Controlling Runoff from Subtropical Pastures Has Differential Effects on Nitrogen and Phosphorus Loads

Patrick J. Bohlen* and Odi R. Villapando

A 4-yr (2005–2008) study was conducted to evaluate the potential of pasture water management for controlling nutrient losses in surface runoff in the Northern Everglades. Two pasture water management treatments were investigated on Bahia grass (*Paspalum notatum* Flüggé) pastures: reduced flow and unobstructed flow. The reduced flow treatment was applied to four of eight 20.23-ha pastures by installing water control structures in pasture drainage ditches with flashboards set at a predetermined height. Four other pastures received the unobstructed-flow treatment, in which surface runoff exited pastures unimpeded. Automated instruments measured runoff volume and collected surface water samples for nutrient analysis. In analyzing data for before–after treatment analysis, the 2005 results were removed because of structural failure in water control structures and the 2007 results were removed because of drought conditions. Pasture water retention significantly reduced annual total nitrogen (TN) loads, which were 11.28 kg ha^{-1} and 6.28 kg ha^{-1}, respectively, in pastures with unobstructed and reduced flow. Total phosphorus (TP) loads were 27% lower in pastures with reduced flow than in pastures with unobstructed flow, but this difference was not statistically significant. Concentrations of available soil P were significantly greater in pastures with reduced flow. Pasture water retention appears to be an effective approach for reducing runoff volume and TN loads from cattle pastures in the Northern Everglades, but the potential to reduce TP loads may be diminished if higher water table conditions cause increased P release from soils, which could result in higher P concentration in surface runoff.

Nutrient runoff from agricultural lands and its contribution to eutrophication of surface water is a major global environmental problem (Carpenter et al., 1998). Globally, phosphorus (P) fertilizer use has increased net P storage in terrestrial and freshwater ecosystems by 75% over preindustrial levels, and a large portion of this increased P is stored in agricultural soils, increasing the risk of P transfer from soil solution to surface water (Sharpley et al., 1994; Bennett et al., 2001; McDowell et al., 2001a,b). Excess nitrogen (N) primarily from agricultural runoff contributes to eutrophication of estuarine systems worldwide (Vitousek et al., 1997). Developing approaches for reducing the impacts of this nutrient loading is one of the major global environmental challenges (Goldberg, 1995).

The Lake Okeechobee watershed in Florida is one region in which excessive nutrient loads contribute to water quality problems in downstream receiving waters. These waterways include Lake Okeechobee and the St. Lucie and Caloosahatchee estuaries. Nutrient loading to the lake has contributed to excessive algal blooms, loss of benthic invertebrate biodiversity, and spread of undesirable vegetation in the littoral zone of the lake (Zhang et al., 2009). Despite years of regulatory effort to reduce P loads into the lake, significant further reduction in P loading will be required to reach the current total maximum daily load (TMDL) for the lake of 140 metric tons of P (Havens et al., 1996; FDEP, 2001a; Havens and James, 2005). Furthermore, discharges of nutrient-laden water from the lake also influence nutrient loads to the St. Lucie and Caloosahatchee coastal estuaries (Alleman et al., 2009). Reducing the impacts of this nutrient loading will require reduction in nutrient runoff from agricultural land in the Lake Okeechobee watershed.

Beef cattle ranching is the largest land use in the watershed, and although nutrient loads from cattle pastures are low relative to other land uses on a per area basis, the large acreage of ranches makes them a significant contributor to overall nutrient loads (Hiscock et al., 2003). In cooperation with the state agriculture and environmental agencies, the Florida Cattlemen's Association developed water quality best management practices guidelines, which include practices for water quality improve-

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Abbreviations: AMSL, above mean sea level; AU, animal unit; BACI, before-after-control-impact; DAP, double acid phosphorus; DIN, dissolved inorganic nitrogen; DON, dissolved organic nitrogen; IER-P, ion-exchange resin P; SRP, soluble reactive phosphorus; TKN, total Kjeldahl nitrogen; TN, total nitrogen; TP, total phosphorus.

ments, from modifications to fencing, drainage, feed and water location, and fertilization to changes in rotational grazing protocols that are expected to reduce P runoff, if implemented (FDACS, 2008). A previous study in the region showed that cattle stocking density did not have any apparent effects on nutrient loading in pasture runoff (Capece et al., 2007). Water management practices that increase retention–detention of drainage waters within cattle pastures are a potential alternative to reducing nutrient loads. Hydrologic modeling of runoff from agronomically improved pastures on a ranch in the region indicated that a detention of 0.6 to 1.3 cm (0.25–0.50 inches) of runoff could reduce P loads by an estimated 20% (Zhang et al., 2006), but little quantitative information is available on the effects of water retention on nutrient loads in surface runoff.

A 4-yr research study (2005–2008) study was done to evaluate the effect of water control structures on reducing surface flow and nutrient runoff from a set of instrumented cattle pastures in the Northern Everglades region north of Lake Okeechobee. The study was done on a set of experimental pastures used previously to assess the effects of cattle stocking rate on nutrient runoff and other ranch management factors, including forage production and economics (Capece et al., 2007; Swain et al., 2007). This paper summarizes the effect of pasture water retention on groundwater elevation, annual runoff, and nutrient loads over 4 yr.

Materials and Methods

Site Description

The study was conducted at the MacArthur Agro-ecology Research Center at Buck Island Ranch (Lake Placid, FL), a 4290-ha cattle ranch owned by the John D. and Catherine T. MacArthur Foundation and leased to Archbold Biological Station. The ranch is located in the C-41 drainage basin (Fig. 1) and is managed at commercial production levels (~3,000 breeding cows) for research purposes. The project area was included in a previous study that examined the influence of cattle stocking density on nutrient runoff from cattle pastures (Capece et al., 2007; Swain et al., 2007). The experimental pastures were established in a nearly level 162-ha area of improved pasture (27°8.7′ N, 81°10.6′ W) with network of drainage ditches and dominated by Bahia grass (*Paspalum notatum* Flüggé). From the early 1970s until 1987, this area was fertilized annually with nitrogen, phosphorus, and potassium (56 kg N ha^{-1}, and 34–90 kg of P_2O_5 and K_2O ha^{-1}), and from 1987 until 1995, it received annual application of only N at 56 kg ha^{-1} (Swain et al., 2007).

The soils at the study consisted of 90% Felda fine sand, a poorly drained fine sand (loamy, siliceous, superactive, hyperthermic, arenic Endoaqualfs). The upper 50 cm of this soil is characterized by moderate permeability (2.9–6.0 m d^{-1}), and the water table is within 25 cm of the surface during the rainy summer season. Less than 2% of area was overlain by a thin layer (2.5–15 cm) of muck, and true wetland muck soils covered about 9% of the site (Swain et al., 2007). The soils had an argillic layer (Bt/clay enriched layer) 50 to 130 cm below the surface with more restricted permeability (0.07 m d^{-1}).

The area was subdivided with fences and berms in 1996 to 1998 into eight 20.23-ha (50-acre) paddocks (SP1–SP8: Fig. 2). Pasture elevations ranged from 7.9 to 8.5 m (National

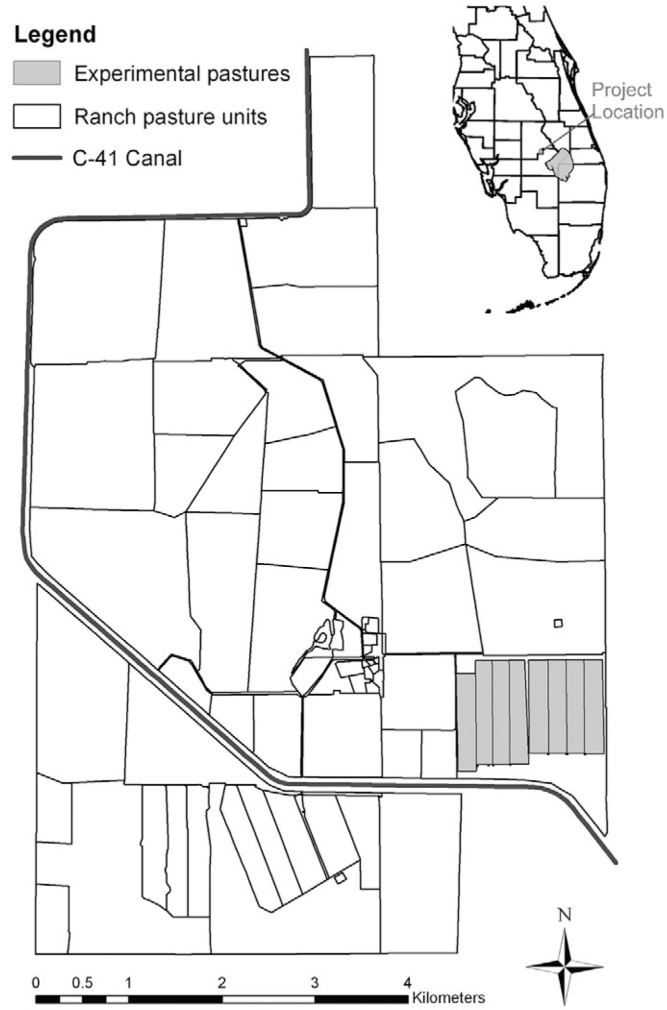

Fig. 1. Project location map and layout of experimental units relative to the C-41 Canal.

Geodetic Vertical Datum of 1929, NGVD29), sloping gradually to the southeast and draining through a series of ditches into the Harney Pond Canal to the south. Surface runoff from each plot was isolated from adjacent plots by the construction of ditches and berms along their margins. Each pasture had a series of regularly spaced shallow (~45 cm deep) ditches oriented east–west and spaced approximately 45 m apart that drained into larger perimeter ditches. The perimeter ditches collected runoff from individual pastures and routed it through a trapezoidal flume at the downstream end of each pasture. Pastures received no surface inflows other than rainfall, as well as backflow that occurred mainly during dry periods when the elevation of the C-41 canal just downstream of the flumes exceeded the flume elevations.

The flumes were equipped with an ISCO 3700 automatic sampler for collection of flow-weighted samples of surface runoff from each pasture. The 0.3-m trapezoidal flumes had a peak flow capacity of 7 cubic feet per second (cfs). Stilling wells, floats, and digital encoders (Model SE-105S, Enviro-Systems, Thousand Oaks, CA) monitored upstream and downstream water depth at each flume. These data were used to calculate flow rates and volumes. Water depth readings were recorded at 20-min intervals by dataloggers (CR10X, Campbell Scientific, Logan, UT) that were programmed to pulse automatic water samplers (Model

3700, ISCO, Inc., Lincoln, NE) to collect discrete samples based on flow volume calculations and hydrograph geometry. The low relief of the pastures relative to the changing water levels in the adjacent Harney Pond Canal required that the discharge measurement and sampling system accommodate flow in both directions, including inflow from the canal as well as runoff to the canal from each individual pasture. Flume elevations ranged from 7.56 to 7.64 m above mean sea level (AMSL) (NGVD29).

Each pasture had a 4.5-m-deep groundwater well for monitoring water table depth and groundwater quality. The wells were fitted with pressure transducers attached to a datalogger that recorded groundwater elevation at 20-min intervals. The data were transmitted telemetrically to the South Florida Water Management District via one of their regional towers. A meteorological station located approximately 50 m from the north end of one of the experimental pastures recorded rainfall, wind speed, relative humidity, and solar radiation at the site.

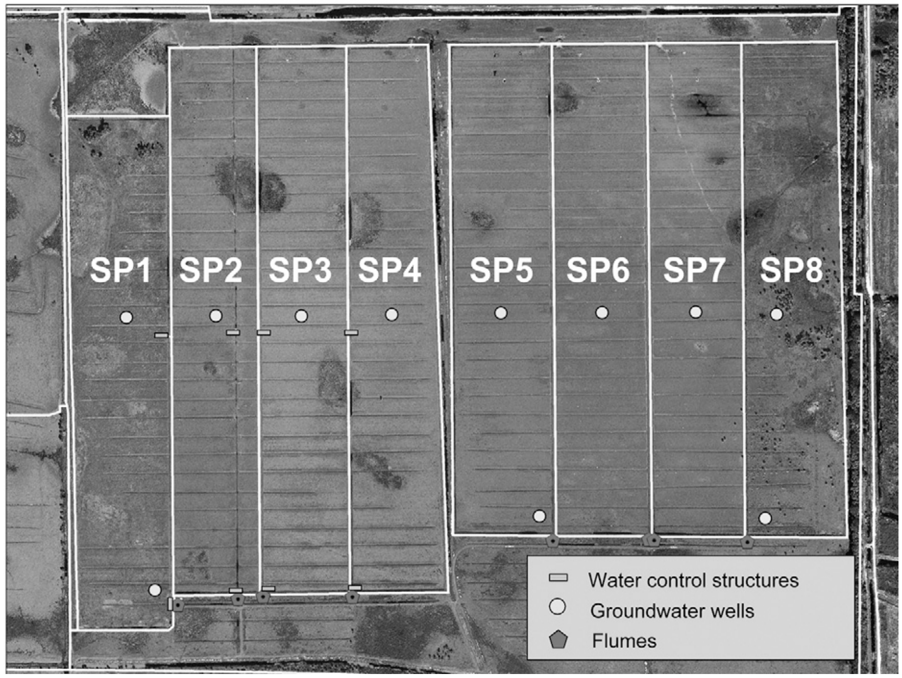

Fig. 2. Aerial image of the experimental pastures showing the location of the flumes, groundwater wells, and water control structures.

Pasture Water Retention Treatments

Two pasture water management treatments were evaluated: reduced flow and unobstructed flow. Reduced flow involved holding back water in the pasture drainage ditches while maintaining an elevated surface depth during flooded periods using riser board water control structures set at a predetermined elevation. The water retention treatment was imposed on pastures SP1-SP4 (Block 1) by installing two water control structures in the main drainage ditch from the pastures; one structure was installed near the existing flume and another at the midsection of the ditch (Fig. 2). Elevations of the boards in the structures were measured in 2005 and 2006 and ranged from 8.17 to 8.32 m AMSL (NGVD29); the boards were kept fixed at the same level throughout the study period. No structures were installed in pastures SP5 to SP8 (Block 2), which served as the unobstructed flow treatment. Cattle were allowed to graze the pastures for various lengths of time from 2005 to 2008, with an effort made to stock the pastures at even rates. The average stocking density from 2005 to 2008 was slightly higher in pastures with reduced flow (1.14 animal units [AU] ha^{-1}; 1 AU = 1 cow–calf pair) than in pastures with unobstructed flow (0.92 AU ha^{-1}). This slight difference in stocking rates between the pasture blocks was not likely to influence any measured runoff variables as previous results from the same pastures showed that different stocking rates (0, 0.74, 0.99, 1.72 AU ha^{-1}) had no influence on nutrient concentrations or loads during 6 yr (1998–2003) of measurement (Capece et al., 2007).

Surface Water Sampling and Analysis

Runoff samples collected by the autosamplers were preserved with sulfuric acid (pH < 2) and were analyzed by an external certified laboratory for total Kjeldahl nitrogen (TKN), nitrate/nitrite (NO_x), ammonium (NH_4^+), and total phosphorus (TP) using standard methods (Environmental Monitoring Systems Laboratory, 1993). Total N (TN) was calculated as TKN plus NO_x. All field sampling activities were performed according to standard operating procedures established by the Florida Department of Environmental Protection (FDEP, 2001b). Flow data from the flumes were combined with nutrient concentration data from the water samples to calculate nutrient loading rates. Flow-weighted concentrations were determined by dividing total loads by runoff volume.

In addition to the autosamples, manual grab samples were collected on six dates in 2005 to 2006 just upstream of each flume during flow events (Fig. 2). Both unfiltered preserved and filtered unpreserved samples were taken. Preserved samples were analyzed for TKN, NO_x, and NH_4^+ as described above. Unpreserved filtered grab samples were analyzed for soluble reactive phosphorus (SRP) and nitrate (NO_3^-). Groundwater elevation data was obtained from the instrumented groundwater wells and groundwater samples were collected quarterly from the wells and analyzed for the same nitrogen and phosphorus species as described above.

Soil Sampling and Analysis

Surficial (0–15 cm) soil samples were collected monthly from June to October in 2005 and 2006. A total of nine composite samples were taken from each pasture at the same locations on each sampling date and extracted with Mehlich I double acid solution (Mehlich, 1953). Phosphorus in the extracts was analyzed colorimetrically using the ascorbic-acid, molybdate-blue method (Olsen and Sommers, 1982). Available soil P was also assessed using ion-exchange resin strips in the field (Cooperband et al., 1999). Anion exchange resin sheets (AR204-SZRA, Ionics, Watertown, MA) were cut into small strips (2 by 5 cm), presaturated with 1 M sodium acetate and rinsed in deionized water. One 2-by-5-cm resin strip was inserted vertically about 5 cm beneath the soil surface adjacent to three forage sampling locations randomly selected within each pasture. The resin strips were left in the field for 1 wk, after which they were retrieved, washed with deionized water, and extracted with 1 M NaCl solution. Extracts were analyzed for P as described above.

Data Analysis

Annual hydrographs for each of the eight experimental pastures were generated from stilling well data for each flume. Errors due to instrument failure or malfunction were corrected with information from regularly collected manual water depth measurements where available. Gaps in electronic data due to equipment failure or malfunction were filled with recorded manual water depth measurements, using linear fits or by tagging estimated values to actual values from the adjacent upstream or downstream shaft encoders.

Nutrient loads were calculated by multiplying runoff volumes by nutrient concentrations of corresponding volumes of runoff and summing these values through time for each year. Nutrient load data and flow-weighted nutrient concentrations were analyzed independently by year using a one-way ANOVA with water retention treatment as the main treatment effect and total cumulative nutrient load as the dependent variable. In addition to flow-weighted nutrient concentrations, average annual nutrient chemistry values were determined by averaging values from all samples collected during the year. Soil chemistry data collected monthly during the summers of 2005 and 2006 were analyzed separately by sampling date using a one-way ANOVA. Groundwater chemistry data were analyzed using a repeated-measures ANOVA with time and water retention treatment as the main effects. All statistical analyses were performed using JMP version 7.0 Statistical Discovery software (SAS Institute, Inc., Cary, NC).

The availability of 6 yr of runoff and nutrient data (1998–2003) from the experimental pastures before applying the water retention treatment made it possible to analyze the nutrient loading and nutrient concentration data using before-after-control-impact (BACI) analysis (Smith et al., 1993). This statistical procedure uses ANOVA to apportion variance due to the before–after period, the control–impact treatment locations, and their interaction. Significant effects of treatment are indicated by a significant interaction between the before–after periods and the control–impact treatment (BA × CI). Before analysis, data was removed from the two severe drought years: one before treatment (2001) and one post-treatment (2007). Data from 2005 was removed because of severe undercutting of the water retention structures described above.

Results and Discussion

Meteorological Conditions

Total annual rainfall and distribution varied among years; it was above the long-term average (~132 cm) for the region in 2005 (144 cm) and 2008 (138 cm) but below average in 2006 (119 cm) and 2007 (85 cm). The drought period during 2006 and 2007 was one of the most severe droughts in the period of record for south Florida. Total rainfall for August through September 2007 was especially low, leading to extremely dry conditions during a period that would normally be associated with flooding and surface runoff.

Pasture Groundwater Elevations

Groundwater elevation varied seasonally and was affected significantly by the water retention structures. There were more prolonged periods of higher groundwater levels in 2005 and 2008 compared with 2006 and 2007 (Fig. 3). The effects of the prolonged drought in 2007 are shown by the single instance that average water depths reached the surface, which happened in August and resulted in the only flow event that occurred in that year. Throughout most of 2005, the groundwater levels remained higher in pastures with water retention structures than in pastures without structures. This pattern persisted through June 2006, when groundwater elevation reached its lowest level due to the drought. In July, backflow events into the pasture occurred when water levels in the adjacent C-41 canal were increased. During this period, groundwater levels were actually lower in pastures with water control structures because the water control structures prevented backflow. The period of heavy rain in late summer 2006 kept groundwater elevations close to the soil surface across all pastures, with little difference between pastures with or without structures. As the surface and groundwater levels in the pastures began to drop at the end of the summer rainy season in late September–early October, water retained by the riser structures kept groundwater elevations higher in pastures with the structures. However, during the extended drought in 2007 when water exchanges between the C-41 canal and the pastures were dominated by backflow, groundwater elevations were higher in pastures without water control structures. Once the soils became saturated again with summer rains starting in late July and early August 2008, groundwater levels remained higher in pastures with water control structures and remained so through the end of 2008 (Fig. 3).

Effects of Water Retention on Runoff Volume and Nutrients

Total net runoff was significantly lower in pastures with riser structures than in pastures with unobstructed flow, especially in 2006 and 2008 (Fig. 4). Analysis of pretreatment data from 1998 to 2003 showed that pastures with water control structures (SP1–SP4) had 20% higher average annual runoff compared with SP5–SP8 before the water control structures were installed (Table 1), but this difference was not significant. Furthermore, the difference in runoff after water control structures were installed was much greater in 2006 (50% lower) and 2008 (48% lower) than during any year in the pretreatment period (Fig. 4), indicating that the riser structures, once stabilized, were effective at reducing runoff from the pastures. The low reduction in flow in 2005 (10%) may have been due to major undercutting of the water control structures that occurred during heavy rains in the early part of the rainy season that year, before the ditch banks at the base of the structures had been stabilized with concrete.

The BACI analysis showed that total runoff and TN loads were significantly reduced by the water retention treatment but that TP loads were not significantly affected by water retention (Table 2, BA × CI interaction). The analysis also indicated that concentrations of TN were significantly higher in the period before compared with the period after the implementation of the water retention treatment (Table 2, BA column; Fig. 5), and that runoff, TN loads, and TP loads were significantly lower from pastures selected for the water retention treatment before establishing the treatment (Table 2, CI column; Fig. 6). Separate analyses of data by individual years generally support the results of the BACI analysis and provide insights into temporal trends in the data.

The water retention treatment did not have a significant effect on flow-weighted concentrations of NH_4^+ or NO_x in surface runoff in any year (Fig. 5). The water retention treatment significantly decreased overall NH_4^+ loads (0.83 vs. 0.42 kg NH_4^+-N ha^{-1}, respectively, in pastures without vs. with riser structures, $P < 0.0001$). The effect was greatest in 2006 and 2008 (Fig. 6). There was no significant effect of the water retention treatment on NH_4^+ loads in 2005, when runoff differences between pastures with or without riser structures were small, and in 2007, when there was a lack of net runoff due to drought conditions; there was actually a net inflow of NH_4^+ into the pastures that year. Average annual loads of NO_x in net surface runoff were significantly lower in pastures with reduced flow (0.007 kg ha^{-1}) than in pastures with unobstructed flow (0.10 kg ha^{-1}, $P = 0.01$, SEM = 0.02), although significant trends were not as apparent in individual years (Fig. 6).

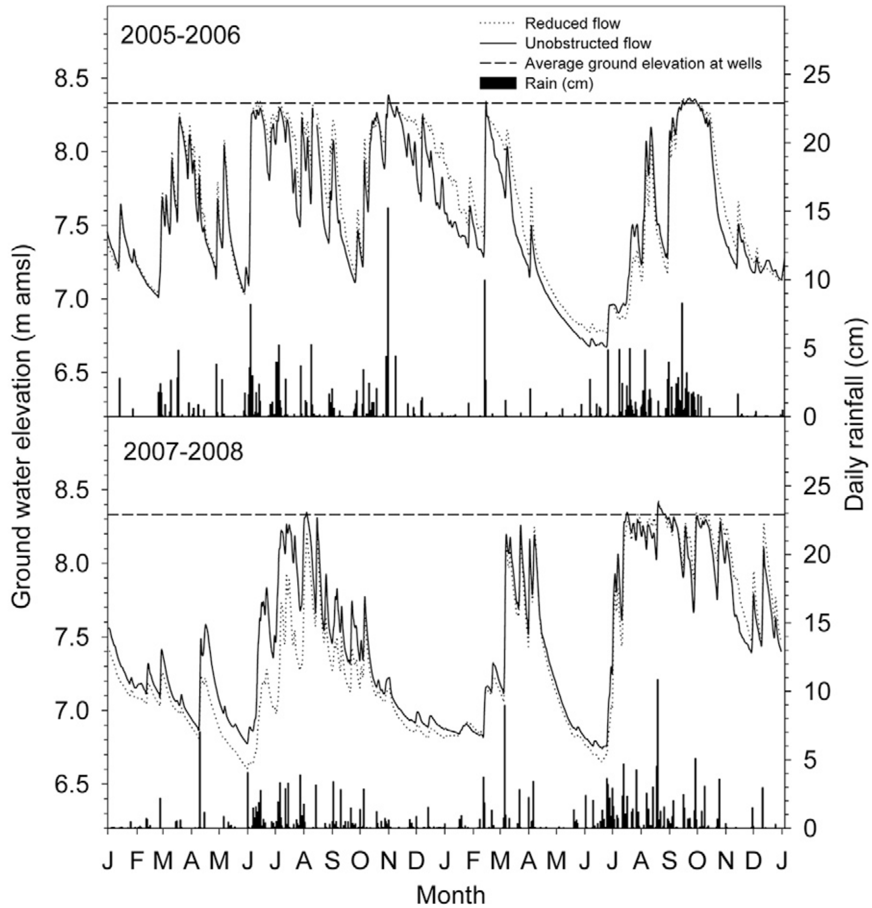

Fig. 3. Average groundwater elevation and daily rainfall totals for 2005 to 2006 (upper panel) and 2007 to 2008 (lower panel) in pastures with reduced (SP1–SP4) or unobstructed (SP5–SP8) flow. (amsl, above mean sea level.)

Average annual TN concentration in runoff was significantly greater in pastures with unobstructed flow (3.31 mg L^{-1}) than in pastures with reduced flow (2.86 mg L^{-1}) ($P = 0.008$). Flow-weighted TN concentrations were greater in pastures with unobstructed flow than in pastures with water control structures in all years following installation of the structures (Fig. 5). The TN loads in surface runoff were significantly affected by water retention treatment ($P < 0.0001$), and there was a significant interaction between year and treatment ($P = 0.0006$). Overall annual TN loads were 11.28 kg ha^{-1} in pastures with unobstructed flow and 6.28 kg ha^{-1} in pastures with reduced flow (SEM = 0.51). This pattern held in all years except the drought year, 2007, when loads were not different between treatments (Table 3). The pastures with water control structures had significantly lower average annual TN loads before the structures were installed (Table 1), but the magnitude of the difference between the pasture blocks was much greater in 2006 and 2008 than in any year before installing the structures (Fig. 6).

Flow-weighted TP concentrations were significantly greater in pastures with reduced flow (0.89 mg L^{-1}) than in pastures with unobstructed flow (0.66 mg L^{-1}) ($P = 0.009$, SEM = 0.11) when the drought year (2007) was excluded from the analysis, but the BACI analysis, which took into consideration any pretreatment differences among sites, did not support that this difference was due to the water retention treatment (Fig. 5, Table 2). The water retention treatment had variable effects on TP loads in the different years. In 2005, TP loads in net surface runoff were 39% higher ($P = 0.06$) in pastures with reduced flow than in pastures with unobstructed flow, but the water

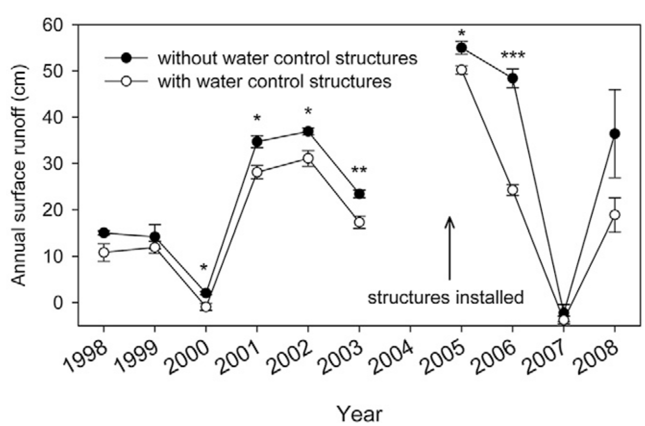

Fig. 4. Average annual runoff (±1 SE) in pastures with and without water control structures (*N* = 4), including data for years before installing the control structures (1998–2003) and after installing structures (2005–2008). Asterisks indicate significant differences between treatments for each sampling date (P* < 0.05, ***P* < 0.01, ****P* < 0.001).**

Table 1. Pretreatment data for the eight pastures used in the pasture water retention projects. Values are average annual characteristics of surface runoff for the years 1998 to 2003, excluding data from 2000 which was an extreme drought ($N = 4$).

Variable†	Pastures SP1–SP4	Pastures SP5–SP8	SEM‡	F-value	Prob > F
Runoff (cm)	24.87	19.86	2.13	2.76	0.105
NH_4^+ load (kg ha^{-1})	1.01	0.59	0.23	1.72	0.205
NO_x load (kg ha^{-1})	0.05	0.03	0.01	1.28	0.264
TN load (kg ha^{-1})	10.70	7.61	0.92	5.63	0.023‡
TP load (kg ha^{-1})	2.36	1.71	0.32	1.93	0.172
NH_4^+ (mg L^{-1})§	0.36	0.27	0.06	0.81	0.374
NO_x (mg L^{-1})§	0.02	0.02	0.00	0.10	0.750
TN (mg L^{-1})§	4.42	3.93	0.21	2.55	0.118
TP (mg L^{-1})§	0.79	0.87	0.08	0.436	0.513

† TN, total nitrogen; TP, total phosphorus.

‡ SEM values are the standard errors of the means.

§ Values are flow-weighted mean concentrations.

Table 2. Probability values for the two-factor ANOVA for the before-after-control-impact design (BACI) examining the effects of the control-impact pasture locations (CI), the periods before and after the water retention treatment was applied (BA), and their interaction. Significant effects of the water retention treatment are indicated by a significant interaction between CI and BA, shown in the last column.

Variable	Prob > F for fixed effects		
	Before-After Treatment (BA)	Control-Impact Pastures (CI)	BA × CI
Runoff (cm)	0.1267	*<0.0001*†	*<0.001*
Total P load (kg ha^{-1})	0.5333	*0.0163*	0.3751
Total N load (kg ha^{-1})	0.3988	*0.0004*	*0.0089*
NH_4^+ load (kg ha^{-1})	0.7194	0.0690	0.5270
NO_x load (kg ha^{-1})	0.1028	*0.0258*	0.0678
TP (mg L^{-1})	0.8617	0.6760	0.2254
TN (mg L^{-1})	*0.0475*	0.0844	0.6927
NH_4^+ (mg L^{-1})	0.6843	0.4556	0.8260
NO_x (mg L^{-1})	0.1534	0.5612	0.9336

† Italic values indicate significant effects at the 0.05 level.

control structures were not functioning due to undermining as noted above, so this difference cannot be attributed to the water retention treatment. In 2006, TP loads were 39% lower in pastures with reduced flow, and in 2008 they were 16% lower, but these differences were not significant in the BACI analysis (Table 2).

Groundwater Nutrient Concentrations

There were significant differences between different sampling dates for NH_4^+, TKN, and NO_3^- but there was no consistent trend through time (Table 4, temporal trends not shown). Nitrate was low for all sampling dates except for a spike in Quarter 1, 2008. Groundwater TN concentrations tended to be greater in pastures with no riser structures, but that pattern was not consistent throughout the study period. The higher mean values for groundwater TP and SRP were not statistically significant and were due to variability resulting from consistently greater TP values in pastures SP3 (1.68 mg L^{-1}) and SP4 (1.38 mg L^{-1}) relative to other pastures (mean = 0.24 mg L^{-1}); these values were consistently greater during 3 yr of pretreatment monitoring and thus were not related to the water control treatment.

Soil Chemistry

Concentrations of double acid phosphorus (DAP) were nearly twofold greater in pastures with water control structures than in pastures without water control structures throughout most of 2005 and remained higher in pastures with water control structures throughout 2006 (Fig. 7). Concentrations of ion-exchange resin P (IER-P) were much more variable seasonally than were DAP concentrations because adequate soil moisture is required for P to diffuse to the membrane surface. Where significant differences occurred, however, IER-P was greater in pastures with water control structures than in pastures with unobstructed flow. Soil moisture levels in collected samples were significantly greater in pastures with water control structures in August, September, and October in 2005 but did not differ between treatments in 2006 (Fig. 8). Although soil moisture was relatively high in October 2006 when the strips were placed in the field, it is probable that the soils dried out considerably during the incubation period, which may explain why resin-P levels were low for that sampling.

Discussion

The significant reduction of TP loads in 2006, a year of normal rainfall, indicates that pasture water retention may significantly reduce P loads under certain conditions, but the pattern was not consistent and thus the BACI analysis showed no significant effects of pasture water retention on TP loads. The only year there was a significant increase in P loads associated with water retention was the first year of the project (2005), when heavy rains early in the wet season caused washouts under the

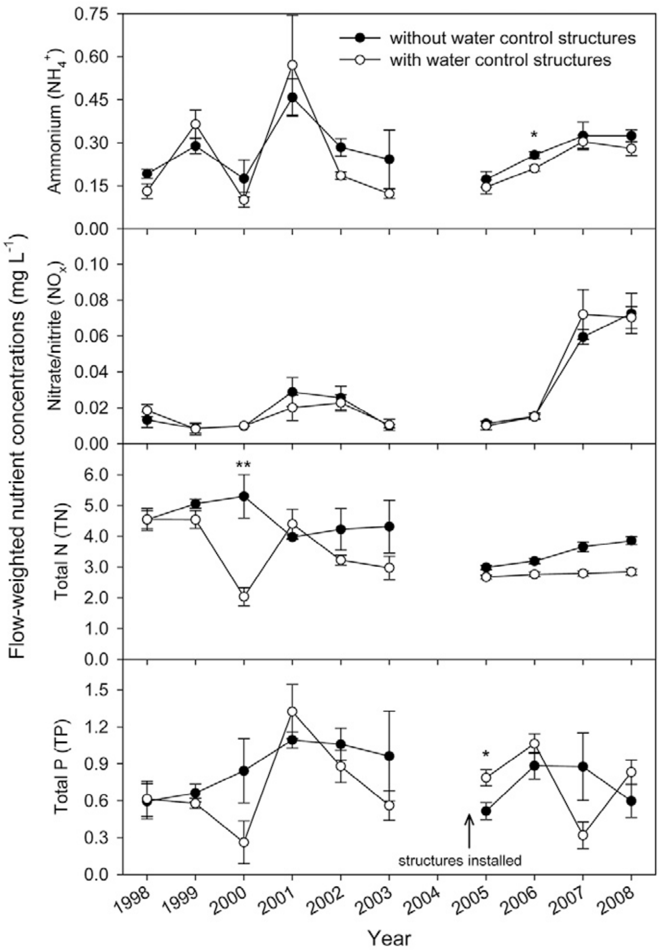

Fig. 5. Average annual flow-weighted nutrient concentrations (±1 SE) in pastures with and without water control structures (N = 4), including data for years before installing the control structures (1998–2003) and after installing structures (2005–2008). Asterisks indicate significant differences between treatments for each sampling date (*P < 0.05, **P < 0.01, ***P < 0.001).

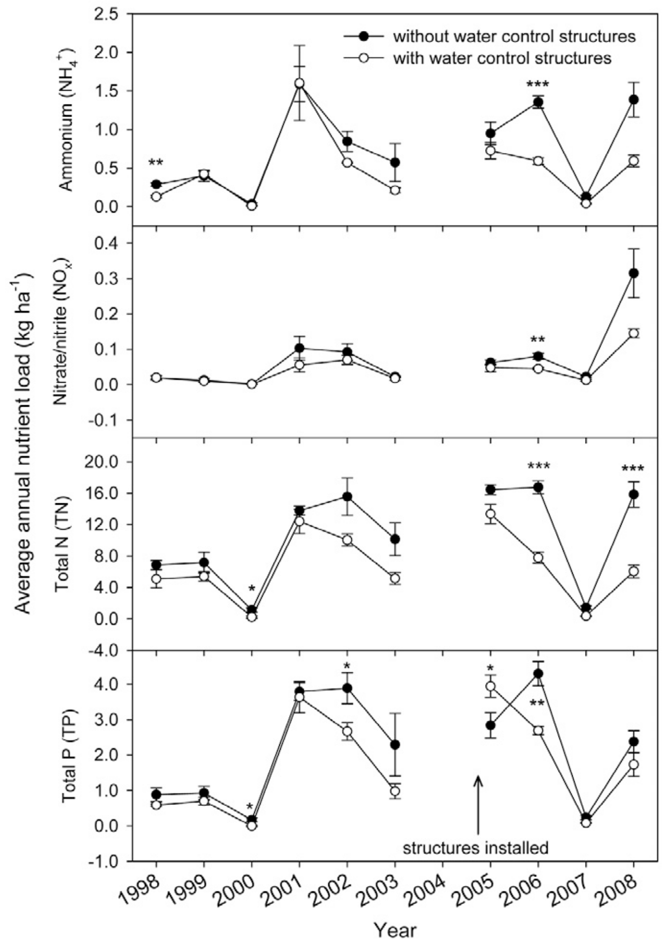

Fig. 6. Average annual nutrient loads (±1 SE) in pastures with and without water control structures (N = 4), including data for years before (1998–2003) and after (2005–2008) installing the water control structures. Asterisks indicate significant differences between treatments for each sampling date (*P < 0.05, **P < 0.01, ***P < 0.001).

water control structures, effectively undermining the water retention treatment. That total runoff and TN loads were significantly reduced by the water retention treatment, but TP loads were not, indicates that P loads were governed by processes different from N and that the relation between TP loads and runoff were altered by the water retention treatment.

A variety of factors control P release from soils to surface runoff. There is often a strong relationship between soil-test P and runoff P, although this relationship varies for different soils (Sharpley et al., 1995; McDowell et al., 2001a,b; Torbert et al., 2002). Our results showed a consistent increase in Mehlich-1 P in pastures with water control structures. During the rainy season, pasture soils in the Lake Okeechobee watershed are exposed to alternating oxidative states associated with flooding and drying. These conditions stimulate release of adsorbed and organic P into soil solution, where it becomes susceptible to transport under wet conditions (Reddy and Patrick, 1975; Villapando and Graetz, 2001; Capece et al., 2007). Flooded conditions can contribute to P release from soils due to the inverse relationship between P release and soil redox conditions (Moore et al., 1998; Fisher and Reddy, 2001). Iron-related P release is considered to be a consequence of the reduction of Fe^{+3} to the more soluble Fe^{+2}, which has been shown to increase SRP concentrations (Patrick and Khalid, 1974; Reddy et al., 1999). Although we did not measure Fe content or redox in the pastures, the higher soil moisture and groundwater elevations in pastures with water control structures would be expected to cause lower redox conditions in the soil.

Other data from wetlands and improved pastures at Buck Island Ranch showed that Fe/Al-P accounted for about 12% of TP in the upper 8 cm of mineral soil and that Al concentrations (355.8 mg kg^{-1}) were much greater than Fe concentrations

Table 3. Average nutrient concentrations (±1 SE) in manual grab samples collected on six dates during flow events in 2005 to 2006 in pastures with unobstructed flow and pasture with reduced flow. There were no significant differences between pasture water management treatments for any variable (P > 0.05, Kruskal–Wallis test).

Variable†	Pasture water management treatment	
	Unobstructed flow	Reduced flow
NH_4^+ (mg L^{-1})	0.131 ± 0.027	0.119 ± 0.025
NO_x (mg L^{-1})	0.019 ± 0.002	0.015 ± 0.002
TN (mg L^{-1})	3.390 ± 0.165	3.309 ± 0.248
SRP (mg L^{-1})	0.809 ± 0.094	0.786 ± 0.077
TP (mg L^{-1})	0.609 ± 0.106	0.563 ± 0.068
SRP/TP	0.66 ± 0.04	0.67 ± 0.03

† SRP, soluble reactive phosphorus; TN, total nitrogen; TP, total phosphorus.

Table 4. Average nutrient concentrations in groundwater samples collected in 2005 to 2008 from wells in pastures with or without riser structures. Values are means ± 1 SD (*N* = 13). *P* values are from a repeated-measures ANOVA performed for the main effects of the water retention treatment (R) and time (T) and their interaction.

Analyte†	No riser	Riser	P		
			Riser	Time	R×T
	mg L^{-1}				
NH_4^+	0.76 ± 0.26	0.93 ± 0.36	0.39	0.00***	0.90
NO_3^-	0.10 ± 0.26	0.05 ± 0.09	0.13	0.00***	0.00***
NO_2^-	0.02 ± 0.03	0.02 ± 0.03	0.65	0.00***	0.34
TN	3.76 ± 0.52	3.23 ± 0.93	0.09*	0.02**	0.00***
SRP	0.18 ± 0.10	0.66 ± 0.17	0.27	0.61	0.97
TP	0.29 ± 0.13	0.85 ± 0.24	0.34	0.14	0.87

*$P \leq 0.05$.

**$P \leq 0.01$.

***$P \leq 0.001$.

† SRP, soluble reactive phosphorus; TN, total nitrogen; TP, total phosphorus.

(13.2 mg kg^{-1}) (Hill, 2003). By contrast, organic P in these pastures and wetland soils accounted for 61% of TP, indicating that mineralization or release of organically bound P may be a likely source of inorganic P released during flooding. Hydrolytic cleavage of particulate organic matter is an important process for P release from peaty soils (Turner et al., 2003). Another source of P release may be dead material and detritus of Bahia grass and other pasture and wetland plants in the pastures. Tweel and Bohlen (2008) showed that the presence of plants and plant detritus in soil cores collected from wetland in improved pastures on Buck Island Ranch resulted in large increases in P release compared with cores with bare soil. In addition to redox conditions, biotic factors, such as changes in microbial activity and release from cell lysis, can affect P release during inundation and may have been important in our study (Wright et al., 2001).

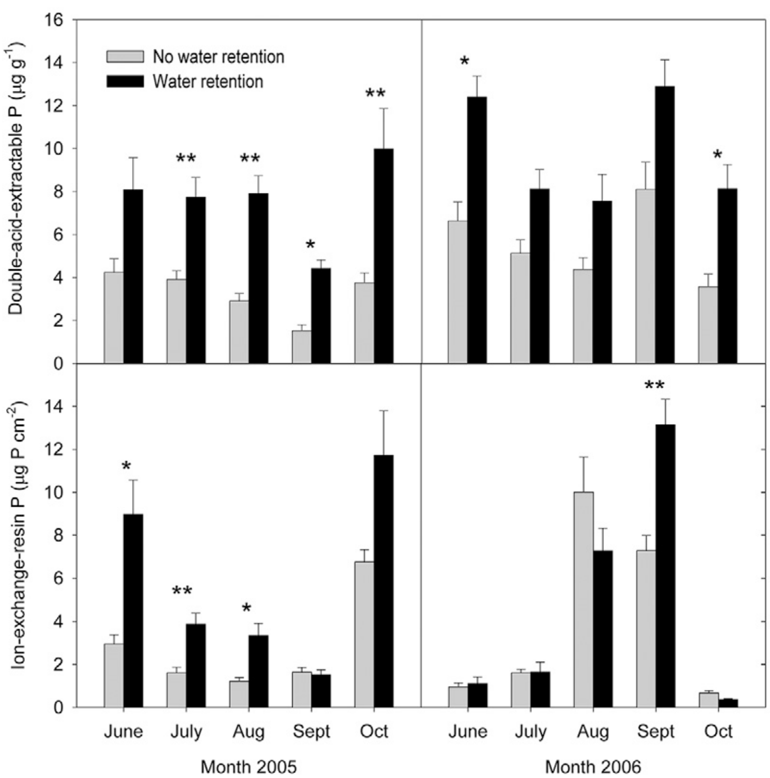

Fig. 7. Double-acid-extractable P (top panels) and ion-exchange-resin P in pasture soils (bottom panels) in 2005 and 2006 pastures with or without water retention structures. Asterisks indicate significant differences between treatments for each sampling date (*$P < 0.05$, **$P < 0.01$).

Nearly 70% of TP in pasture runoff was SRP, the most biologically reactive form of P, whereas only about 5% of TN was in the inorganic form (mainly NH_4^+ with small amounts of NO_3^-; Table 3). Increased concentrations of P due to pasture water retention were related to release of SRP from pasture soils or other in-pasture sources such as dead plant material or detritus. Although we did not measure available N in soil, there was no evidence from surface runoff that inorganic N concentrations were affected by water retention. Furthermore, TN concentrations were significantly lower in pastures with reduced flow (Fig. 5) so there is little evidence that pasture water retention caused increases in dissolved inorganic nitrogen (DIN) or dissolved organic nitrogen (DON). It is possible that the longer retention time of water in pastures with reduced flow allowed more time for N forms to be taken up or processed by aquatic organisms within the ditches and other wet areas of the pasture or released into the atmosphere in some form of gaseous N due to denitrification processes. Whatever the mechanism for reduced TN concentration in pastures with reduced flow, they contributed to consistently lower TN loads from pastures with water control structures, especially when combined with reduced runoff from these pastures. Thus, water retention appears to be a highly effective management alternative for reducing total N loads from improved pastures in the Lake Okeechobee watershed.

Most of the emphasis in this region has been on reducing P loads, but the need to reduce N loads is gaining more attention, in part due to the negative effect of N loading on water quality in estuaries downstream of Lake Okeechobee (USEPA, 2008) and the recognition that DON could be a significant source of N loss in agricultural runoff (van Kessel et al., 2009). The effects of N on estuaries are not limited to inorganic N but also include effects of DON, which accounts for most of the N in pasture runoff. Dynamics of DON are complex and not well understood but include processing of DON into DIN via microbially mediated mineralization, or sequestration of DON in sediments where some fractions can be transformed into highly recalcitrant forms. Although DON has historically been considered recalcitrant in aquatic ecosystems, it is actually involved in dynamic N cycling processes (Bronk et al., 2007). A significant fraction of DON in surface waters can become bioavailable to phytoplankton and bacteria in days to weeks in marine, estuarine, and freshwater ecosystems and thus must be incorporated into coastal nitrogen budgets (Berman and Bronk, 2003; Wiegner et al., 2006; Bronk et al., 2007). Bioavailability of DON can contribute to harmful microalgae blooms and coastal eutrophication (Seitzinger and Sanders, 1997; Vargo et al., 2008). Concentrations of DON in aquatic systems are strongly associated with humic substances (Wiegner et al., 2006; Bronk et al., 2007), which are prevalent in the surface waters of south Florida, giving them their characteristic dark brown color.

In a long-term experiment (1998–2003) at the same pastures used in this study, TN loads in runoff from improved pastures were significantly higher, in 3 of 6 yr, than in runoff from seminatural pastures that had never been fertilized (Capece et al., 2007). It is probably that long-term fertilizer inputs to the improved pastures contributed to the increased N loads; however, these differences were relatively small and did not occur in all years. By contrast, TP loads were consistently five- to sevenfold greater from improved pastures than from the seminative pastures. The increase in P loads was related to the "legacy" fertilizer P accumulated in pasture soils that release P during flooded periods through the mechanisms discussed above (Zielinski et al., 2006). Past N fertilizer use may contribute to current N loadings but not to the same degree as P, possibly due to the high biological demand for N but also because of high denitrification activity in flooded surface soils and the lack of sorption dynamics of N forms with Al, Fe, or other soil constituents.

Net P imports to improved pastures in the Lake Okeechobee watershed declined from the late 1980s to the late 1990s but still account for about 32% of total net imports to the Lake Okeechobee watershed (Hiscock et al., 2003). Estimates are that 70% of the P imported into the Okeechobee watershed is stored in upland soils, which make these soils a significant sink for the legacy P stored in the watershed (Reddy et al., 1996; Hiscock et al., 2003). However, the P assimilative capacity of soils and wetlands in the region has apparently declined over the past several decades, increasing the likelihood that these sinks will become sources with continued loading. Our results indicate that retaining water on pastures may help reduce the offsite transport of legacy P to downstream waterways, but this effect appears to be counteracted to some degree by the influence of pasture water retention on increased P release from pasture soils. Thus, management measures must be taken to ensure that any increased P release from soil does not result in increased P runoff. Under the management scenarios and P legacy characteristics of the sites used in this study, P loading was not increased by pasture water retention, but neither was it significantly decreased. In addition to maximizing reduction in runoff volumes, additional management options that could decrease P loads include capturing the "first flush" of nutrients at the start of the wet season when concentrations tend to be highest and increasing water retention times within the pasture to maximize the P removal from the water column via biological uptake or P sorption by sediments. Water retention practices appear to have great promise for reducing total N runoff from pastures in this region.

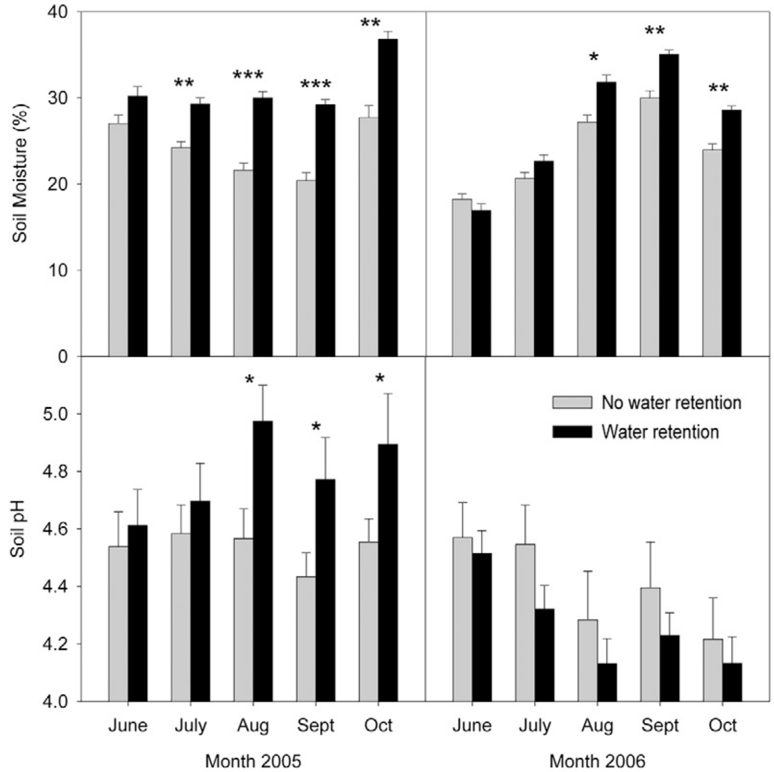

Fig. 8. Soil moisture and pH in pastures with or without water control structures. Asterisks indicate significant differences between treatments for each sampling date (*$P < 0.05$, **$P < 0.01$).

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