An evaluation of peat loss from an Everglades tree island, Florida, USA

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SUMMARY

The tree islands of the Everglades are considered to be biodiversity “hotspots”, where the majority of terrestrial species of the Everglades are found. Drainage for agricultural and urban development in the early 1900s has had a severe impact, converting many of them into “ghost tree islands” which have lost most of their woody vegetation and much of their altitude (elevation). A survey conducted in 1973 on one of the prominent ghost tree islands, named “Dineen Island”, provides insights into the past. We compared the results of the 1973 survey with those of a survey conducted in 2009, in order to examine changes in Dineen Island that had taken place over 36 years and to provide information about general trends in the Everglades. Peat loss at Dineen Island was roughly 4 mm yr^{-1}. This subsidence, as a consequence of peat loss, has been accompanied by losses in nitrogen and phosphorus of 234 and 2.5 metric tons (4.5 and 0.05 metric tons per hectare), respectively. As many of the Everglades tree islands have been lost from the landscape due to historical water management practices, quantifying nutrient losses from this ecosystem may be useful in helping to predict non-anthropogenic nutrient biogeochemistry shifts in Everglades oligotrophy.

KEY WORDS: carbon; ghost tree island; nitrogen; peatland; phosphorus; restoration

INTRODUCTION

Starting in 1884, water was drawn from Lake Okeechobee as a first step toward draining the Everglades (McVoy *et al*. 2011). In the early 20th century, the State of Florida initiated the dredging of additional canals cutting north-west to south-east through the Everglades. The first of these, the North New River Canal, was opened in 1912, whereas the last, the West Palm Beach Canal, was opened in the early 1920s. In the 1940s, concerns about over-drainage of the Everglades, inadequate drainage of the agricultural lands close to Lake Okeechobee and the need for flood control after the deadly flood of 1947 prompted initiation of an extensive water control project, the Central and Southern Florida (C&SF) Flood Control Project (USACE & SFWMD 1999) for flood control and other purposes. A system of levées and canals now separates five Water Conservation Areas (WCAs). Canals create low-resistance paths that reduce the overland flows that are essential for the wetland. This has resulted in the strong patterning of ridges and sloughs, including tree islands, becoming blurred or being eliminated (Davis *et al*. 1994, Willard *et al*. 2006, McVoy *et al*. 2011).

Tree islands are unique landscape features and critical habitat for maintaining biodiversity within the greater Everglades freshwater ecosystem (Sklar *et al*. 2002). Research also indicates that the islands are nutrient hotspots which sequester a considerable amount of the phosphorus entering the central Everglades marsh (Wetzel *et al*. 2005). The tear-drop shaped tree islands appear to have been shaped (with a broader head region and a narrower tail pointed downstream) by the surficial flow of nutrients. The heads of tree islands have been found to have soils enriched in phosphorus, the concentration of which is several orders of magnitude higher than found in the sediments of the surrounding sloughs (Sklar *et al*. 2002).

Many tree islands also serve as biodiversity hotspots by supporting a disproportionately high number of plant and animal species relative to the surrounding marsh (Sklar *et al*. 2002, Lodge 2005, Godfrey & Catton 2006). However, both of these functions (concentrating biodiversity and nutrients) are likely to have been compromised because many of the tree islands that existed in the 1940s have been degraded and the canopy is now significantly reduced in size or has been lost completely (Hofmockel *et al*. 2008).

Tree islands have been severely degraded due to a number of causes, including: oxidation and fires resulting from the drainage initiated during the late 19th century; and shifting hydrological regime and changes in water level in response to artificially altered hydroperiods since the early to middle twentieth century (Davis *et al*. 1994, Willard *et al*. 2006). Although many of the islands have disappeared completely from the landscape, their remnants in the form of "scars" (typically expanses of sawgrass, *Cladium jamaicense* Crantz) are seen on aerial photographs, and are now referred to as ghost tree islands.

The C&SF project impounded and divided the Everglades north of the Tamiami Trail into three Water Conservation Areas (WCAs). These are WCA 1, WCA 2 and WCA 3; two of which are further subdivided into WCAs 2A, 2B, 3A and 3B (Figure 1). These WCAs experience little of the flow that characterised the original Everglades but allow water managers to retain water in them, which was not possible following building of the original canals.

The tree islands in WCA 2A (Figures 1, 2) have experienced greater impacts than those in most of the Everglades system due to the extreme drying and fire events of the late 1800s through the early 1900s, followed by high water levels induced by the flood control project. The tree island patterning still exists in most of WCA 2A (Figure 2), but the majority of it is now formed by sawgrass rather than by trees. Dineen Island, named after the renowned Everglades researcher J. Walter Dineen, was a large strand tree island (Figures 2, 3) located in the south-eastern part of WCA 2A of the Everglades Protection Area (EPA). Once a distinct island, it now exists as a small stand of trees and shrubs surrounded by a large area of sawgrass, essentially having been converted to a large sawgrass ridge. Aerial photographs from 1973 and 2003, along with a recent oblique aerial photograph, demonstrate the process and show the sawgrass expanse that now marks the footprint of this former tree island (Figure 3).

Very little is known of the physical, chemical and biological changes that have occurred in tree islands since they have been degraded. Limited information is available on landscape-scale ecological patterns in terms of changes in microtopography (DeBusk *et al*. 2001, Rivero *et al*.

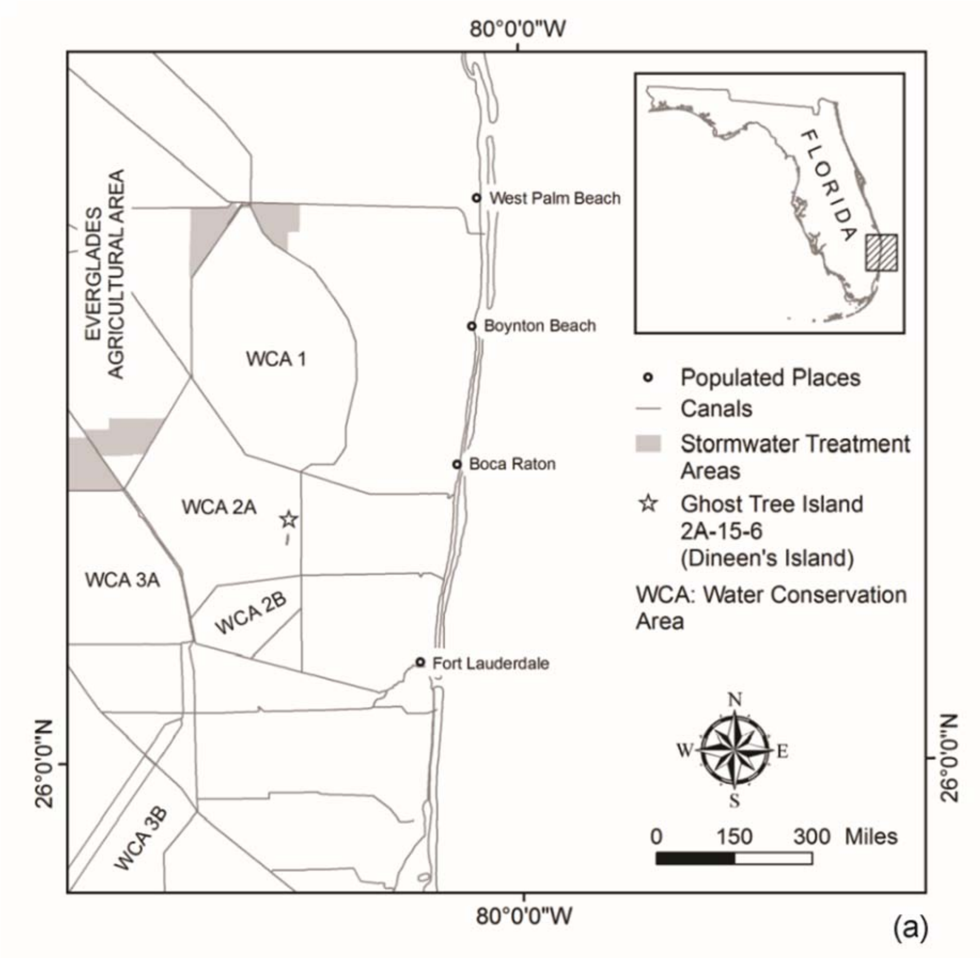

Figure 1. Map of the study area showing the Everglades Water Conservation Areas. The location of Dineen Island is indicated with a star.

2007), nutrients (Wetzel *et al*. 2005, 2009) and the species composition of the affected vegetation (Worth 1988).

From 1940s imagery, it appears that Dineen Island had already undergone some significant changes but still had a substantial stand of trees at that time. A land survey was conducted in 1973 (Central and Southern Florida Flood Control District 1973) and, from aerial photography taken that year, it was evident that there were fewer trees but the tree island was still distinguishable from the surrounding slough and ridges. Therefore, the condition of Dineen Island in 1973 can be regarded as degraded, although we are unable to evaluate changes prior to that time. It is apparent from aerial photographs that the tree canopy changed considerably between the 1940s and the present. A quote from Dineen (1974) clarifies some of the changes that had occurred prior to the 1973 survey: “In 1963, the island was clearly visible for miles as a long, green strand of live willows extending from north to south for about one mile. By 1965, it was difficult to locate the island on the horizon because most of the trees had died and were defoliated. By 1967, all sign of living trees was gone.”

To gain a better understanding of the possible role of water management in the maintenance and restoration of oligotrophic marsh habitats in the Everglades, we performed an analysis to evaluate some of the changes in Dineen Island that occurred between 1973 and 2009, using the 1973 land survey data and a series of measurements made in 2009.

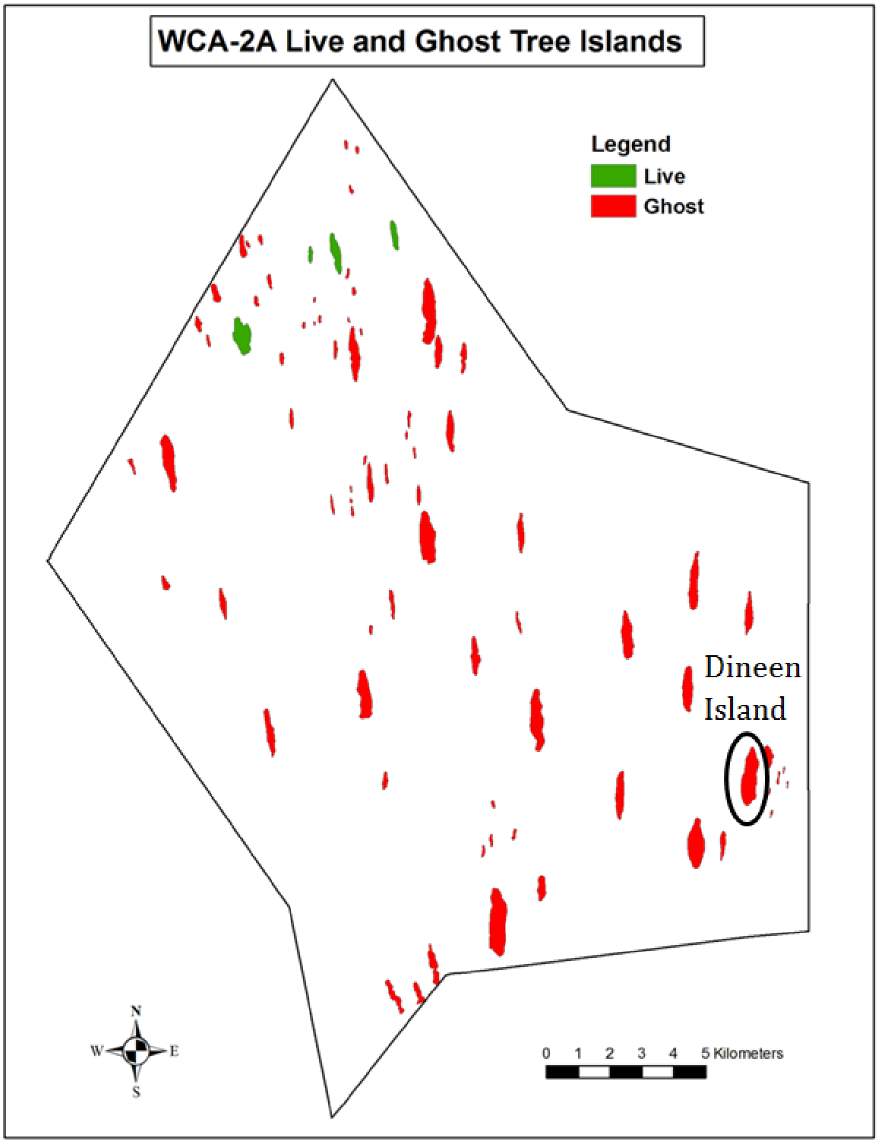

Figure 2. A recent map of ‘live’ and ‘ghost’ tree islands in Water Conservation Area (WCA) 2A (Rutchey 2009). The majority are now ghost tree islands.

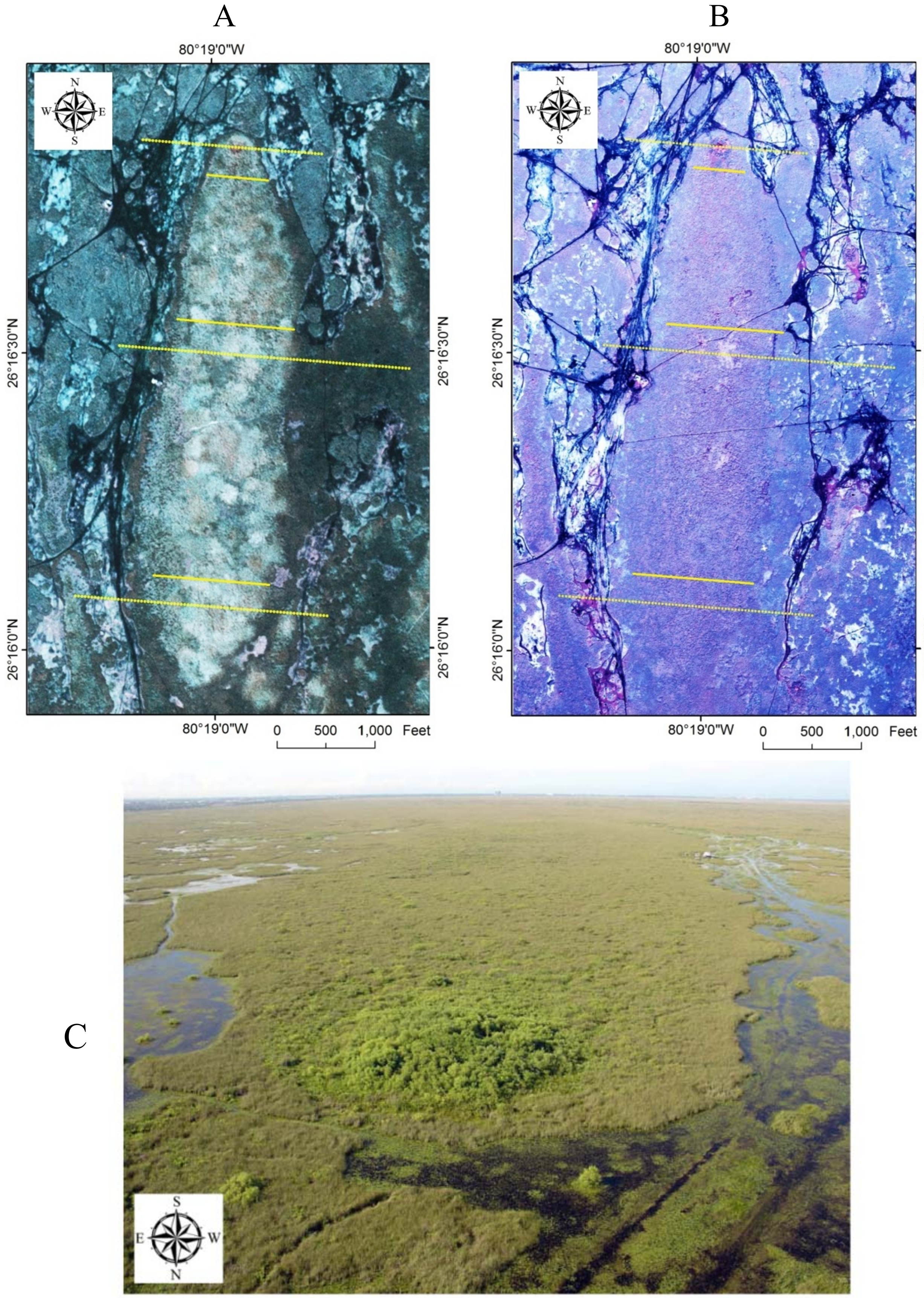

Figure 3. (A) an aerial photograph of Dineen Island from 1973; (B) an aerial photograph of Dineen Island from 2003; (C) an oblique aerial photograph of Dineen Island taken in 2009, from the north looking south. In (A) and (B), solid lines indicate the 1973 transects and dotted lines the 2009 transects for this study.

METHODS

We used a historical survey from 1973 and a surface altitude survey from 2009 to evaluate the change in volume of Dineen Island during the intervening 36 years. Both surveys were recorded in Imperial units and converted to SI units for volume and mass calculations. In addition, a vegetation survey, a bedrock altitude survey and an analysis of soil cores collected in 2009 were used to characterise the island. Bulk density measured in shallow cores was used to convert the change in volume to change in mass. The carbon, nitrogen and phosphorus contents of the shallow cores were used to estimate the changes in storage of each of these elements that accompanied the changes in peat volume.

Historical survey of Dineen Island

The historical survey of Dineen Island was commissioned by the Engineering Division of the Central and South Florida Flood Control District (1973). The boundary of the island at that time (perimeter 3725 m) was established by the surveyors from the extent of burned tree stumps. The area surveyed was 519,485 m^2 or 52 ha. A transit and level survey of peat surface altitude, referenced to a local benchmark, was conducted in twelve linear transects spanning the tree island within the defined boundary. The spacing between survey locations ranged from 15 m at the head of the tree island to 30 m at the near tail and far tail.

Recent topographical survey of Dineen Island

The second topographical survey was conducted in July 2009 by Ewe *et al*. (2009). The head of this tree island was found to be located on a pinnacle rock at approximately 26° 16' 49.5" N, 80° 18' 56.3" W. Its dimensions at this time were assumed to be 1,700 m long and 350 m wide. While conducting the survey, the July 2009 edge of the island was determined as the boundary between woody species or sawgrass and marsh vegetation.

The topographical survey was implemented in three linear transects across the head, mid-island (near tail) and far tail of the tree island (Figure 4). Each transect spanned beyond the boundary of the island itself, into the sloughs and nearest ridges on either side. The actual surveyed lengths were 540 m for the head transect, 880 m for the near tail transect and 760 m for the far tail transect.

A sounding rod was used to assess surface microtopography (i.e. depth to peat surface) by determining the water depth at each location (all of the survey locations being submerged on the sampling date). Subsequently, peat surface altitude at each of the survey locations was calculated by subtracting these measurements from the average water level recorded for the same date by the nearest marsh gauge within WCA 2A, and assuming a 'flat pool'. The records of water level were obtained from the DBHYDRO database created and managed by South Florida Water Management District (SFWMD 2010).

Depth from the water surface to bedrock was assessed using a 3.3 m long stainless steel probing rod (8.3 mm diameter). The spacing between the bedrock altitude survey locations ranged from 10 m on the head transect to 20 m on the near tail and far tail transects (Figure 5). Bedrock surface altitude for each location was again calculated by subtracting the probe measurement from the average water level recorded by the nearest WCA 2A marsh gauge (SFWMD 2010) for the date of survey.

Geospatial analyses

For comparison purposes, the second transect of the historical (June 1973) survey corresponds to the recently surveyed (July 2009) head transect, the historical fifth transect relates to the recent near tail transect and the historical tenth transect is comparable to the recent far tail transect. Figure 6 depicts the peat surface altitudes measured along these transects in 1973 (A′–A′ with 12 points, B′–B′ with 13 points and C′–C′ with 11 points) and 2009 (A″–A″ with 55 points, B″–B″ with 89 points and C″–C″ with 77 points). The A transects represent the head portion of the island, the B transects represent the near-tail portion and the C transects represent the far tail (Figures 4 and 5).

All data produced from the surveys were georeferenced, compiled and organised in the form of a GIS database for subsequent analysis (Aronoff 1989, Bonham-Carter 1994, Lo & Yeung 2002). Data from the surveys shown in Figure 6 were used to create interpolated surfaces for Dineen Island in 1973 and 2009 (Figure 7) by performing 'Ordinary Kriging' operations using 'Gaussian Semivariogram Models' on the historical and recent survey records of surface topography. Following the 'Ordinary Kriging' operations, we performed spatial analyses using ArcGIS® (ESRI 2004a, b, c) to compute the peat gain and loss at Dineen Island. For application of this interpolation technique, a minimum number of nine points is required and randomly distributed data points would provide better spatial autocorrelation. Although our datasets were not randomly distributed, we had no other data and, therefore, no choice other than to use the transect-based linear sampling locations to create the interpolated surfaces.

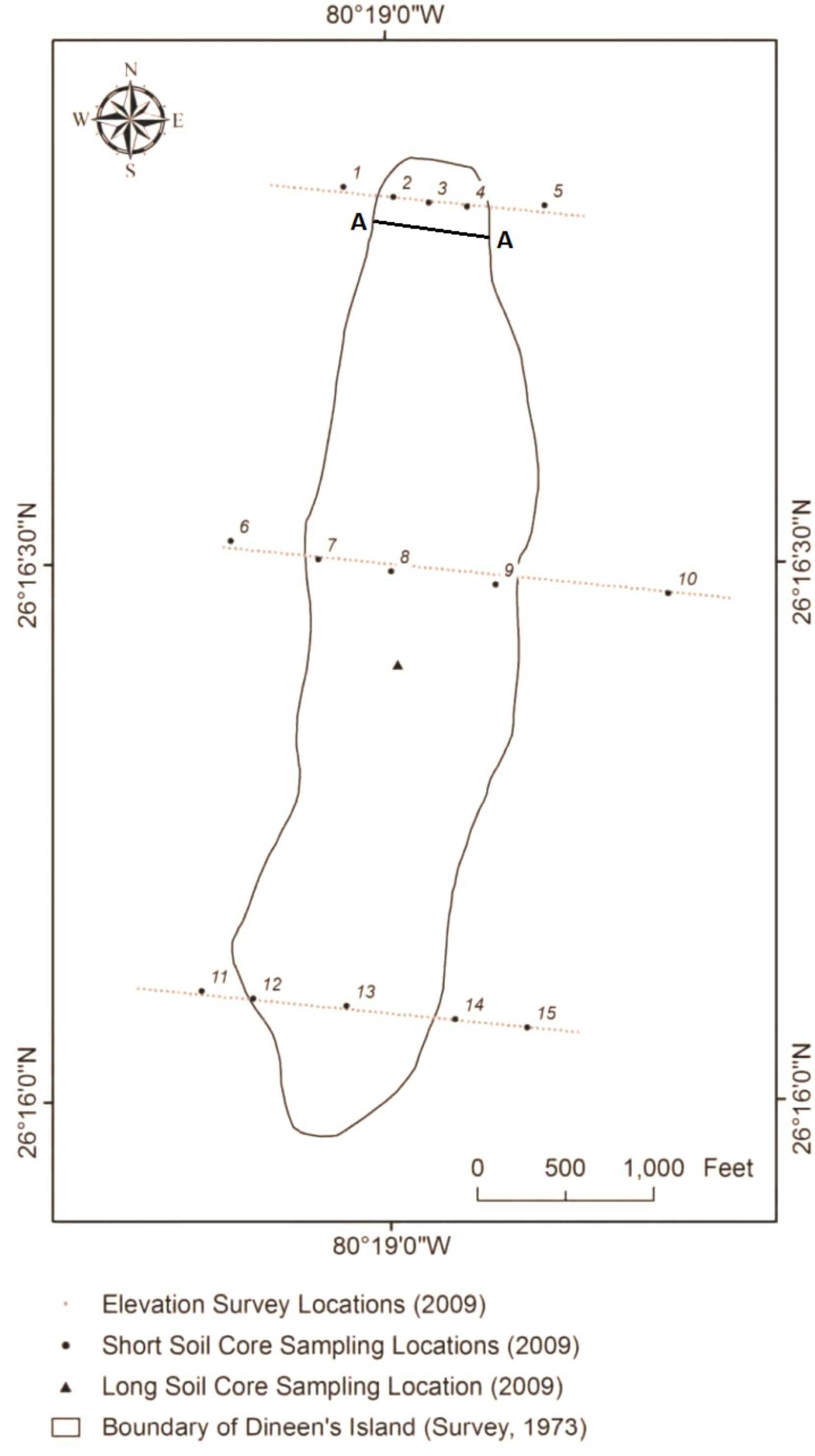

Figure 4. Map of Dineen Island showing the locations of altitude (= 'elevation') survey measurements and soil cores. Line A–A denotes the demarcation between the head region (north) and the tail region.

Because the values used in our spatial analysis were not randomly distributed, we performed basic calculations to provide a check on our results. For this check, we compared corresponding altitude values between the 1973 and 2009 transects. As the survey locations were closer together in 2009 than in 1973, averages for groups of the 2009 values were calculated to correspond with the 1973 survey points. Thus, the 2009 values used for comparison were means of five measurements along the A″ transect and seven measurements along the B″ and C″ transects. The differences between the altitudes

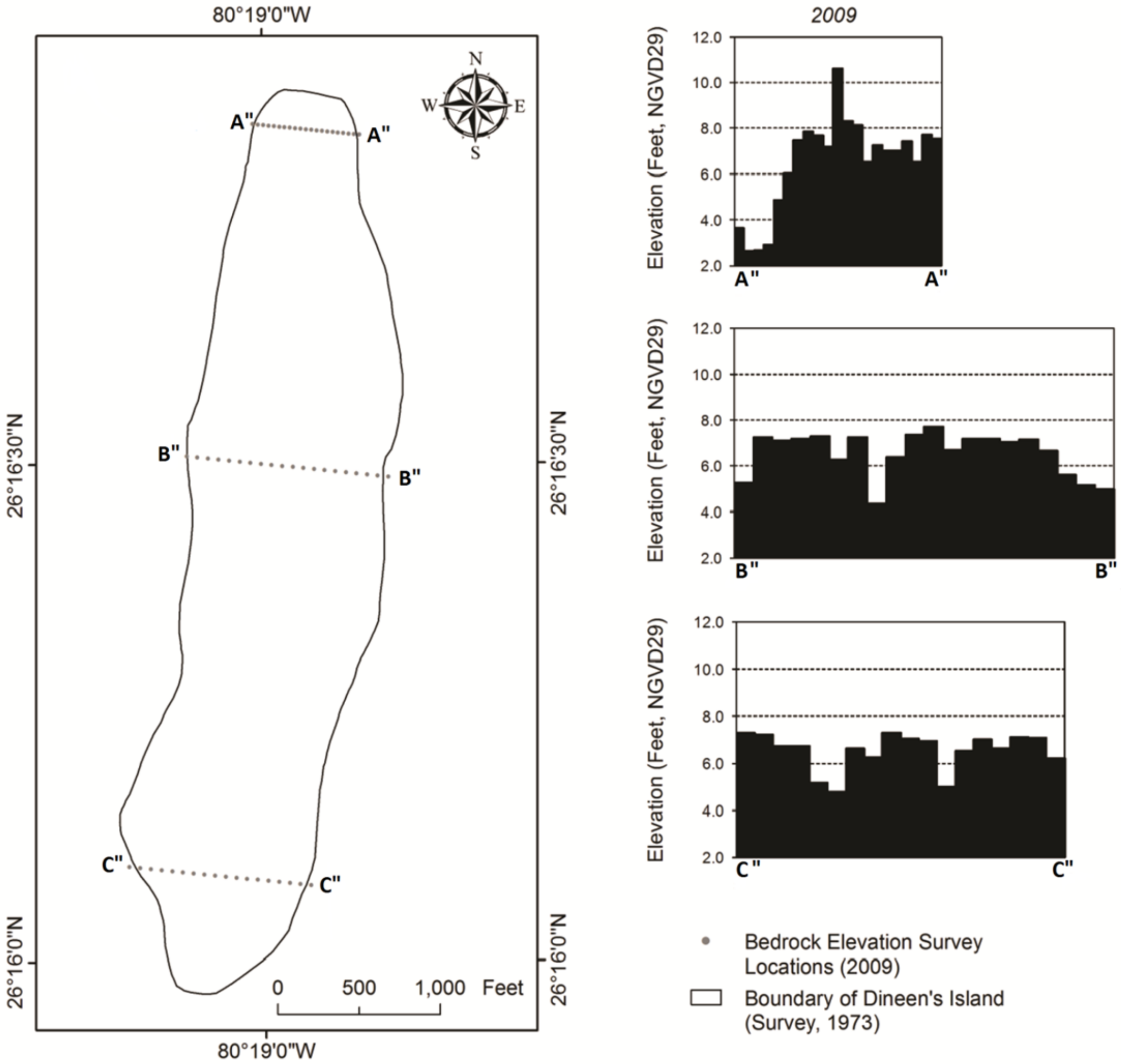

Figure 5. Bedrock altitude (= 'elevation'; in feet above sea level) measured along three Dineen Island transects in 2009. The datum is the National Geodetic Vertical Datum of 1929 (NGVD29).

at the 1973 points and the corresponding mean values for 2009 were calculated. For each transect, the mean (and standard deviation) of the difference values was calculated to provide a rough estimate of the amount (and variability) of subsidence that had occurred between the times of the two surveys.

Soil cores

Soil cores were collected in July 2009 at the locations shown in Figure 4 (Ewe *et al*. 2009). The cores were sectioned at 2.5 cm (from surface to 10 cm depth) or 5 cm (from 10 to 30 cm depth) intervals over the full depth of the core. The sections were individually analysed for bulk density (BD) as Mg m^{-3}; total phosphorus (TP) as mg kg^{-1}; total nitrogen (TN) as %; total organic carbon (TOC) as %; and loss on ignition (LOI) as % (USDA 2009). For each attribute measured, we calculated a weighted average value to represent each of three regions of Dineen Island (Figure 4): the head (cores 2, 3 and 4), the near tail (middle; cores 7, 8 and 9) and the far tail (farthest downstream; cores 12 and 13). To calculate the weighted average value, the content (concentration) of the attribute for each core section was multiplied by the fraction of its own core that it represented, then an average for all core sections per region was determined. The weighted average values were used along with the change in volume at the head and tail regions between 1973 and 2009 to determine the apparent losses of peat mass, carbon, phosphorus and nitrogen. Average bulk density values by depth were determined using the value by depth of the 30 cm (shallow) cores from the head, near tail and far tail, respectively. Although the bulk density values for a long core that was also taken in 2009 indicate a slightly

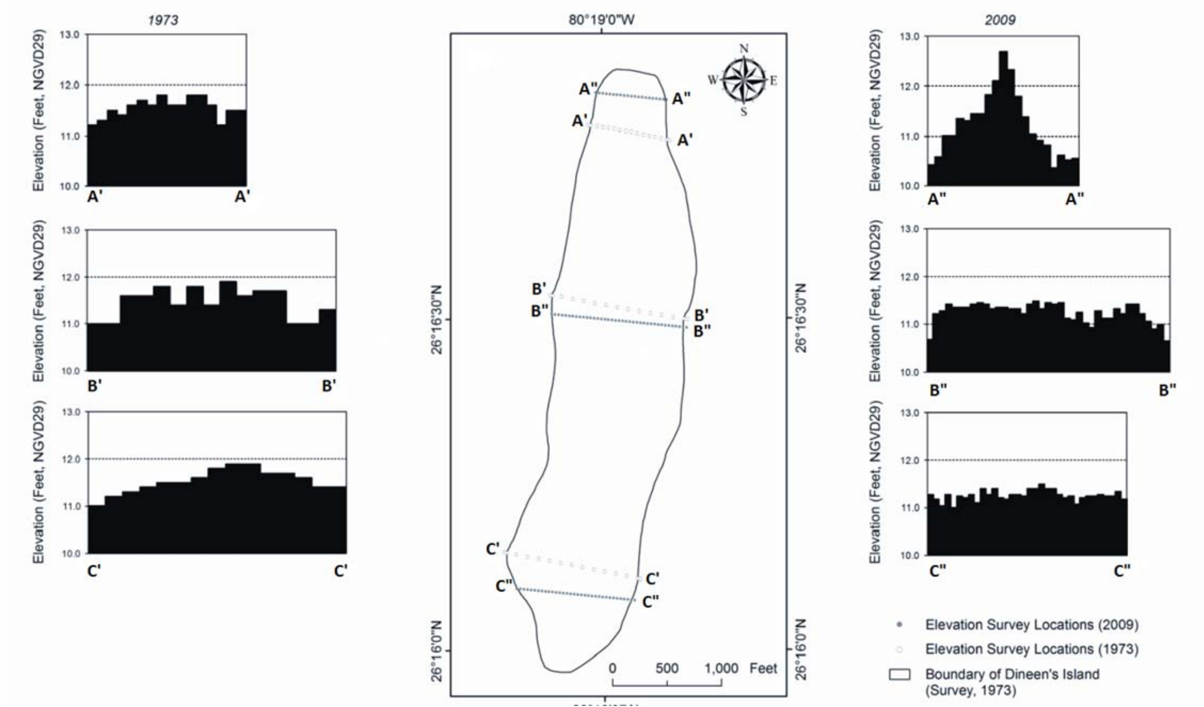

Figure 6. Peat surface altitude (= 'elevation') measured along three transects on Dineen Island in 1973 (left) and in 2009 (right). The datum is the National Geodetic Vertical Datum of 1929 (NGVD29).

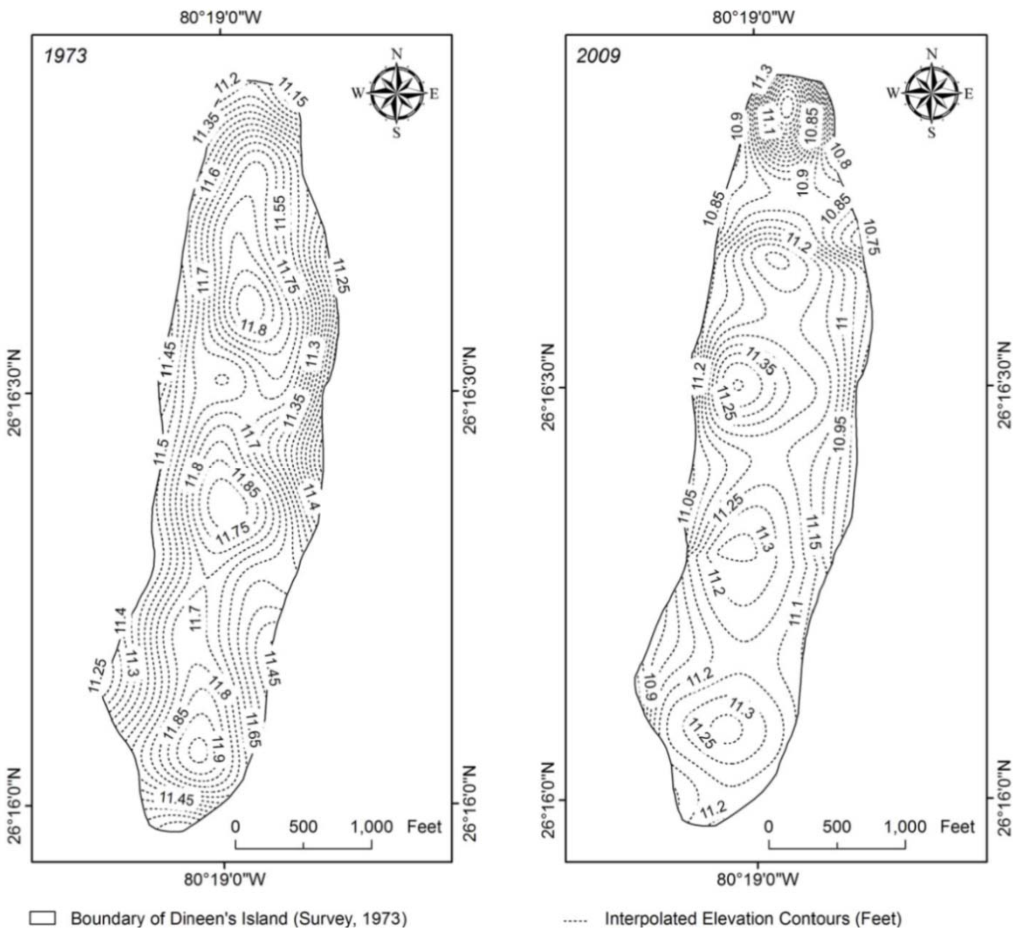

Figure 7. Interpolated peat surface altitude (= 'elevation') contours for Dineen Island (altitudes in feet above NGVD29): 1973 (left) and 2009 (right).

greater bulk density below 30 cm (mean values 0.131 Mg m^{-3} for 0–30 cm and 0.175 Mg m^{-3} for 30–60 cm), as we were interested in the loss of peat from the surface of the island, the values from 0–30 cm transect cores were used.

We used the weighted average, average maximum and minimum values by core of bulk density and total carbon for the head transect to calculate the potential range of the mass of peat, carbon gained and of the carbon dioxide sequestered or lost. We combined the values for the near and far tails, as these are similar in nature on ghost tree islands, to calculate the range of peat and carbon lost. In addition, we used the weighted average value, plus the average maximum and minimum TP and TN contents by core, to calculate the bulk mass of each of these nutrients that had been sequestered at the head, as well the mass that had been lost from the rest of the island.

RESULTS

The total number of bedrock altitude measurements carried out in July 2009 was 53; the minimum and maximum values obtained were 0.8 m and 3.2 m (NGVD29 vertical datum), respectively. Bedrock depressions up to 1 m deep and 40 m across were observed, as was a high degree of topographical heterogeneity in the bedrock surface.

Comparison of the peat surface altitudes from the historical and recent surveys indicates that there is a prominent high point (pinnacle rock) on the head of this tree island that was recorded during the recent survey but not during the historical survey, when the pertinent transect was placed a little farther to the south. The pinnacle rock covers a very small area of the head region surface and did not significantly affect the calculations of change in peat volume, although it may have contributed to the result from our spatial analysis that a small amount of accretion, rather than subsidence, had occurred in the head region.

In 2009 the mean peat thickness at the head of Dineen Island was 1.29 m, at the near tail it was 1.38 m and at the far tail it was 1.33 m. The average peat thickness for the whole island, as determined from the interpolated surface, was also 1.33 m. The recent differences in surface altitude between the tree island and the surrounding slough were 0.27 m in the head region, 0.19 m in the near tail region and 0.14 m in the far tail region. The current head is a nearly circular stand of woody vegetation approximately 70 m across (Figure 3C). Vegetation records from the 2009 survey indicate that the head vegetation included some native species such as buttonbush (*Cephalanthus occidentalis* L.) but was dominated by the invasive Brazilian pepper (*Schinus terebinthifolius* Raddi) (Ewe *et al*. 2009).

By comparing the interpolated surfaces we found that, between 1973 and 2009, approximately 567 m^3 of peat was gained at the head region over an area of 10,949 m^2, whereas 72,951 m^3 of peat was lost, mainly in the near tail and far tail regions, over an area of 507,751 m^2 (Figure 4). Hence, the average peat subsidence (based on the interpolation) due to oxidation over 36 years was calculated to be about 0.14 m, which is equivalent to 4.0 mm yr^{-1}. This result compares well with the average peat subsidence of approximately 4.2 mm yr^{-1} over 130 years which was calculated for the entire landscape of WCA 2A by Aich & Dreschel (2011).

The differences between transect altitudes derived by comparing (a) the three transects from the two surveys and (b) all 12 transects from 1973 with the three transects from 2009 (results from the latter comparison are shown in parentheses below) were calculated as a check on the results obtained by comparing the interpolated surfaces. These calculations indicated that the northern (head) of the island lost an average of 240 (220) mm, the near-tail an average of 180 (220) mm, and the far-tail an average of 180 (180) mm. Overall, the island lost about 200 mm (210 mm) of peat (mean value) with a standard deviation of 110 mm (110 mm), or approximately 100,000 (108,000) ± 55,000 (58,000) m^3. This translates to an average peat subsidence of 5.5 (5.8) mm yr^{-1} (range 2.8–8.5 (2.7–8.6) mm yr^{-1}). Thus, we consider that comparison of the interpolated surfaces provides a reasonable rough estimate of the changes in peat volume. These results also indicate that the peat loss can be as little as half of, or as much as 1–1.5 times, our reported average values.

The average values and ranges of BD, TOC, TP and TN, calculated per region of the tree island, are shown in Table 1. For the head region, the mass of peat and carbon gained, together with the bulk mass of phosphorus and nitrogen that had been sequestered into additional peat, were calculated directly from the values in Table 1 and are shown in Table 2. The masses of peat, carbon, phosphorus and nitrogen that had been released into the marsh and/or the atmosphere from the tail of the island, derived by combining values for the near and far tails from Table 1, are also shown in Table 2.

Weighted average values for peat bulk density, carbon, phosphorus and nitrogen were used to calculate means. Average minima and maxima (by transect) of the same attributes were used to report

Table 1. Weighted average, maximum and minimum average (by core) values of selected soil attributes measured for Dineen Island peat cores in 2009.

Location on island	Core numbers (Figure 4)	Value description	BD (Mg m^{-3})	TOC (%)	TP (mg kg^{-1})	TN (%)
Head	2, 3 and 4	weighted average	0.10	41.1	13618	2.75
		minimum	0.07	33.0	460	1.91
		maximum	0.12	47.2	33427	3.13
Near tail	7, 8 and 9	weighted average	0.11	44.8	416	2.94
		minimum	0.10	44.3	343	2.86
		maximum	0.12	45.2	498	3.05
Far tail	12 and 13	weighted average	0.10	44.9	359	2.94
		minimum	0.09	44.6	322	2.88
		maximum	0.11	45.1	397	3.99

Table 2. Results of the calculations of changes in the volume and mass of Dineen Island peat between 1973 and 2009. Positive values indicate gains of volume and mass.

Tree island region	Value description	Volume (m^3)	BD (Mg m^{-3})	Mass (Mg)	C (Mg)	TP (Mg)	TN (Mg)
Head	weighted average	567	0.10	57	25	0.77	1.6
	minimum	567	0.07	40	13	0.02	0.8
	maximum	567	0.12	68	32	2.27	2.1
Near and far tails	weighted average	-72951	0.11	-8025	-3604	-3.10	-235.9
	minimum	-72951	0.10	-7295	-3232	-2.35	-208.6
	maximum	-72951	0.12	-8754	-3948	-4.36	-349.3

ranges (in parentheses). Between 1973 and 2009, the head of Dineen Island gained about 56 (39.7–68.0) Mg (metric tons) of peat containing 25 (13–32) Mg of carbon, 0.8 (0.02–2.3) Mg of TP and 1.6 (0.8–2.1) Mg of TN. On the other hand, the remainder of the island (near tail and far tail) lost 8,025 (7,295–8,754) Mg of peat resulting in the release of 3,603 (3,231–3,948) Mg of carbon (as carbon dioxide, methane or dissolved/particulate organic carbon), 3.1 (2.3–4.6) Mg of TP and 236 (209–349) Mg of TN. Overall, there was a net loss of 7,967 (7,255–8,686) Mg of peat, 3,578 (3,219–3,916) Mg of carbon, 2.3 (2.1–2.3) Mg of TP and 234 (208–347) Mg of TN. These values represent just 36 years of change at Dineen Island.

DISCUSSION

The characteristics of Dineen Island make it an ideal tree island for study. The presence of the pinnacle rock at its head is consistent with one of the proposed formation mechanisms for many tree islands, which involves initiation by the development of herbaceous then woody vegetation on a bedrock summit (Sklar *et al*. 2002). In addition, the bedrock surface beneath the island is highly heterogeneous leading to a peat layer of varying thickness with a relatively smooth surface.

The changes documented in this study come after a period of severe degradation and are, thus, a very conservative estimate of the net losses that have actually occurred. The remaining woody vegetation on the head (at the pinnacle rock) is dominated by a non-native invasive tree species, which may explain why there was a net increase in peat at the head over the 36-year period of this study. Alternatively, the fact that the 2009 transect line crossed the pinnacle rock whereas the historical survey just missed it may have introduced a slight anomaly to the spatial analysis, such that the indicated small positive change in head altitude is spurious. Nonetheless, the potential for non-native species invasions must be considered when planning for the restoration of tree islands in the Everglades.

Vegetation mapping of WCA 2A (including tree islands) was conducted from 2003 aerial imagery (Rutchey *et al*. 2008) and used to produce Figure 2. The total area of ghost tree islands was determined to be 1,124 ha (Rutchey 2009). Our analysis indicated that the area of Dineen Island in 1973 was approximately 52 ha and its area from the 2003 map was approximately 67 ha.

The cores provide a 'peek into the past' because the accretion of peat is accomplished over an extended period of time. Moving down-core, we obtained a glimpse of the history of this tree island. The average bulk density values of the peat from the top sections of the cores indicate a landscape feature with soil densities similar to those of a typical sawgrass ridge. In a literature review of peat characteristics from the Everglades, Aich *et al*. (2013) found that bulk densities of the deep peats in unimpacted sawgrass ridges were similar to those found in the surface peat of Dineen Island and were relatively constant with depth. As we move down the cores from Dineen Island, we find that the peats at the centre of the island become denser, possibly due to compaction typical of the denser soils that one would expect in a tree island (Figure 8).

Phosphorus concentrations in peat at the heads of tree islands are typically orders of magnitude higher than those in their near tail and tail regions, which are in turn normally higher than those in the surrounding sloughs (Sklar *et al*. 2002). We were interested in determining whether a degraded tree island loses phosphorus to the surrounding sloughs, perhaps causing local areas of eutrophication in the extremely low-nutrient Everglades. As anticipated, the phosphorus content of the peat is elevated in the middle of Dineen Island and declines toward the edges, particularly in the remaining head region (Figure 9).

A number of uncertainties must be considered when evaluating the results of this exercise. The transects used for the surface interpolations were not in precisely the same locations and the data were not randomly distributed. We did not have any other spatially uneven data points, which would depict a better spatial autocorrelation. Still, the simple transect analysis that was conducted yielded values that were similar to the results of the spatial analysis and the subsidence value for the island agrees closely with the value determined for the entire Water Conservation Area. However, the physical and chemical peat characteristics used in the calculations were measured only on recent soil samples. During the 36 years that elapsed between the two surveys, there were surely changes in soil composition which we were unable to take into account given our limited data set. It was assumed that the loss of peat was due entirely to oxidation at the surface of the island, that the bulk density of the surface peat had not changed significantly during the 36-year period, and that the entire loss of altitude was due to loss of peat (ignoring any compaction that may have occurred). From examining the variation in bulk density values with depth (Figure 8), it appears that compaction at the surface had not been significant. It is not known whether the subsidence was due to microbial oxidation, fire, dissolution of organic carbon or deep peat methanogenesis. Fire may have played a role, as there was a comment on the 1973 survey that the edge of the island was identified by the presence of burned stumps. Soil profiles from three similar transects conducted on a "live" tree island during the 2009 sampling show similar bulk density profiles to those shown in Figure 8 (data from Ewe *et al*. 2009). Finally, the weighted average values derived from the cores may not be representative of the attributes of interest. We present these results as an initial attempt to quantify tree island degradation by providing a rough estimate of the changes that have occurred during a specific period during the life of a tree island, which spans several millennia.

The total area of ghost tree islands in WCA 2A is about 22 times the area of Dineen Island at the time of the 1973 survey. Field observations and aerial photography indicate that the changes to Dineen Island are typical for the other ghost tree islands of the region (Ewe *et al*. 2009). On this basis, we estimate that 175,000 Mg of peat, 79,000 Mg of carbon, 51 Mg of TP and 5,100 Mg of TN were lost from ghost tree islands in WCA 2A between 1973 and 2009.

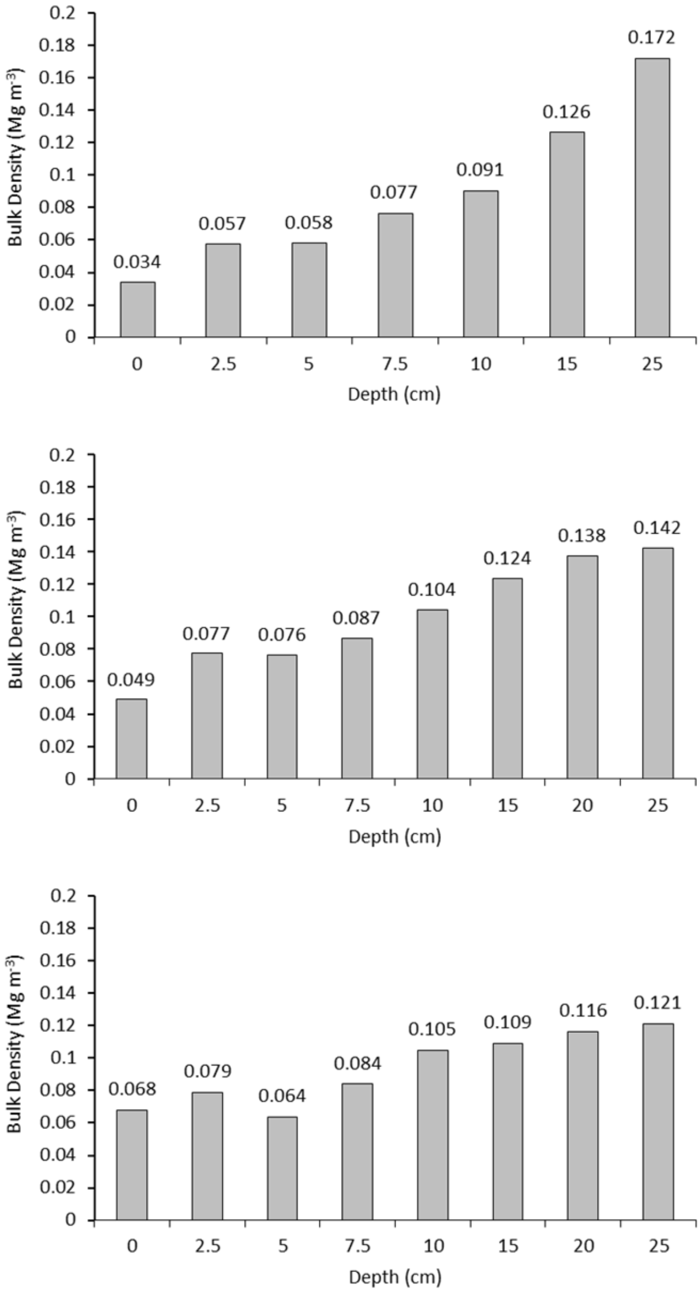

Figure 8. Profiles of mean (weighted average) peat bulk density for each region of Dineen Island: top=head (cores 2, 3 and 4); middle=near tail (cores 7, 8 and 9); bottom=far tail (cores 12 and 13). The abscissa indicates the depth of the top of the core section. For core locations, refer to Figure 4.

CONCLUSIONS

The objective of this study was to quantify the impacts of peat loss from tree islands and identify the types of information needed for successful restoration of the ghost tree islands. Our volume calculations compare well with the rate of peat loss estimated by Aich & Dreschel (2011) for the entire WCA 2A. They concluded that the rate of peat loss from the entire landscape was 4.2 mm yr^{-1} over 120 years, which is similar to the result from this study that Dineen Island lost peat at a rate of 4.0 mm yr^{-1} over 36 years. Thus, it appears that the rate of peat loss on Dineen Island may be representative of the other ghost tree islands in WCA 2A.

Evaluating the changes in a large ghost tree island over multiple decades increased our understanding of the impacts of tree island degradation within WCA 2A, on both the tree island itself and the surrounding marsh. The information from this investigation provides a baseline description of the degree and rate of change against

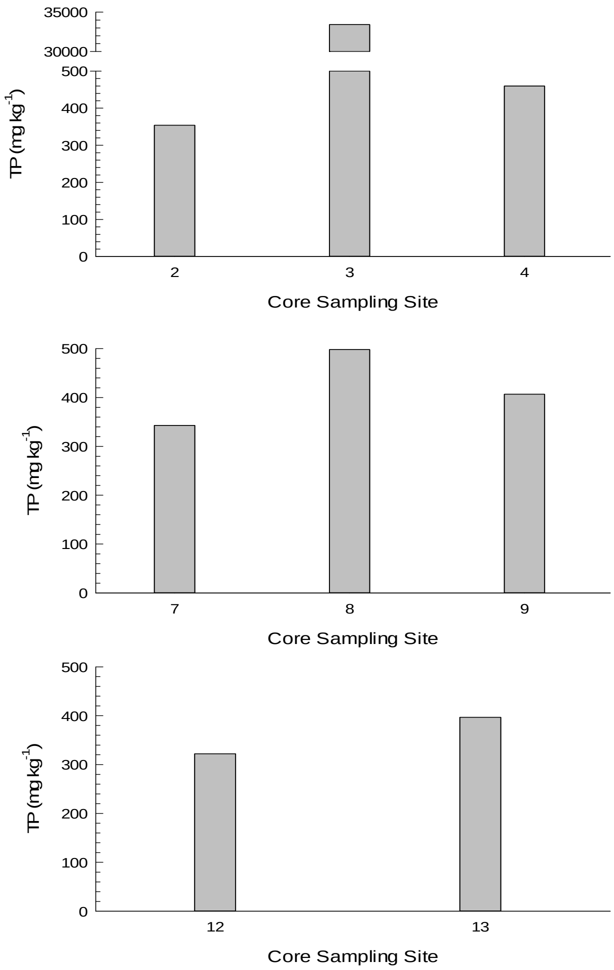

Figure 9. Weighted average (over depth) soil core total phosphorus across each region of Dineen Island by sample location: top=head; middle=near tail; bottom=far tail. For core location, refer to Figure 4. The standard deviations for the short core peat phosphorus (mg kg^{-1}) by site were: 2=170; 3=32,067; 4=228; 7=154; 8=180; 9=245; 12=137 and 13=209.

which future impacts of tree island degradation and the potential benefits of tree island restoration can be gauged. In addition, there is increasing concern over processes that release carbon dioxide into the atmosphere, contributing to climate change (Baes *et al*. 1977). Our investigation provides a rough method for estimating the amount of carbon lost to the atmosphere when a tree island degrades, as well as how much carbon might be sequestered by a tree island if it were successfully restored. Despite the fact that the island has lost P and N to the marsh, the marsh vegetation on and surrounding the island has remained oligotrophic. It appears (from aerial photography) that the initial degradation of the island resulted in the spread of cattail (primarily *Typha domingensis* Pers.) that was later replaced by sawgrass. This indicates that the loss of nutrients has been readily absorbed or dispersed and has not led to persistent local eutrophication. Although degraded, Dineen Island still maintains some altitude above the surrounding sloughs, and higher density peats are still present in the lower parts of the soil profile. These features are encouraging in that they may indicate that there is strong potential for restoring this and other ghost tree islands.

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