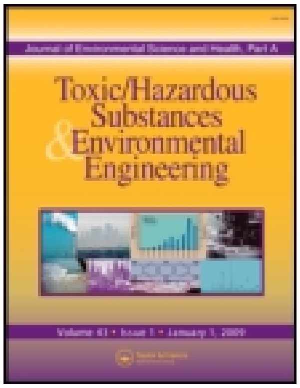

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Chemical evolution and vegetation response in an altered wetland ecosystem, Hula Valley, Israel (1988-2004)

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Chemical evolution and vegetation response in an altered wetland ecosystem, Hula Valley, Israel (1988–2004)

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The Hula Nature Reserve (HNR) (0.3 km^2) in northern Israel is a semiarid wetland ecosystem within the greater Hula Valley. In the 1950s, approximately 60 km^2 of wetlands were drained and converted to farmland. The HNR was established during this time to preserve some of the native flora and fauna. Agricultural runoff and a reflooding of the area with peat water in 1999 resulted in high sulfate ($SO_4{}^{2-}$) concentrations of 66.67 ± 4.00 mg/L. We identified the existence of $SO_4{}^{2-}$, nitrate ($NO_3{}^{-}$), and ammonium ($NH_4{}^{+}$) nutrient gradients as well as related mechanisms affecting the growth and dieback of *Cyperus papyrus*. The observed changes in the *C. papyrus* populations were caused primarily by fluctuations in $SO_4{}^{2-}$. After two key events that affected levels of $SO_4{}^{2-}$ in the HNR, *C. papyrus* coverage was altered by more than 80%.

Keywords: Altered wetlands, semiarid wetlands, peat water, nutrient gradient, *Cyperus papyrus*.

Introduction

The Egyptians called it *Samchuna*, in Aramaic it is *Hulata*, and the Talmud refers to it as *Yam Sumchi*. Today, in Modern Hebrew, it is known as *Agam Huleh*–Lake Hula–nestled in the heart of a unique wetland ecosystem between the Golan Heights and Eastern Galilee Mountains.[1] Prior to the 1950s, the Hula Valley consisted of a shallow lake and approximately 60 km^2 of wetlands that varied significantly in size with seasonal and interannual changes in water level.[1]

During the 1950s, Lake Hula and the surrounding wetlands were drained and converted to farmland. Despite the complete transformation of the landscape, the drainage project included some conservation efforts. A 0.3 km^2 area known as the Hula Nature Reserve (HNR) was established in the southern end of the wetland area in order to maintain the existence of native flora and fauna (Fig. 1).[2] In addition to the HNR, the Einan Reservoir was constructed in 1984 to store and recycle effluent from fishponds and ultimately reduce nutrient outflow.[1]

In 1994, the Hula Restoration Project (HRP) was implemented to address the ecological and agricultural problems of the Hula Valley system.[1] The goals of the plan included the preservation of peat soils for future generations, protection of Lake Kinneret from nitrate contamination, and ecotourism revenue generation as a source of compensation for local landowners who agreed to cease agricultural practices on portions of their land.[1] As part of the HRP, the 1 km^2 Lake Agmon was constructed during the summer of 1994 in the northern portion of the former wetlands area.[3] In recent years, this has made the area an important interface for ecotourism, agriculture, and the natural environment.

Although research on the historic Hula wetlands and Jordan River ecosystem is extensive,[4–8] the HNR has yet to be studied in a regular and systematic way. The body of research on the HNR tends to lack an integration of ecosystem components and processes at different spatial and temporal scales. Additionally, the research is largely descriptive rather than empirical. Many articles propose speculative results without sufficient numerical data and analysis necessary to support more concrete conclusions about the landscape. These research voids apply not only to the HNR but semiarid wetlands in general because they tend to exist in the most impoverished regions of the world with little or no funds available to support scientific studies.

As a result, visible changes in the landscape, particularly with regard to emergent vegetation, have yet to be sufficiently explained. Prior to the commencement of the drainage projects in the 1950s, the historic Lake Hula was dominated by *Cyperus papyrus* (85%) and to a lesser extent *Phragmites australis* (∼10%).[9] Today, *P. australis* coverage in the HNR far exceeds that of *C. papyrus*. Despite the fact that hydrological conditions, especially in water-starved, semiarid wetland ecosystems are known to affect nutrient inputs[10] and consequently wetland vegetation,[11]

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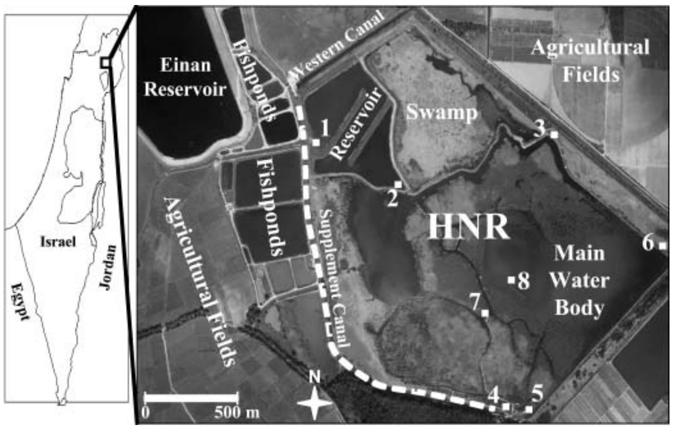

Fig. 1. Map of the Hula Nature Reserve (HNR) with the locations of the eight sampling stations. Water from the Western Canal enters the Einan Reservoir, which is pumped into the HNR. The Supplement Canal (dashed line) is also a source of water for the system with an inflow point near station 4.

there have been no efforts to make these connections in the HNR.

This study attempted to address this gap by comprehensively gathering and organizing data on the HNR and then creating a database in order to (1) understand the chemical trends of the HNR from 1988–2004, (2) identify specific hydrological events affecting the chemistry of the water, and (3) relate the chemical trends and hydrological events to responses in the vegetation.

Materials and methods

Study area

The Hula Valley is located in northeastern Israel (33°05′ N, 35°35′ E) and occupies an area of approximately 177 km^2 (25 km long by 6–8 km wide).[1] The 0.3 km^2 HNR is part of this larger landscape and divided into three general areas: Reservoir, Main Water Body, and Swamp (Fig. 1). The HNR is surrounded by agricultural fields on all sides and a series of fishponds to the west.

Data collection

The data set is comprised of surface grab samples previously collected from designated water quality sampling stations in the HNR. Over time, as many as 18 different sampling stations have been used, but only eight have been consistently operational since 1988. These eight stations are strategically located throughout the HNR (Fig. 1). Stations 1, 3, 4, 5, and 6 are located at key inflow/outflow points while stations 2, 7, and 8 are located in the interior. In this study, only data collected from these eight stations were utilized in order to capture key trends in seven parameters from 1988–2004: sulfate (SO_4^{2-}), calcium (Ca^{2+}), sodium (Na^+), nitrate (NO_3^-), chloride (Cl^-), phosphate (PO_4^{3-}), and ammonium (NH^{4+}).

In addition to chemical data, four aerial photographs of two different *C. papyrus* stands in the Main Water Body were analyzed in a process known as change detection mapping. ArcView Geographic Information System (GIS) was used to quantitatively measure temporal changes in *C. papyrus* coverage with standard techniques including geometric correction, contrast modification, and density slicing.[12–14] The images were altered with geometric correction using ground control points (GCPs) in order to recognize the same object at different spatial scales and resolutions on multiple images.

Additionally, contrast modification through stretching was utilized to increase the digital number (DN) space–the relative reflectance values assigned to pixels in an image. The images were then divided into regions based on DN values to create a simple, monospectral system for classification in density slicing. The resulting change detection maps were compared in order to quantify the evolution in *C. papyrus* coverage over time.

Results and discussion

Water chemistry trends

The HNR is a wetland system that experiences drastic changes in water chemistry over a relatively short time scale of months and years as a result of both natural fluctuations and anthropogenic alterations to the ecosystem. Average annual concentrations of SO_4^{2-}, Ca^{2+}, Na^+ from 1988–2000 as well as PO_4^{3-}, NO_3^-, Cl^- from 1988–2004 illustrate chemical trends in the waters of the HNR over time (Fig. 2). These trends can be related to a combination of specific natural and human-induced events.

Average SO_4^{2-} levels in the HNR from 1988–2000 were 66.67 ± 4.00 mg/L. Until September 1999, SO_4^{2-} levels averaged 47.64 ± 2.57 mg/L with a slight spike between 1991 and 1993. Then, a dramatic increase in SO_4^{2-} levels began in 1999. During this time, several stations had over four times the average amount of SO_4^{2-} recorded in previous years. The high levels of sulfate in the HNR can be attributed to agricultural runoff that has played a role in the ecosystem since its transformation to farmland in 1950s as well as a reflooding event that occurred in 1999. During that year, peat water with high concentrations of SO_4^{2-} from nearby Lake Agmon was used to rehydrate the system following a severe drought (for detailed explanation see Vegetation Responses to Changes in Water Chemistry).

This high level of SO_4^{2-} is common in highly impacted areas of wetland ecosystems. Pristine areas of the Everglades, for example, have average SO_4^{2-} concentrations of

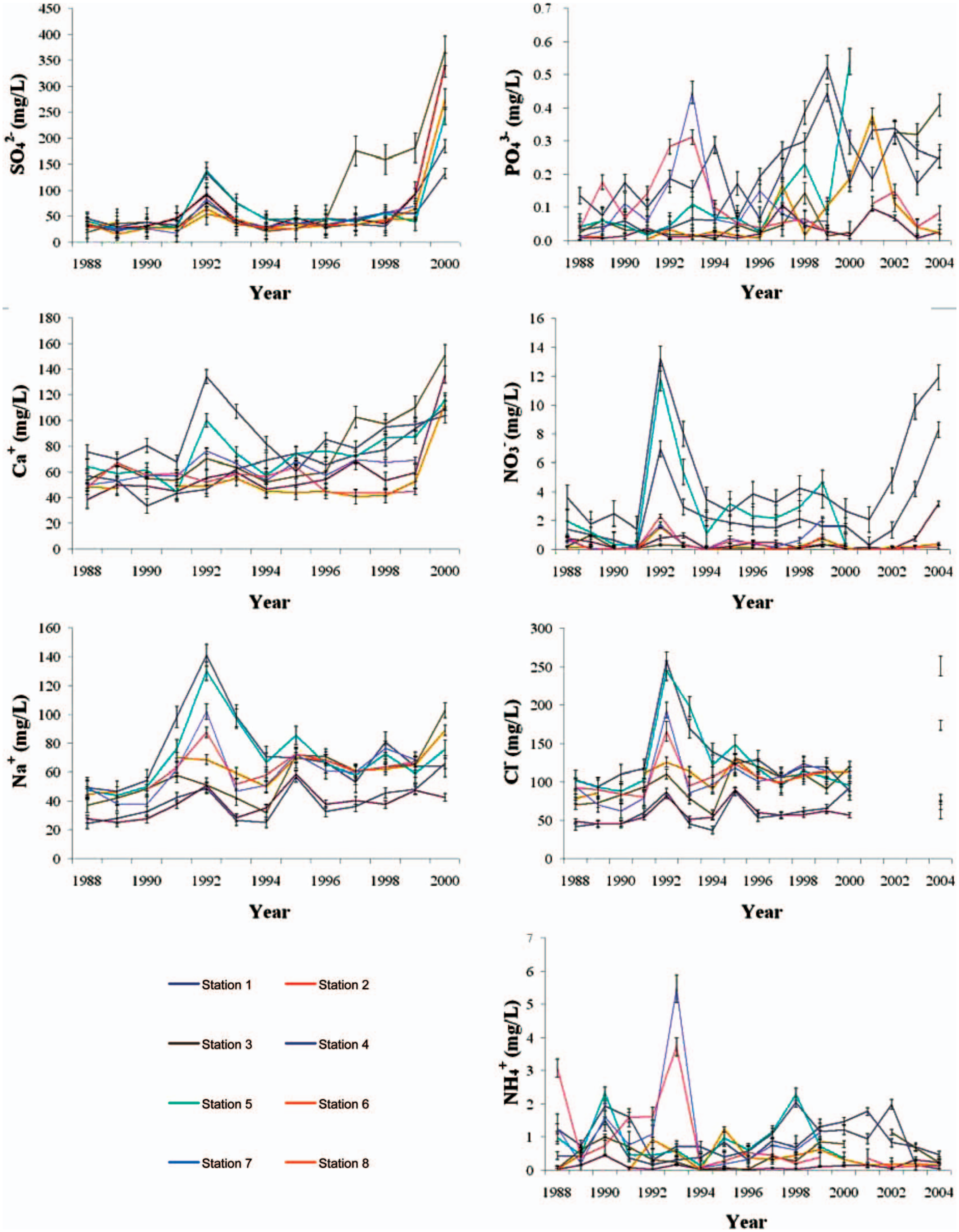

Fig. 2. Annual averages and corresponding errors for SO_4^{2-}, Ca^{2+}, Na^+, NO_3^-, Cl^-, PO_4^{3-} and NH^{4+} at each of the eight sampling stations (color figure available online).

$\leq$1 mg/L compared to nearly 50 or 60 mg/L for areas directly affected by agricultural runoff.[15, 16] In the HNR, average SO_4^{2-} levels from 1988–2000 were similarly high at 66.67 $\pm$ 4.00 mg/L.

Average levels of Ca^{2+} and Na^+ from 1988–2000 were 69.94 $\pm$ 1.57 mg/L and 56.66 $\pm$ 1.30 mg/L, respectively. Average levels of NO_3^- and Cl^- from 1988–2004 were 1.65 $\pm$ 0.13 mg/L and 95.97 $\pm$ 2.24 mg/L, respectively. Levels of all four of these parameters followed a similar pattern with peaks between 1991 and 1993. Additionally, the increases in Ca^{2+} and Na beginning in 1999 exhibited the same trend as SO_4^{2-}. Levels of NO_3^- and Cl^- experienced increases after 2001. It is possible that levels of SO_4^{2-}, Ca^{2+}, and Na^+ also ultimately peaked and decreased, but data collection for these parameters ended in 2000 as a result of financial constraints at the HNR.

Average levels of PO_4^{3-} and NH^{4+} did not display the same distinct patterns as the other five parameters. Nevertheless, PO_4^{3-} exhibited a slight peak between 1991 and 1994 when levels of PO_4^{3-} increased from 0.05 $\pm$ 0.01 mg/L to a high of 0.13 $\pm$ 0.05 mg/L in 1993. A second peak was evident from 1997–2001 with levels of PO_4^{3-} increasing from approximately 0.06 $\pm$ 0.01 mg/L prior to 1997 to a maximum average of 0.42 $\pm$ 0.18 mg/L during September-December 1999 immediately following the reflooding of the HNR with peat water from Lake Agmon. NH^{4+} exhibited a later peak between 1992 and 1994 when average levels increased from 0.73 $\pm$ 0.11 mg/L to 1.47 $\pm$ 0.52 mg/L in 1993, but no peak occurred following the reflooding event in 1999.

Nutrient gradients

The water flow scheme in the HNR was intended to clean the water before it traveled downstream. Water from the Einan Reservoir, which is fed by the Western Canal, is supposed to flow into the Reservoir and cycle through the Main Water Body and then into the Swamp in a counterclockwise pattern (Fig. 3). However, a secondary water flow scheme originates from the adjacent fishponds, flows into the Supplement Canal, and enters the Main Water Body near station 4. This nutrient-rich water never flows through the entire HNR, which would naturally filter the effluent and prevent it from traveling farther downstream.

Over time, a gradient has been created where nutrient levels at the inflow point around stations 4 and 5 are high and gradually decrease in the Main Water Body near stations 7 and 8. There is an inverse relationship between nutrient concentration and distance from the inflow point that establishes the gradient. The total concentration is higher at station 4 and decreases toward station 8 as distance from the inflow point increases. Median nutrient concentrations of NO_3^-, SO_4^{2-}, and NH_4^+ over the course of an 11-year period from 1988 to 1999 illustrate this gradient (Fig. 4).

Although little information exists with regard to nutrient gradients in semiarid wetland systems, this type of gradient is not uncommon in other altered wetlands. In the Florida

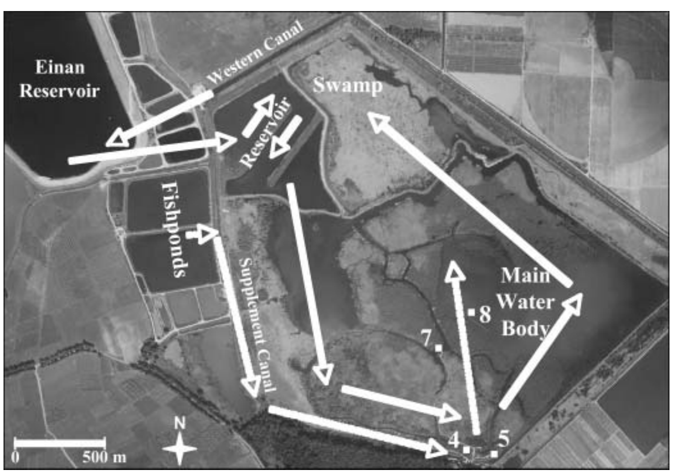

Fig. 3. Map of the water flow scheme in the Hula Nature Reserve (HNR). The primary path of water flow (solid arrow) is from the Western Canal into the Einan Reservoir, which then pumps into the HNR. The secondary path of water flow (dotted arrow) is runoff from the fishponds entering the Supplement Canal, which then flows into the HNR near station 4.

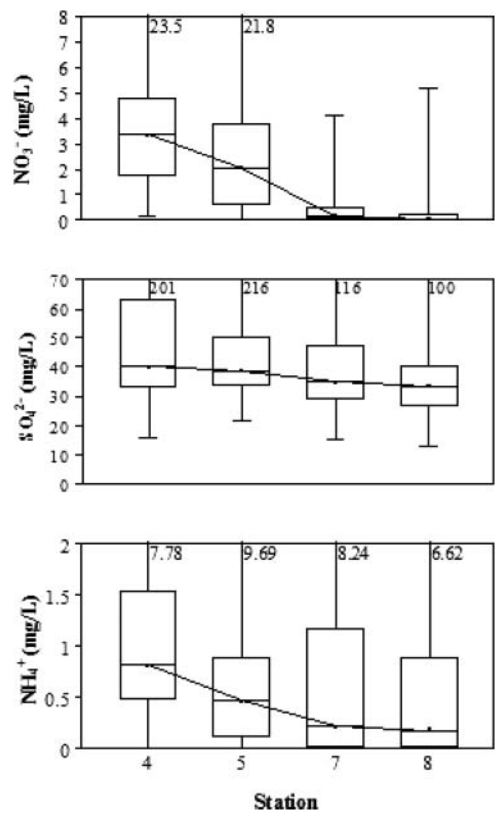

Fig. 4. Box plots indicating the 10th, 25th, 50th (median), 75th, and 90th percentile concentrations of NO_3^-, SO_4^{2-}, and NH4$^+$ for stations 4, 5, 7, and 8 from 1988–1999. Mean concentrations for the same time period are indicated by the closed black dot. The existence of a gradient is evident as the median nutrient concentrations progressively decrease with increased distance from the inflow point located near station 4.

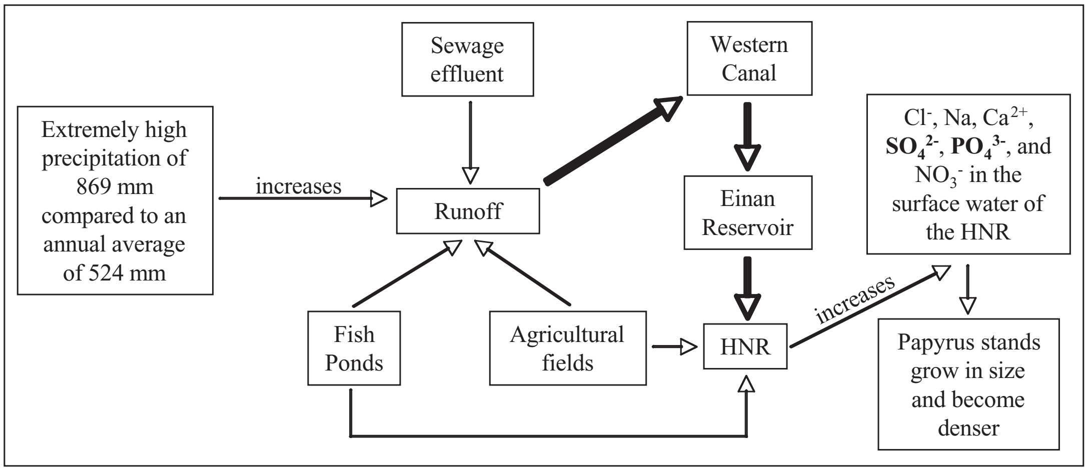

Fig. 5. Process of the papyrus growth event during the winter of 1991–1992. The primary flow of runoff (bold arrows) caused an increase in several chemicals in the waters of the HNR.

Everglades, for example, extensive research on nutrient concentrations has uncovered the existence of several gradients where nutrient concentrations decrease with increasing distance from the inflow point. Average levels of surface water SO_4^{2-} decrease along a north-south gradient in the Northern Everglades.[15] Additionally, NO_3^- gradients associated with runoff in the Everglades have also been observed.[17]

Vegetation responses to changes in water chemistry

Since the drainage efforts in the 1950s that led to the creation of the HNR, there have been no large-scale, observable vegetation shifts attributable to normal, annual growth patterns or low-grade physical impacts on the system. Instead, there have been two major events with notable effects on *C. papyrus* populations. First, extremely high precipitation during the winter of 1991–1992 resulted in larger, denser stands of *C. papyrus* (Fig. 5).

The high precipitation increased runoff from sewage effluent, fishponds, and agricultural fields into the HNR. The primary flow of runoff travels through the Western Canal, which feeds the Einan Reservoir and ultimately the HNR. Additional secondary flows of non-point source runoff flow directly into the HNR from the surrounding fishponds and agricultural fields. During this particular event, runoff increased levels of Cl^-, Na^+, Ca^{2+}, SO_4^{2-}, PO_4^{3-}, and NO_3^- in the surface waters of the HNR.

High levels of SO_4^{2-} may have been a factor that supported *C. papyrus* growth since it has been implicated as a limiting nutrient for *C. papyrus*.[18] Although SO_4^{2-} has existed in relative abundance in the HNR since the landscape alterations made in the 1950s, the large increase in SO_4^{2-} concentrations following this rain event–from an average of 30.9 ± 1.4 mg/L to 92.0 ± 10.6 mg/L–likely stimulated the growth of *C. papyrus* beyond any point previously observed. Aerial photographs of an existing *C. papyrus* stand (existing stand) in the east-central portion of the HNR taken in December 1991 before (Fig. 6a) and after (Fig. 6b) the precipitation event shows how the vegetation grew in size and became more dense. A GIS analysis using change detection mapping indicated that coverage in the existing stand changed by 83% after high levels of precipitation and SO_4^{2-} entered the system, while only 17% remained unchanged (Fig. 6c).

Fluctuations in SO_4^{2-} and Ca^{2+} followed similar trends over time as a result of gypsum ($CaSO_4$) dissolution. Although SO_4^{2-} can originate from a variety of external sources, including runoff and the release of peat water into the HNR, increases in Ca^{2+} in conjunction with SO_4^{2-} are attributable to internal dissolution processes. During wet periods, such as the 1991–1992 winter precipitation event, $CaSO_4$ dissolved and resulted in the increase of both Ca^{2+} and SO_4^{2-} in the water column. Ashkenazi et al.[19] cited the dissolution of gypsum in nearby Lake Agmon as a source of SO_4^{2-} loading in the ecosystem. Ultimately, the increases in SO_4^{2-} from both internal and external processes contributed to the growth in size and density of the existing stand.

In 1999, a second, more dramatic *C. papyrus* event began to occur as a result of extreme fluctuations in water level and chemical composition in the HNR. Peat water with high concentrations of SO_4^{2-} from nearby Lake Agmon was used to restore water to the HNR in September 1999 following a severe drought. The addition of the peat water temporarily increased the average level of SO_4^{2-} from approximately 50 ± 3 mg/L to 210 ± 15 mg/L. During this time, an almost entirely new *C. papyrus* stand (new stand) formed in the extreme eastern portion of the HNR. Then, as SO_4^{2-} levels likely began to decrease in 2001 from their artificial spike in 2000, the new stand crashed. Aerial photographs depict the emergence of the new stand following the reflooding in August 2000 (Fig. 7a) and subsequent dieback in February 2002 (Fig. 7b). GIS change detection

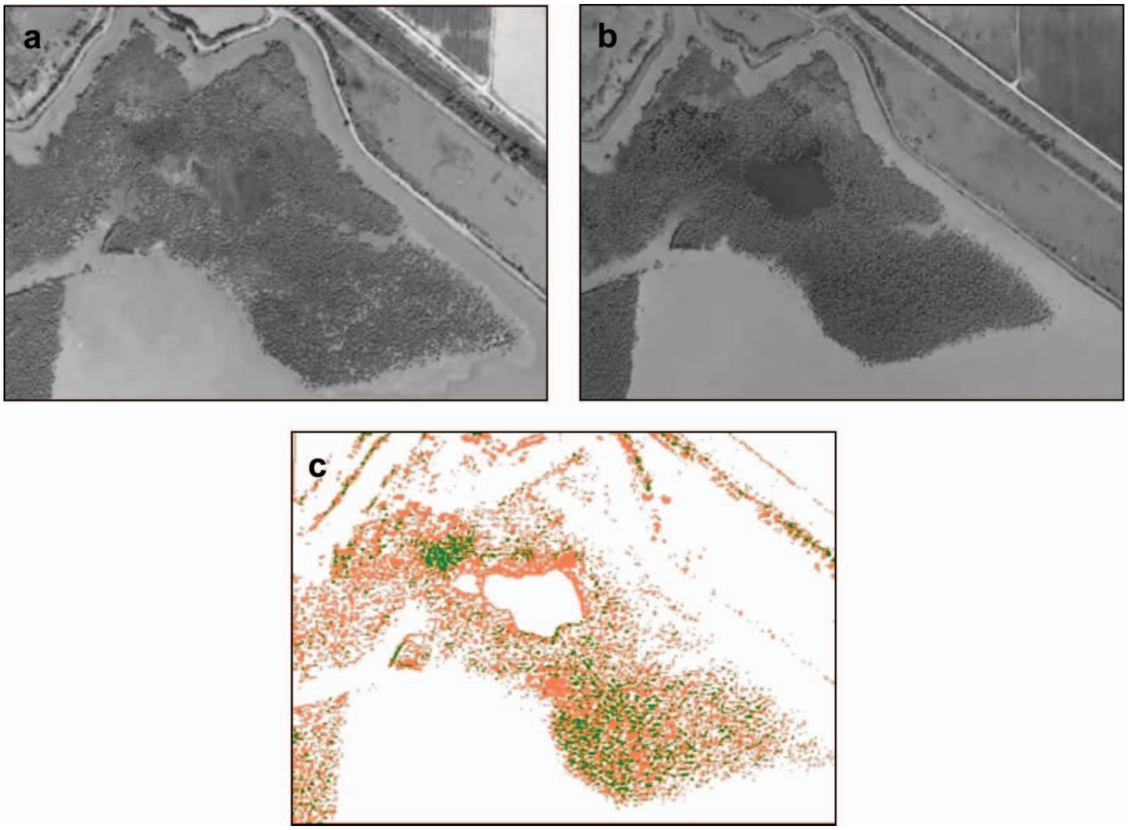

Fig. 6. Aerial photographs depicting the growth in size and density of an existing *C. papyrus* stand in the HNR before (a) and after (b) the winter 1991–1992 precipitation event. A colorized change detection map (c) was created to show the areas that were changed (orange) and unchanged (green) following the precipitation event (color figure available online).

mapping indicated that 85% of the coverage area of the new stand was changed while only 15% of the area remained unchanged (Fig. 7c).

In 2002, the existing stand in the east-central portion of the HNR continued to decrease in size possibly as a result of a decline in SO_4^{2-} levels below the 50 ± 3 mg/L average that existed prior to the release of peat water into the HNR. Essentially, the decreased levels of SO_4^{2-} were no longer able to fully support the existing stand. Unfortunately, it is impossible to know the true levels of SO_4^{2-} in the HNR during and after the *C. papyrus* dieback since measurement of this parameter ceased in September 2000. Nevertheless, these fluctuations in SO_4^{2-} provide a plausible causal mechanism for this large-scale vegetation change in the HNR.

In addition to SO_4^{2-}, fluctuations in levels of PO_4^{3-} and NO_3^- are also possible causes of these two *C. papyrus* growth and dieback events. PO_4^{3-}, primarily in the form of H_2PO_4 and HPO_4, enters the water column from agricultural runoff and fertilizers. Additionally, the drying of the soil, which occurs in the HNR both seasonally and as a result of management practices, oxidizes the P and makes it available to the overlying water column once the area is rehydrated.[9,20]

The effect of P dynamics on *C. papyrus* growth has been examined in several studies. For example, Nalubega and Nakawunde[21] reported a minimum P concentration for *C. papyrus* of 2 mg/L below which it tends to be out-competed. Ssegawa et al.,[22] by contrast, did not find any significant correlation between P primarily from the peat soil root zone and *C. papyrus* growth.

Although PO_4^{3-} dynamics in the HNR do not exhibit the same distinct trends as SO_4^{2-} or NO_3^-, a slight peak is evident between 1991 and 1994 when average levels of PO_4^{3-} increased from 0.05 ± 0.00 mg/L to 0.10 ± 0.03 mg/L. During 1997–2001, a second peak occurred with levels of PO_4^{3-} increasing from 0.09 ± 0.01 mg/L to 0.19 ± 0.02 mg/L. However, PO_4^{3-} cannot be the sole cause of the observed *C. papyrus* growth, because these peaks do not correspond with the timing of the growth events in 1991–1992 and 2000, the fluctuations in concentration are relatively small when compared to those of SO_4^{2-}, and the concentrations are lower than those found to affect growth in previous studies.

In addition to SO_4^{2-} and PO_4^{3-}, high levels of NO_3^-, originating primarily from agricultural and municipal runoff, are also known to influence wetland vegetation patterns. Increasing levels of N in root solution have been

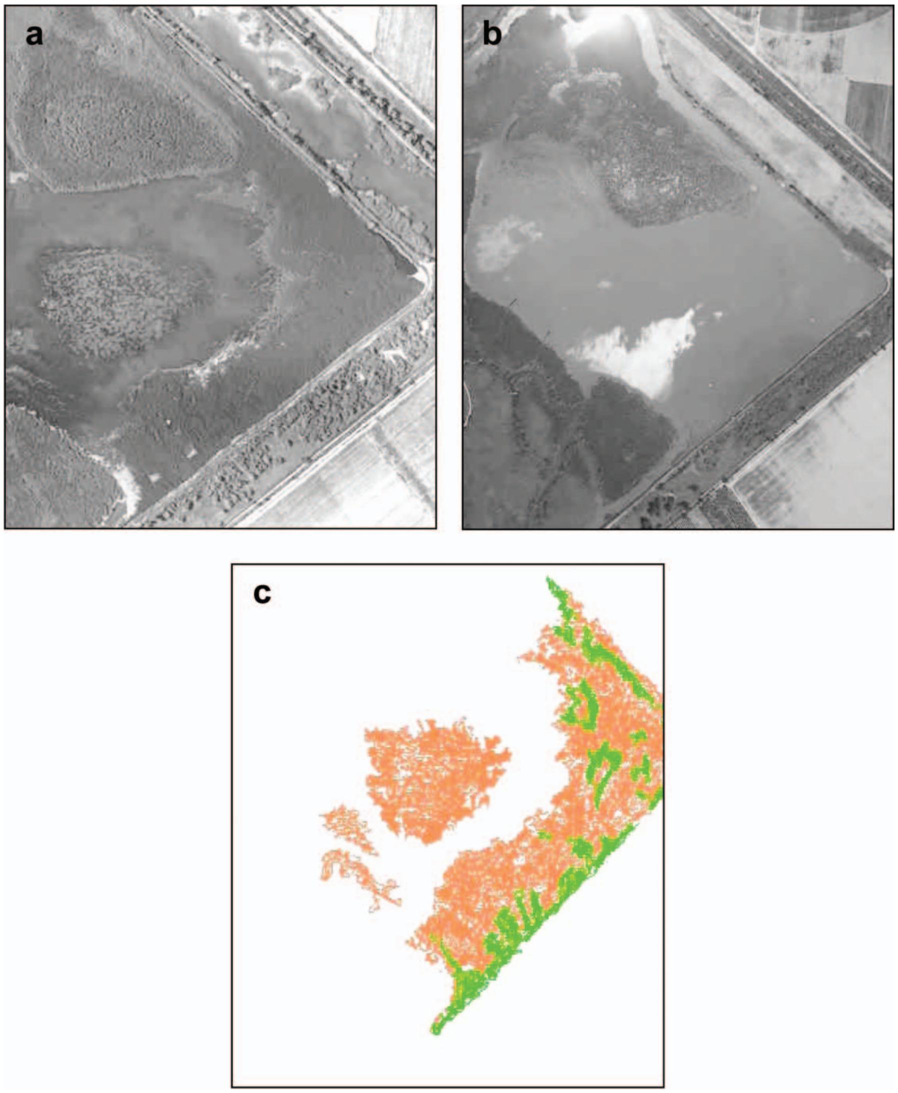

Fig. 7. Aerial photographs depicting the emergence of a new *C. papyrus* stand following the 1999 reflooding of the HNR with sulfur-laden peat water (a) and subsequent dieback (b). The colorized changed detection map (c) illustrates the areas that existed prior to (orange) and after (green) the reflooding (color figure available online).

shown to significantly affect the growth rate of *Phragmites australis*, while P did not have any detectable effect.[23] Additionally, Ashkenazi et al.[19] identified NO_3^- as an important nutrient for *Typha domingensis* in nearby Lake Agmon. *T. domingensis* invasions have likewise been associated with NO_3^- nutrient gradients in the Florida Everglades.[17]

Levels of NO_3^- showed fluctuations similar to SO_4^{2-} during 1991–1992. Average levels of NO_3^- increased from 0.81 ± 0.10 mg/L prior to 1991 to 4.83 ± 1.85 mg/L following the precipitation event during the winter of 1991–1992. However, the later spike in levels of NO_3^- from an average of 1.18 ± 0.10 mg/L during 1993–2001 to 2.62 ± 0.55 mg/L in 2002 neither coincides with the reflooding of the HNR in 1999 nor the subsequent *C. papyrus* growth observed in 2000. Additionally, unlike SO_4^{2-} and PO_4^{3-}, NO_3^- is not a nutrient known to affect *C. papyrus* growth. Thus, it appears that the fluctuation in SO_4^{2-} either alone or possibly in combination with PO_4^{3-}, rather than NO_3^-, is responsible for the observed *C. papyrus* growth and dieback events in the HNR.

Conclusions

In this study, the creation of a single, comprehensive database for analyzing information about the HNR helped describe the chemical and vegetation dynamics in an altered wetland ecosystem over a 16-year period from 1988–2004. We uncovered the existence of SO_4^{2-}, NO_3^-, and NH_4^+ nutrient gradients and identified SO_4^{2-} as the most likely cause of two major *C. papyrus* growth and dieback events.

These vegetation changes underscore the importance of improving data collection in semiarid wetlands in order to uncover trends over longer periods of time. Many of the chemical mechanisms affecting wetland vegetation patterns in the short-term, such as levels of SO_4^{2-}, PO_4^{3-}, and NO_3^-, are likely to play a role in long-term vegetation shifts. *C. papyrus*, for example, was the dominant vegetation in the historic Lake Hula prior to the 1950s,[9] but today, *P. australis* coverage is far greater. A more complete understanding of the ecosystem that utilizes chemical trend data can reveal causal mechanisms for such vegetation shifts as well as help improve management efforts to prevent changes that place stress on the ecosystem and ultimately result in a loss of biodiversity.

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