 m wide with the floodplain being separated into five pools created by size lock and dam structures constraining the floodplain into the C-38 canal. Incrementally over the past several decades, the Kissimmee River floodplain was restored through the removal of lock and dam structures (S65B 2001, S65C 2017; Table 1), backfilling of the C-38, and degrading spoil areas (Table 1). The physical restoration of the Kissimmee River was recently completed (July 2021) leading the way for hydrologic and ecological restoration of the floodplain [16].

Table 1 – Major Actions and events related to the Kissimmee River Restoration Project and regional water control.

Time Period	Major Action/Event
1954	United States Congress authorizes the C&SF Project
1962	Construction commences of C38 Canal and other features
1971	Construction complete
1971	The state of Florida recommends the restoration of the Kissimmee River
1978 - 1985	Federal feasibility study notes the potential for restoration [49]
1984 - 1990	Kissimmee River Demonstration Project
1987 - 1990	Drawdown of upstream lakes (Lake Tohopekaliga and East Lake Tohopekaliga) [39]

1991	2 nd Federal feasibility study recommends a partial backfill plan [50]
1994	Construct test backfill and conduct high-flow tests on backfill stability
1995 - 1997	Drawdown of upstream lakes (Lake Jackson and Lake Kissimmee) [39]
1996	Headwaters Revitalization Feasibility Study Complete [51]
1999 - 2001	Phase I backfilling complete (12 km canal backfilled)
2001	S-65B water control structure removed
2006 - 2010	Phase IV backfilling complete (9 km canal backfilled)
2010 - 2015	Supplemental construction to support the Kissimmee River Restoration effort [52]
2015 - 2021	Phases II & III backfilling complete (~14 km canal backfilled)
2017	S-65C water control structure removed
2021	Kissimmee River Restoration Construction Activities Complete

Data Sources

Water quality and discharge data were retrieved from the South Florida Water Management District (SFWMD) online environmental database (DBHYDRO; www.sfwmd/dbhydro) for site routine monitoring locations along the Kissimmee River (Fig 1). Data collected between water year (WY) 1979 to 2022 (May 1, 1979 - April 30, 2022) were considered for this study. This period was selected for several reasons, 1) it bookends the synoptic lake sediment surveys; 2) includes several years where major hurricanes and tropical storms came in the vicinity of the lake; 3) includes a period of a notable shift in the Atlantic Multidecadal Oscillation (AMO) index and; 4) and spans the period of pre-restoration and ongoing restoration activities within the greater Everglades ecosystem [16,18,19]. Water column parameters evaluated in this study include total phosphorus (TP) and TN. For purposes of data analyses and summary statistics, data reported less than the method detection limit (MDL) was assigned a value of one-half the MDL.

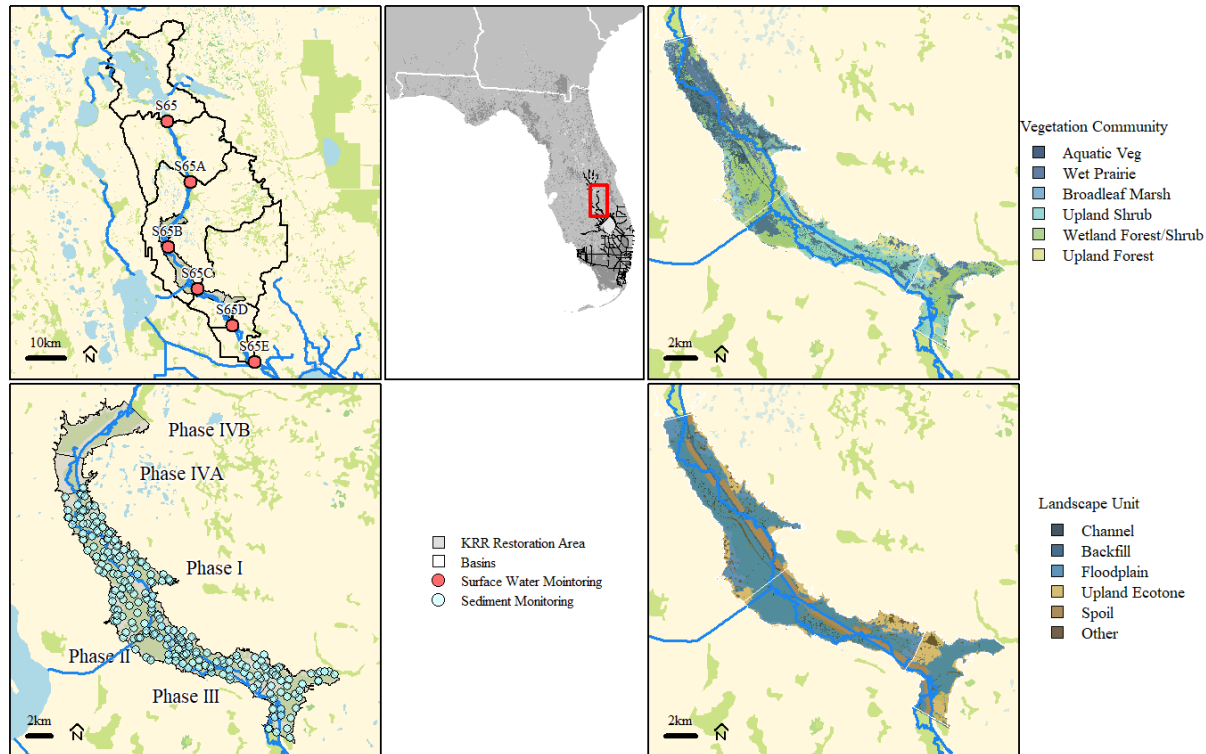


Figure 1 – Surface water monitoring locations (top left) for the entire Kissimmee River basin; sediment monitoring locations (bottom left) specific to Phase I, II, and III segments of the Kissimmee River floodplain; vegetation (top right) and landscape unit (bottom right) coverages within the lower segments of the Kissimmee River floodplain.

Surface soil samples (0 -10 cm) were collected at predetermined locations within Pools C and D (restoration phases I and II/III; Fig 1) of the Kissimmee River floodplain. Samples were taken using two methods, a manual push corer, and a piston corer. Manual push coring used stainless steel coring tubes (10 cm in diameter and 50 cm in length) manually inserted into the soil to a depth of 20 cm. The piston corer used the same methodology as the manual push corer with the assistance of a vacuum piston and an extendable handle (up to 5 m) to sample underwater sediments in the river channel or marsh soils in greater than 1 m of water. Samples were extruded in the field in two sections (0-10 cm and 10-20 cm increments). For purposes of this study, only data from the 0 -10 cm increment was used. For purposes of this study, soils were analyzed for bulk density, loss-on-ignition, TP, TN, and total carbon (TC). Soil samples were dried at 70°C and

weighed to determine moisture content and bulk density. Total P content was determined from digestate concentrations prepared by ashing and 1.0 M HCl hot-block digestion using the ascorbic acid automated colorimetric procedure (Method 365.1; [20]). Total carbon and nitrogen were determined on oven-dried, ground samples using a Flash EA 1112 Elemental Analyzer (CE Instruments, Upper Saddlebrook, NJ). Loss-on-ignition (LOI) was calculated using percent ash values subtracted from 100%.

Data Analysis

To evaluate long-term changes in nutrient concentrations and loading annual total discharge volumes, TP and TN loads, and flow-weighted mean (FWM) concentrations were calculated for each water control structure along the Kissimmee River. Loads and FWM concentrations were estimated by interpolating water quality concentrations daily from grab samples collected at each respective structure during days of observed discharge. Daily interpolated water quality concentrations were then multiplied by daily flow and summed for each WY. Annual FWM values were calculated by dividing the total annual nutrient load by the total annual flow. Mann-Kendall trend analysis was performed on annual TP and TN FWM concentrations and load for each structure using the `kendallTrendTest` in the EnvStats R-package [21].

Nutrient load export of the Kissimmee River floodplain was estimated as the difference of TP and TN loads between S65D and S65 (i.e. $S65D - S65$). To determine changes in load export of the floodplain, segmented regression was applied to cumulative annual nutrient export using the `segmented` function in the segmented R-package [22].

To evaluate the spatial distribution of surface sediment (0 – 10 cm) TP, TN and TC within the Kissimmee River floodplain, specifically pools C and D (i.e. restoration phases I and II/III) geostatistical methods were used. Variogram models were fit using the variogram function in the gstat R-package (Benedikt et al., 2016). The parameters of the variogram model are the nugget, sill, and range where the nugget describes the small-scale variability of the data, the sill is the maximum variability between point pairs and the range is the distance after which data are no longer correlated (Fortin, 1999). Models with a relatively high goodness of fit (R^2) values were used for ordinary kriging. The spatial structure or nugget-to-sill ratio (NSR) for each variogram was evaluated by comparing the nugget to the sill. To improve variogram fit, TP concentrations

were log-transformed. The final kriged surface was back-transformed and corrected, consistent with methods used in prior studies. [23,24].

To provide a finer resolution spatial interpolation, residual kriging was also used. Using vegetation and landform spatial data [25] (Fig 1), average soil property values were calculated for each of the unique vegetation and landform classifications. For each property, the average values were paired with existing polygons and converted to a raster file. At each sampling location, the average soil property was subtracted from the measured soil property (i.e. residual value). These residuals were then modeled using ordinary kriging as identified above. The residual model interpolation was then added to the corresponding spatial average values.

Results

Water Quality Conditions

Over the past 44 water years, annual nutrient loads entering the Kissimmee River floodplain via Lake Kissimmee (i.e. S65) range from 834 to 211,233 kg TP Y⁻¹ and 26,218 to 3,515,506 kg TN Y⁻¹. Watershed area normalized nutrient loads range from 2.0 to 504 kg TP km⁻² Y⁻¹ and 63 to 8,387 kg TN km⁻² Y⁻¹ (Table 2). Meanwhile, nutrient loads leaving the KRR floodplain to Lake Okeechobee (i.e. S65E) range from 10,436 to 348,449 kg TP Y⁻¹ and 112,253 to 4,125,749 kg TN Y⁻¹. Floodplain area normalized nutrient loads range from 6.0 to 201 kg TP km⁻² Y⁻¹ and 64.7 to 2,379 kg TN km⁻² Y⁻¹ (Table 2).

Table 2 – Total phosphorus (TP) and total nitrogen (TN) annual load and flow-weighted mean concentration summary statistics for water control structures along the Kissimmee River floodplain.

Variable	Parameter	Statistic	S65	S65A	S65B	S65C	S65D	S65E
Load	TP (kg yr ⁻¹)	Mean	56499	62577	53038	74270	118647	138426
		Min	834	3980	8	4040	8597	10436
		Max	211233	165613	166524	203444	383061	348449
		SD	45451	41589	39070	49958	79803	82252
		N	44	44	23	39	44	44
	TN (kg yr ⁻¹)	Mean	1238417	1277163	1289658	1375850	1625018	1685533
		Min	26218	62151	138	111078	126163	112253
		Max	3515506	3044856	3488465	3422184	3922393	4125750

Variable	Parameter	Statistic	S65	S65A	S65B	S65C	S65D	S65E
FWM	TP ($\mu\text{g L}^{-1}$)	SD	789083	736539	912158	840922	968248	994486
		N	44	44	23	39	44	44
		Mean	58.0	64.5	55.7	69.5	94.6	111.9
		Min	30.7	34.3	31.8	34.7	57.4	65.5
		Max	94.3	134.8	92.2	162.9	201.2	228.0
		SD	17.6	19.8	14.7	25.9	29.9	36.2
		N	44	44	23	39	44	44
	TN (mg L^{-1})	Mean	1.35	1.32	1.35	1.29	1.31	1.32
		Min	0.81	0.87	0.95	0.88	0.99	0.97
		Max	2.19	1.90	1.95	1.97	1.96	2.02
		SD	0.26	0.21	0.30	0.26	0.23	0.22
		N	44	44	23	39	44	44

During the 44 water-year period of record, annual TP loads have significantly increased for most of the water control structures along the floodplain, except S65B presumably due to the shorter period of record and variability in the annual time-series (Table 3 and Fig 2). Additionally, annual flow-weighted mean TP concentration significantly increased for most locations except S65D and S65E (Table 2 and Fig 3). Trends in annual TN loads did not significantly change over the period of record for water control structures along the floodplain (Table 3 and Fig 2). Despite a lack of annual loading trends, annual flow-weighted mean TN concentration significantly declined for S65B and S65C, both structures which were removed as part of the restoration activity (Table 3 and Fig 3).

Table 3 – Total phosphorus (TP) and total nitrogen (TN) annual load and flow-weighted mean concentration Mann-Kendall long-term trend results for water control structures along the Kissimmee River floodplain.

Variable	Parameter	Statistic	S65	S65A	S65B	S65C	S65D	S65E
Load	TP	Kendall τ	0.28	0.29	0.12	0.30	0.26	0.16
		ρ -value	<0.01	<0.01	0.43	<0.01	<0.05	0.12
		Thiel Sen Slope ^A	1058	1206	1189	2027	2237	1604
	TN	Kendall τ	0.11	0.11	-0.11	0.10	0.14	0.06
		ρ -value	0.32	0.32	0.46	0.36	0.20	0.55
		Thiel Sen Slope ^A	10341	9419	-27066	11055	14240	7913
FWM	TP	Kendall τ	0.41	0.33	0.30	0.39	0.18	0.03
		ρ -value	<0.01	<0.01	0.05	<0.01	0.08	0.78
		Thiel Sen Slope ^B	0.72	0.60	0.90	0.93	0.50	0.09
	TN	Kendall τ	-0.10	-0.17	-0.63	-0.22	-0.19	-0.19

Variable	Parameter	Statistic	S65	S65A	S65B	S65C	S65D	S65E
		ρ -value	0.35	0.11	<0.01	0.05	0.06	0.07
		Thiel Sen Slope ^C	-0.003	-0.004	-0.027	-0.008	-0.005	-0.005

^A Units: kg yr⁻¹; ^B $\mu\text{g L}^{-1} \text{ yr}^{-1}$; ^C $\text{mg L}^{-1} \text{ yr}^{-1}$

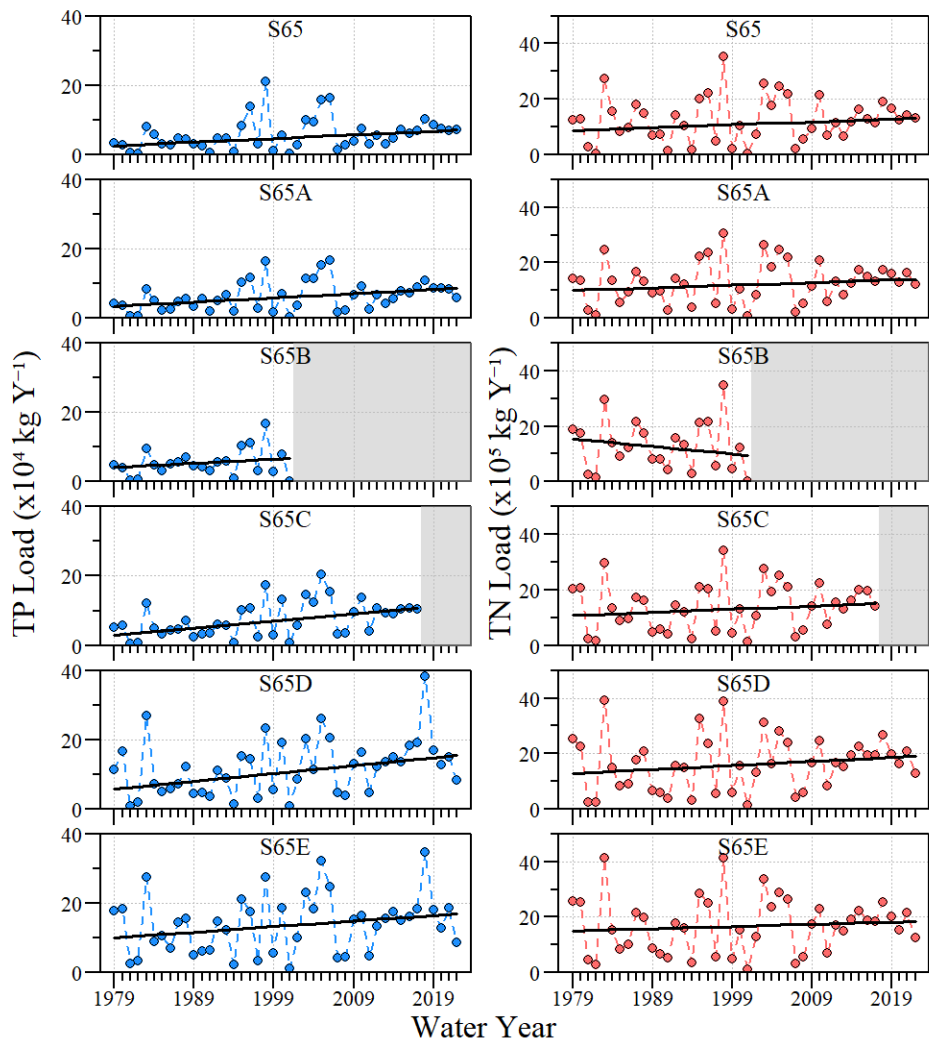


Figure 2 – Total phosphorus (left; TP) and total nitrogen (right; TN) total annual load for each structure along the Kissimmee River floodplain from water year (May – April) 1979 to 2022. The black line through each time series indicates the monotonic trend in annual values for each respective structure and parameter. Grey-shaded areas for S65B and S65C indicate when the structures were removed as part of restoration efforts.

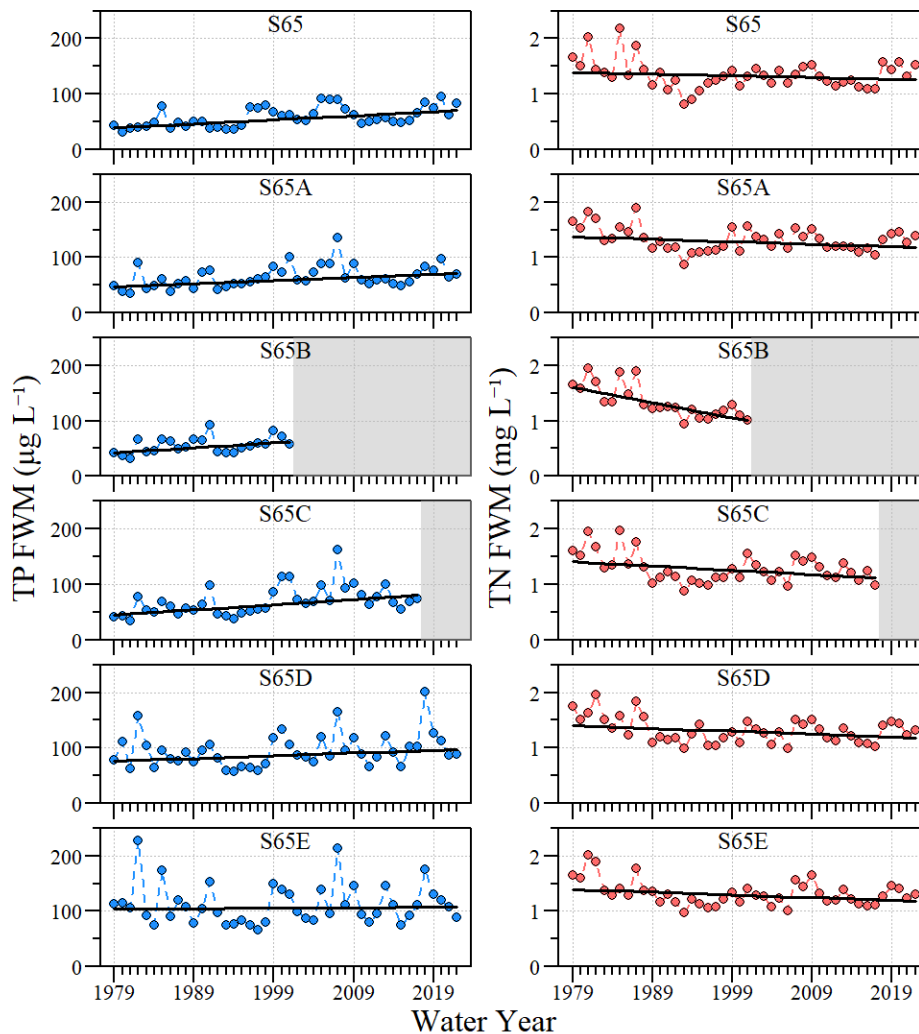


Figure 3 – Total phosphorus (left; TP) and total nitrogen (right; TN) annual flow-weighted mean concentration for each structure along the Kissimmee River floodplain from water year (May – April) 1979 to 2022. The black line through each time series indicates the monotonic trend in annual values for each respective structure and parameter. Grey-shaded areas for S65B and S65C indicate when the structures were removed as part of restoration efforts.

During the period of record, loads at S65D were always greater than loads estimated for S65 for both TP and TN suggesting that the Kissimmee River floodplain is a consistent nutrient exporter to downstream water bodies. However, significant breakpoints were detected in the cumulative annual TP export from the floodplain ($R^2 = 1.00$, $F_{(9,34)} = 2080$, $\rho < 0.01$). The breakpoints in the cumulative annual TP export correspond to WY1984, 1998, 2014, and 2019 (Fig 4) corresponding

to climatic events (i.e. hurricanes, low/high discharge years, etc.) and restoration activities (i.e. backfilling) within the floodplain. Similarly, significant breakpoints were detected in the cumulative annual TN export from the floodplain ($R^2 = 1.00$, $F_{(9,34)} = 1341$, $p < 0.01$). The breakpoints in the cumulative annual TN export correspond to WY1983, 1991, 2003, and 2009 (Fig 4), while these breakpoints differ from the TP export breakpoints they generally corresponds to events that affect discharge and loading dynamics.

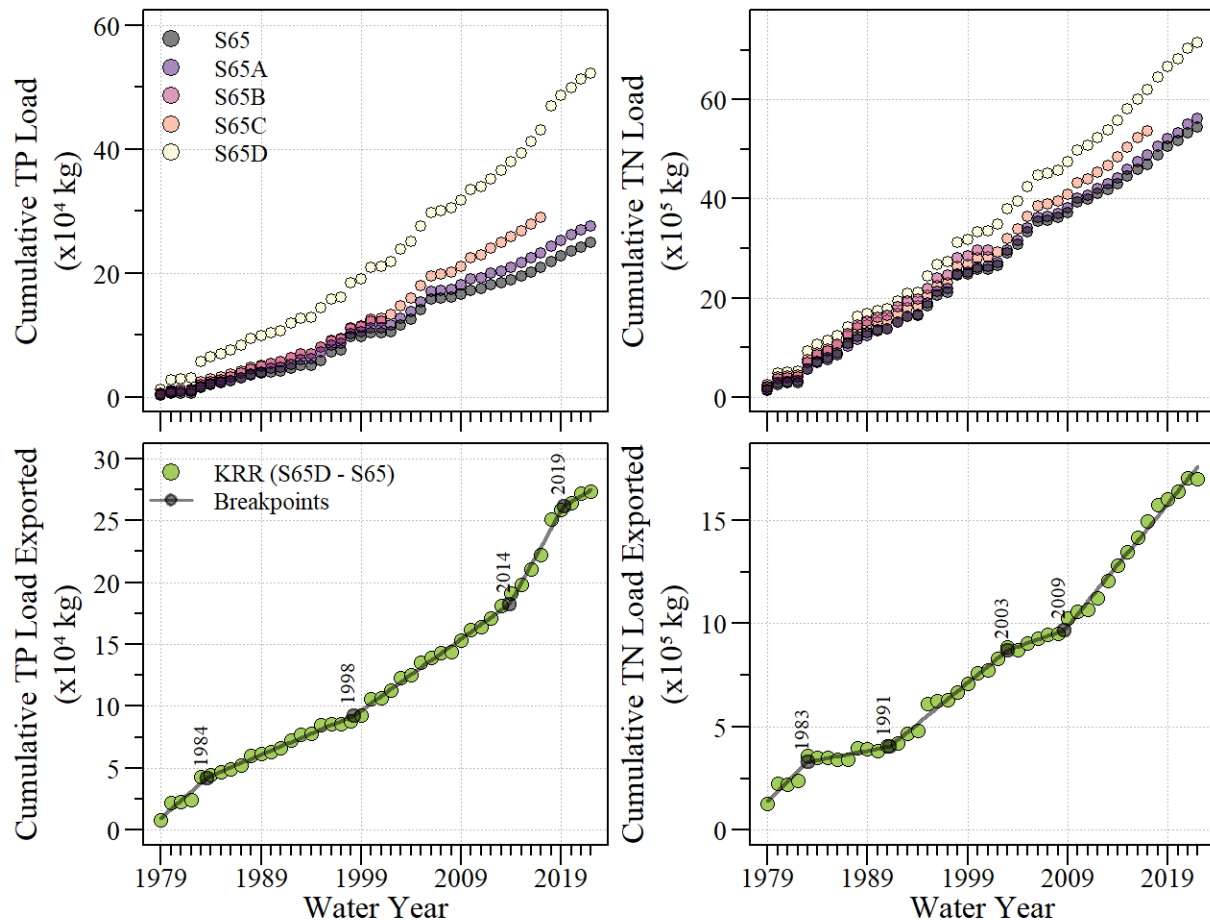


Figure 4 – Top: Cumulative annual load for each water control structure within the Kissimmee River floodplain for total phosphorus (left; TP) and total nitrogen (right; TN). Bottom: cumulative annual TP and TN load exported from the Kissimmee River during the water year 1979 to 2022 period of record.

Soil Nutrient Distribution

Surface soil (0 – 10 cm) nutrient concentrations including TP, TN, and TC significantly varied across the floodplain. Sediment TP concentrations ranged from 15 to 3,251 mg kg⁻¹ with significant differences between vegetation communities ($\chi^2 = 31.91$; df = 5; $p < 0.01$) and landscape form (Fig 5; $\chi^2 = 1150.10$; df = 5; $p < 0.01$). Between the two pools of the floodplain, soil TP concentrations were similar between several vegetative communities with broadleaf marsh having the greatest median concentration and variability (Fig 5). Similarly, soil TP concentrations were similar across the different landscape units with the spoil and backfill landscape units having the greater mean concentrations and variability (Fig 5 and Table 4). Soil TN concentrations ranged from 0.06 to 30.0 g kg⁻¹ with significant differences between vegetation communities ($\chi^2 = 75.8$; df = 5; $p < 0.01$) and landscape form (Fig 5; $\chi^2 = 82.2$; df = 5; $p < 0.01$). High soil TN concentrations were observed in aquatic vegetation, broadleaf marsh, and wetland forests vegetation communities and channel, floodplain, and other landscape units (Fig 5 and Table 4). Soil TC concentrations ranged from 0.3 to 473.3 g kg⁻¹ and followed similar patterns to that of TN concentrations (Fig 5 and Table 4) with significant differences between vegetation communities ($\chi^2 = 64.9$ df = 5; $p < 0.01$) and landscape form ($\chi^2 = 56.6$; df = 5; $p < 0.01$).

Table 4 – Soil summary statistics by vegetation community and landscape unit across the Kissimmee River floodplain (Phases I and II/III). Values are represented as mean \pm standard deviation (sample size) for bulk density, loss-on-ignition (LOI), total phosphorus (TP), total nitrogen (TN), and total carbon (TC).

		Mean \pm SD (N)				
Units	Classification	Bulk Density (g cm ⁻³)	LOI (Percent)	TP (mg kg ⁻¹)	TN (g kg ⁻¹)	TC (g kg ⁻¹)
Vegetation Community	Aquatic Veg	0.57 \pm 0.36 (31)	29.3 \pm 24.0 (35)	625 \pm 448 (35)	10.7 \pm 8.7 (35)	140.1 \pm 120.2 (35)
	Wet Prairie	0.78 \pm 0.34 (54)	17.0 \pm 18.5 (58)	514 \pm 558 (58)	5.9 \pm 6.3 (58)	79.3 \pm 93.1 (58)
	Broadleaf Marsh	0.52 \pm 0.31 (25)	33.6 \pm 29.0 (29)	705 \pm 531 (29)	11.7 \pm 10.1 (29)	159.0 \pm 141.5 (29)
	Upland Shrub	0.93 \pm 0.30 (51)	11.3 \pm 11.3 (58)	533 \pm 710 (58)	3.7 \pm 3.7 (58)	52.1 \pm 56.3 (58)
	Wetland Forest/Shrub	0.52 \pm 0.33 (42)	28.6 \pm 25.1 (43)	591 \pm 561 (43)	9.4 \pm 8.1 (43)	136.2 \pm 124.0 (43)
	Upland Forest	0.91 \pm 0.28 (28)	10.4 \pm 8.8 (32)	480 \pm 802 (32)	2.9 \pm 2.4 (32)	49.4 \pm 45.3 (32)
Landscape Unit	Channel	0.48 \pm 0.31 (17)	29.0 \pm 28.7 (17)	521 \pm 449 (17)	10.3 \pm 9.8 (17)	142.6 \pm 145.3 (17)
	Backfill	0.90 \pm 0.34 (13)	8.4 \pm 7.2 (13)	1003 \pm 496 (13)	2.4 \pm 2.5 (13)	34.9 \pm 31.8 (13)
	Floodplain	0.63 \pm 0.35 (102)	26.4 \pm 24.4 (113)	470 \pm 379 (113)	9.1 \pm 8.1 (113)	124.7 \pm 119.3 (113)
	Upland Ecotone	0.90 \pm 0.30 (38)	10.3 \pm 10.7 (42)	187 \pm 243 (42)	3.4 \pm 3.6 (42)	51.5 \pm 57.4 (42)
	Spoil	0.94 \pm 0.28 (34)	10.3 \pm 9.9 (37)	1183 \pm 1089 (37)	2.9 \pm 3.0 (37)	43.1 \pm 42.8 (37)

Mean \pm SD (N)						
Units	Classification	Bulk Density (g cm ⁻³)	LOI (Percent)	TP (mg kg ⁻¹)	TN (g kg ⁻¹)	TC (g kg ⁻¹)
Other		0.66 \pm 0.37 (27)	24.1 \pm 20.9 (33)	521 \pm 369 (33)	8.6 \pm 7.6 (33)	116.5 \pm 106.4 (33)

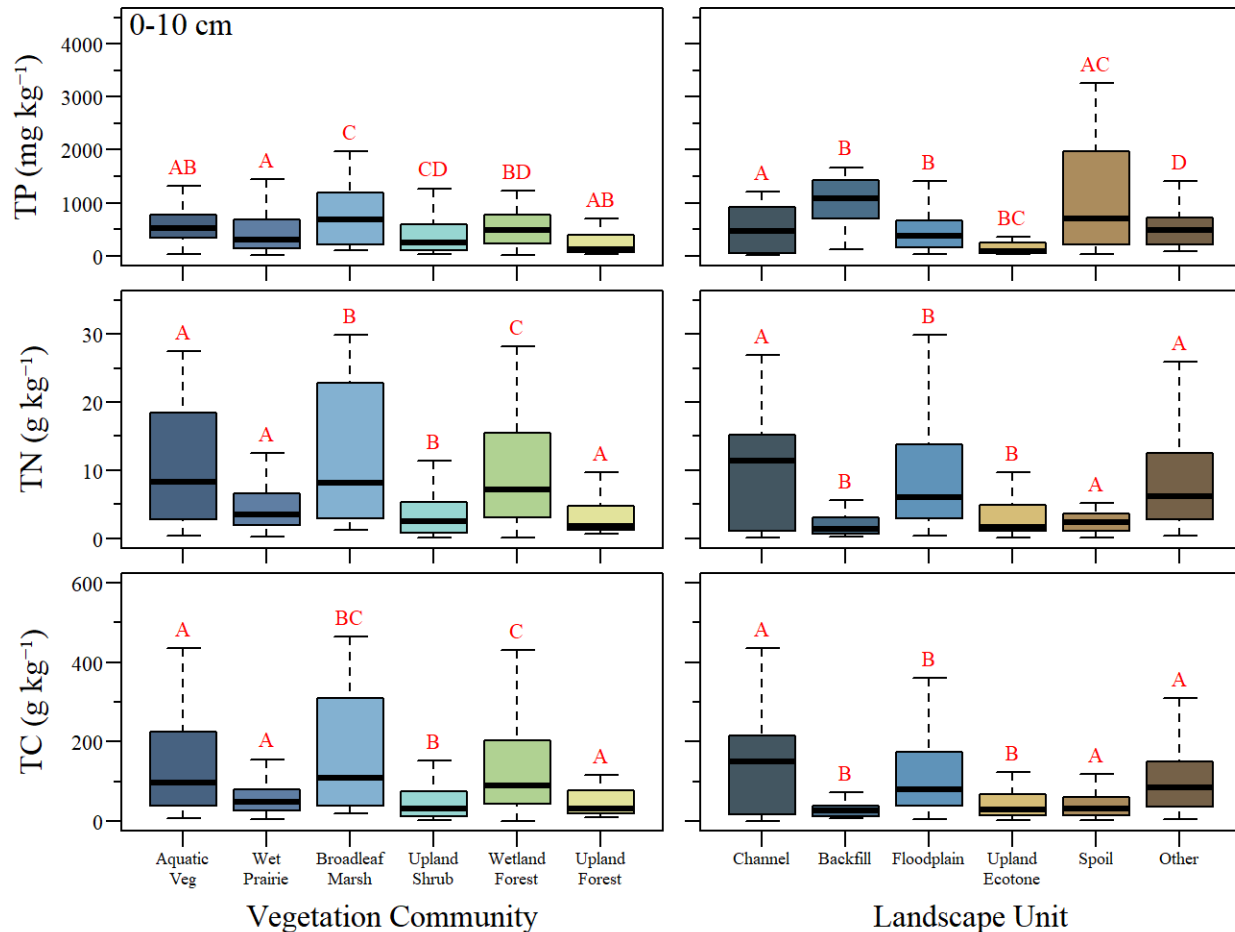


Figure 5 – Surface sediment total phosphorus (top; TP), total nitrogen (middle; TN) and total carbon (bottom; TC) boxplots grouped by vegetative community (left) and landscape unit (right). The letters above boxplots indicate statistically significant differences between groups for each parameter. Vegetative community and landscape unit were tested separately.

The comparison of soil nutrient concentrations between landscape units (Fig 6) indicates that soils associated with backfill and spoil landscape units contain a higher proportion of TP relative to TC and TN. Overall soil TP is positively correlated with TC ($r = 0.65$; $p < 0.01$) and TN ($r = 0.58$;

$p < 0.01$). However, these pairwise relationships differ when grouping soils into spoil/backfill and other landscape units. The pairwise relationship between soil TP and TC for spoil/backfill soils ($r = 0.49$; $p < 0.01$) varies from that of the remaining landscape units ($r = 0.88$; $p < 0.01$). Similarly, the pairwise relationship of soil TP and TN concentrations for spoil/backfill soils ($r = 0.24$; $p < 0.05$) differs from that of the other landscape units ($r = 0.89$; $p < 0.01$). Overall, greater variability in soil TP concentration is apparent for low TN and TC concentrations of spoil/backfill soils. Additionally, high bulk density and low LOI values suggest that P in these soils are potentially from a geologic origin (deep soils overturned during excavation).

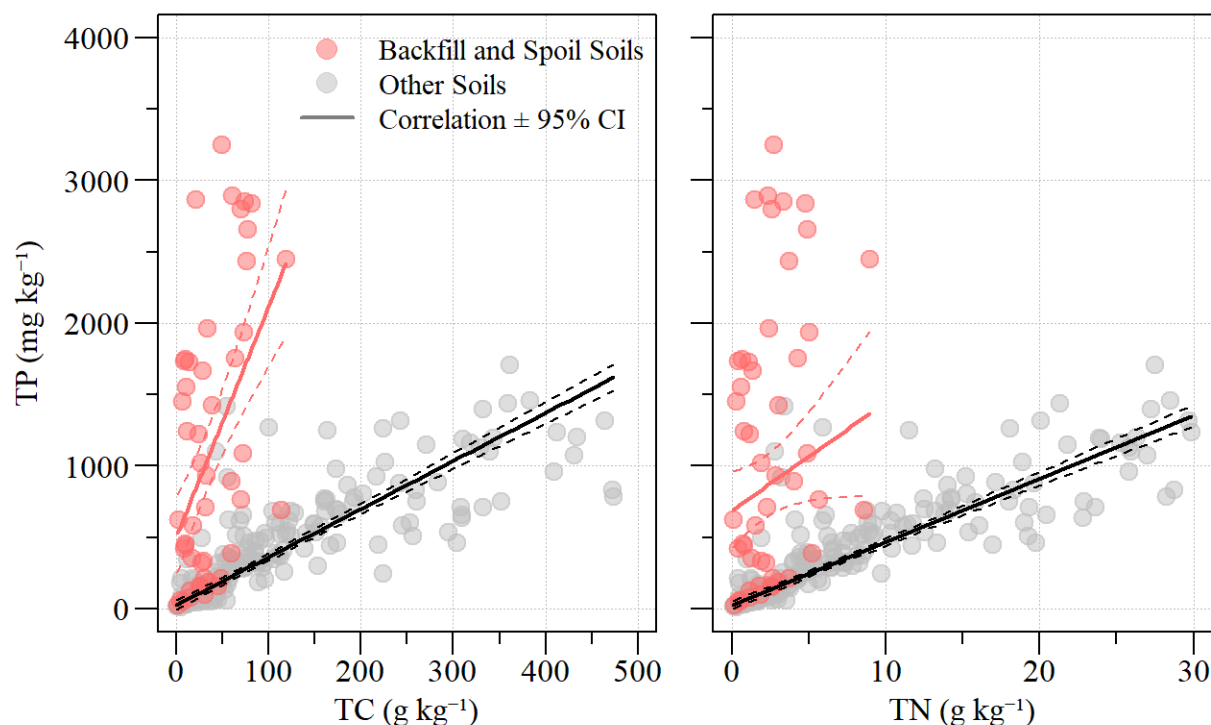


Figure 6 – Comparison of soil total phosphorous (TP) and total carbon (TC) and TP and total nitrogen (TN) between backfill and spoil soils versus other soils with correlations identified.

Geostatistical analysis

The spatial autocorrelation of ordinary kriging varied between soil TP, TN, and TC distributions with range values of 2.97, 1.03, and 1.09 km, respectively (Table 4). Meanwhile, the sill-to-nugget ratio for soil TP, TN, and TC were 0.55, 2.22, and 1.85, respectively (Table 5). Based on the sill-to-nugget ratio soil TP demonstrated a greater proportion of spatial dependent variation relative to

the other soil parameters. Sill-to-nugget ratios of soil TN and TC were greater than 1.0 suggesting a lower proportion of spatial dependent variation (i.e. stronger spatial pattern). Visually this is apparent in the spatial interpolations where ordinary kriging results indicate generally two areas of high soil TP concentration meanwhile, TN and TC soil concentrations are relatively variable (Fig 7).

Table 5 – Semivariogram parameters and kriging prediction error statistics for soil total phosphorus (TP), total nitrogen (TN), and total carbon (TC) using ordinary and residual kriging. Semivariogram model abbreviations are Sph for spherical and Exp for exponential models.

Kriging Method	Parameter	Model	Nugget	Sill	Range (m)	Sill:Nugget	RMSE	R ²
Ordinary	TP	Exp	0.99	0.55	2973	0.55	0.005	1.00
	TN	Sph	17.8	40	1035	2.22	1.8	0.96
	TC	Sph	4175	7733	1079	1.85	23.9	1.00
Residual	TP	Sph	0.43	0.18	5306	0.42	0.001	1.00
	TN	Exp	0.39	0.32	739	0.83	0.007	0.99
	TC	Sph	0.44	0.41	1292	0.93	0.030	0.93

Spatial patterns of soil TN and TC were very similar but differed from those of soil TP (Fig 7). Extremely high levels of P in spoil material dominate the interpolations, leveraging (masking) those areas over the trends of TP with organic matter observed at the lower concentrations. The overall effect of the highly leveraged TP values in the spoil is a less dynamic and informative mapped surface as the low concentration trends (patterns) are not visible. Given this spatial pattern, residual kriging results provide a finer-scale interpolation of soil characteristics. Moreover, residual kriging further stratifies the landscape to increase the detail and credibility of the interpolations, and to reduce the spatial effect of the highly leveraged spoil and backfill materials concerning TP.

As expected, sill-to-nugget ratios of residual kriging results were relatively low (< 1 ; Table 5). The residual kriging interpolation results of TP indicate very clearly the influence of spoil and backfill materials. However, these areas do not influence the entire landscape as was the case with the ordinary kriging results (Fig 7). The spatial trend observed in the residual kriging of TC and to some extent, TN suggests higher soil TC and TN in broadleaf marsh areas of the floodplain

wetlands and depressional areas (Fig 7). Meanwhile, the spoil and backfill areas with relatively lower TN and TC are visible (Fig 7).

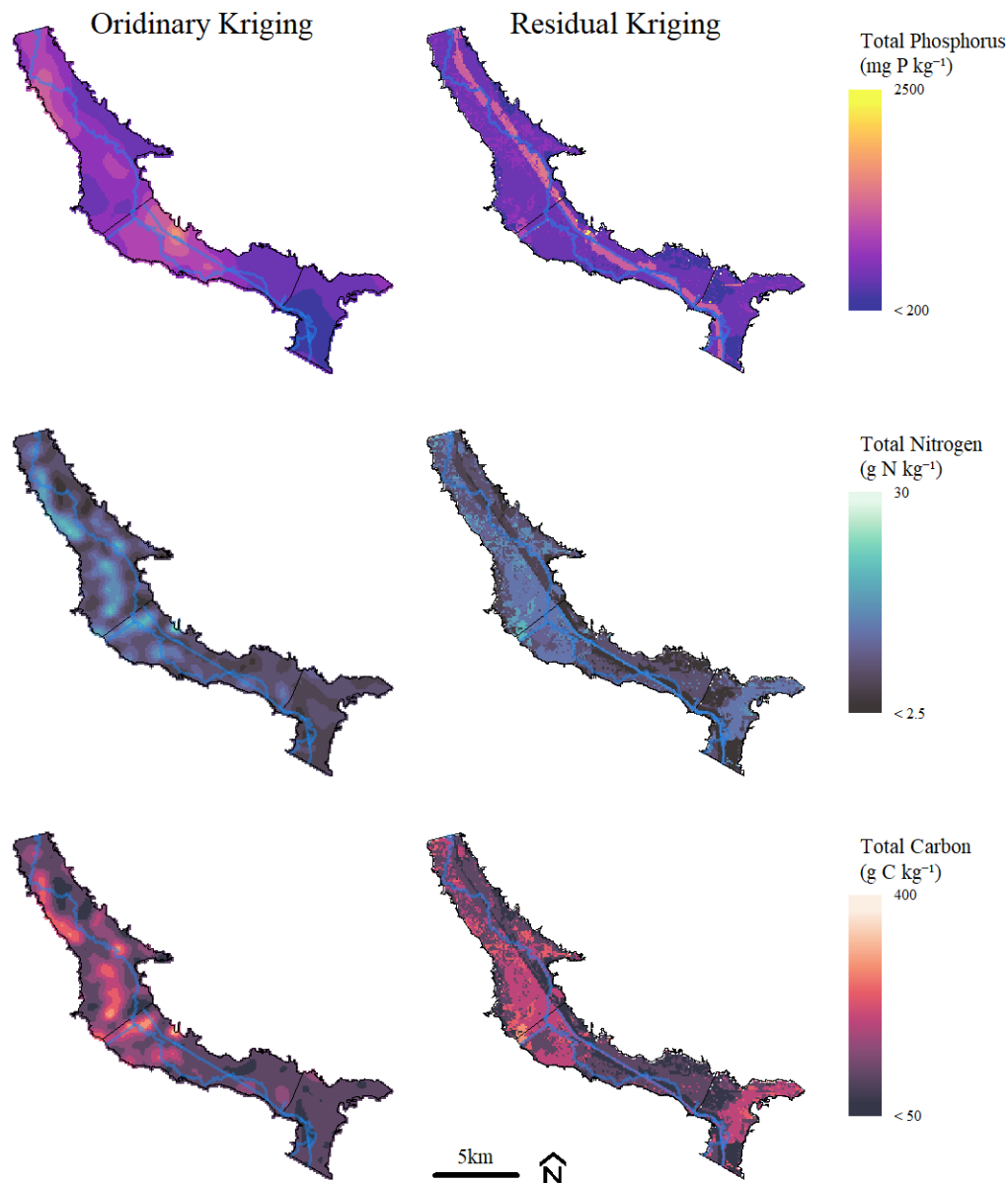


Figure 7 – Spatial interpolation of soil properties using ordinary (left) and residual (right) kriging results for total phosphorus (top; TP), total nitrogen (middle; TN), and total carbon (bottom; TC) within the Kissimmee River floodplain.

Discussion

Generally, as water moves through a floodplain (i.e. in and out of the main channel) geochemical and microbial processes result in the hydrologic and material (i.e. nutrients, biomass, etc.) exchange across the floodplain and to downstream waters. Moreover, the residence time of these exchanges ultimately influences the downstream process and the quality of receiving waters [4]. Modifications to floodplains through channelization or hydrologic manipulation can significantly influence the lateral hydrologic exchange of flow and nutrients affecting not only the floodplain system but also downstream ecosystems [3,26].

Nutrient mineralization, plant uptake, and sedimentation are important mechanisms of nutrient retention in floodplain ecosystems and are dependent upon floodplain hydrogeomorphology [27,28]. Floodplain ecosystems can trap large proportions of annual river loads by sequestering nutrients, or export less-bioavailable nutrient fractions, from rivers to downstream aquatic ecosystems [27,29]. However, human management and modifications to floodplain ecosystems can reduce hydrologic connectivity and sediment depositional characteristics [29]. In disconnected floodplain ecosystems (i.e. channelized rivers), floodplain hydrogeomorphology is disrupted by disconnecting geomorphic functional units of varying hydrologic connectivity potentially reducing the ecological functions [30,31].

In the Kissimmee River floodplain, the system was significantly modified to facilitate water management and navigation. These modifications included channelization the river and compartmentalization of the floodplain which almost eliminated flow through the floodplain [32–34]. In doing so, geomorphic functional units along the river were hydrologically disconnected, except in extremely rare circumstances. The disconnected hydrology resulted in a fundamental alteration to plant communities, wildlife habitats, and nutrient cycling. With the combination of physical modifications and water management strategies, nutrients are rapidly transported through the system resulting in limited in-river/canal interactions. As water moves from Lake Kissimmee, through the Kissimmee River floodplain, and into Lake Okeechobee nutrient loads and concentrations generally increase (Fig 2 and 4, Table 2). However, notable changes in the loading rates are apparent and could correspond to climate events and/or restoration activity.

River-Floodplain Nutrient Loading

The lake of the Upper Kissimmee Basin (including Lake Kissimmee) has been impacted by point source pollution since the 1950s and 1960s including four municipal wastewater treatment plants.

By the late 1970s, phosphorus and nitrogen loading to Lake Tohopekaliga was several times greater than natural conditions. Several efforts were initiated to address point-source nutrients in the early 1980s with measurable improvements in water quality in other Upper Basin lakes, including Lake Kissimmee [35]. The improvement in water quality conditions could explain the breakpoints early in P and N cumulative load time series (Fig 4) where the loading rate and nutrient export decrease relative to the prior period. Despite these minor improvements, loading and export continued to increase during the 1990s potentially linked to upstream ecosystem management (lake drawdowns), restoration activities and climatic events (i.e. hurricanes, tropical storms, drought, etc) (Table 1). However, breakpoints for both N and P cumulative load time series do not exhibit identical times suggesting that either N or P are more or less sensitive to hydrological restoration or other actions such as climatic conditions and watershed improvements.

In recent years (since 2019) the rate of TP export from the floodplain has changed presumably due to the progression of restoration activities (Table 1 and Fig 4). Phosphorus in the form of legacy inputs, internal cycling (organic), or geologic in nature could be mobilized as more of the system is restored. By the late 2010s, most of the canal backfilling had been completed across the Kissimmee River floodplain. As portions of the canal were incrementally backfilled, the potential for more areas of the floodplain to be hydrated became possible. However, hydrologic restoration in the form of adjusted water management is still needed to fully realize the complete restoration effort (i.e. Headwater Revitalization Schedule) and meet hydroperiod targets for floodplain vegetative communities [12,16,36]. This partial restoration (i.e. physical) can lead to two potential sources of nutrients, as water becomes available to hydrate formerly dry portions of the floodplain and potentially mobilize nutrients from the soil to the water column. The majority of the soils used in the backfilling of the canal were sourced from spoil mounds of the original floodplain soil within the Kissimmee River floodplain. These soils have mineral/inorganic characteristics with high P, low N, C, and OM (Table 4, Fig 4,5,6). Soils of the Lake Okeechobee Basin contain phosphate minerals such as vivianite, apatite, and others [37] and could be a potential source of P to downstream systems. Additionally, legacy and organic nutrients could be mobilized through the rehydration of oxidized soils as areas become hydrated [11,38]. The *in-situ* sources of nutrients combined with agricultural run-off [39] inputs have caused the exceedance of the assimilative capacity of the Kissimmee River floodplain, therefore, making the floodplain a consistent net exporter of nutrients (Fig 4). While still a net exporter the rate of P export has shifted by 2019 to

a decreased cumulative rate potentially signaling restoration success and/or recovery from recent hurricane impacts (i.e. Hurricane Irma). As floodplain function in the Kissimmee River continues to be restored and managed, additional effort may be needed to address nutrient inputs and internal legacy nutrients.

Floodplain Soils

In a fully functioning floodplain, the ecosystem hydrologic connectivity should lead to strong spatial gradients of soil nutrients [27,40]. The interaction of flood inundation, flow hydraulics, and sediment during floods facilitate the distribution of sediment nutrients across the floodplain [41]. Despite being virtually disconnected from the river the Kissimmee River floodplain does exhibit some spatial gradients of sediment nutrients linked to vegetative communities and landscape units (Fig 5 and 7). More specifically, soils in spoil areas generally have the highest P and lowest N and C (Fig 5). While a significant correlation is expected between soil C and P due to observed associations of P with organic matter in many other regional soils [42–44] the C versus P relationship of soils in spoil and backfilled areas are different than those of other landscape units (Fig 5 and 6). Backfill and spoil soils exhibited low C and N with high P concentrations (Fig 6). The low C associated with these high P values potentially suggests Pliocene-aged P-bearing soil mineral [45]. Moreover, the apparent expansion of TP enrichment in the backfill areas of Phase I suggests that disturbance of spoil materials will increase the overall spatial extent of elevated soil P and contrasts with the relatively small spatial footprint of high TP materials in Phase II/III (Fig 5).

In addition to variable P distributions along the Kissimmee floodplain, soil N and C concentrations were highly variable between vegetation communities and landscape units (Fig 5). Most notably floodplain and channel landscape units have relatively higher N and C concentrations suggesting the potential surficial accumulation of organic matter. However, restoration discharges are expected to “flush” organic debris and sediment from the active river channel [11]. The interaction of flood dynamics/seasonal inundation and biological succession creates a dynamic mosaic of biogeochemically active patches across the landscape [46]. As such soil N and C distribution were greatest in riparian and floodplain wetlands (Fig 5). Consistent with past studies [46,47] these

results suggest that landscape position is a strong driver in floodplain organic matter and nitrogen dynamics.

Conclusion

Despite being hydrologically disconnected for more than half a century the Kissimmee River floodplain is consistent with other floodplain ecosystems [29,46–48] where soil N concentrations were strongly associated with OM accumulation and P accumulation was strongly correlated with mineral sediment deposition. Floodplains function as important nutrient sinks along the terrestrial-aquatic continuum. However, legacy nutrient impacts and hydrologic disconnections for flood control measures reduce the ability of the floodplain to function and store nutrients. Moreover, physical restoration is not enough to restore floodplain function, hydrologic restoration is also needed to actualize complete restoration benefits.

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