

## Use of Soil Amendments to Reduce Leaching of Nitrogen and Other Nutrients in Sandy Soil of Florida

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### ABSTRACT

Nitrogen is a nutrient often associated with accelerated eutrophication of surface water. Amending sandy soils is considered one of the best management practices (BMPs) to reduce N loss. The effectiveness of soil amendments (CaCl<sub>2</sub>, CaCO<sub>3</sub>, cellulose, Al(OH)<sub>3</sub>, and mill mud) in reducing leaching of N and other nutrients from a typical acidic sandy soil (Ankona sand: sandy, siliceous, hyperthermic, ortstein Arenic Haplaquods) in Florida was determined by laboratory column leaching. Amendments were applied at the rate of 15 g kg<sup>-1</sup> for a single amendment and 7.5 g kg<sup>-1</sup> each if two amendments were combined. Leaching (250 ml of deionized water, equivalent to 90 mm rainfall or two pore volume of the soil column) of 1 kg soil mixture (20 cm deep, in a 6.6cm column) was conducted every four days for 32 days. With different soil amendments, the cumulative losses of NO<sub>3</sub><sup>-</sup>-N and NH<sub>4</sub><sup>+</sup>-N ranged from 41-82% and 13-33%, respectively, of total applied N. Reduction in total inorganic N loss was most significant when the soil was amended with cellulose, CaCl<sub>2</sub>, or CaCl<sub>2</sub> + CaCO<sub>3</sub>, which reduced N loss by 43, 32, and 33%, respectively. The effects of mill mud, Al(OH)<sub>3</sub>, and mill mud + Al(OH)<sub>3</sub> on reduced total inorganic N leaching were moderate (23, 22, and 21%, respectively). Calcium carbonate was not effective in reducing total inorganic N leaching. Application of CaCl<sub>2</sub> or CaCl<sub>2</sub>+CaCO<sub>3</sub> significantly decreased K, Mg, and Cu, but increased Zn concentration in leachate. These results indicate that amendment of CaCl<sub>2</sub>, or CaCl<sub>2</sub> + CaCO<sub>3</sub> were effective in reducing leaching losses of N, K, Mg, and Cu and therefore can be considered in the development of BMPs for the sandy soil regions.

### INTRODUCTION

Water quality throughout South Florida has been a major concern for many years (Chamberlain and Hayward, 1996). The St. Lucie watershed is a major citrus production area in Florida where citrus crops are grown on flatwood soils. These soils are characterized by low moisture and nutrient holding capacities and a shallow hardpan or argillic horizon, which acts as a confining layer to reduce the downward migration of pollutants and increase lateral movement of nutrients to surface drainage (He et al., 2000b). Most of the citrus acreage in Florida is on extremely sandy soils characterized by sand content often in excess of 90% (Hoogeweg and Hornsby, 1997). Frequent applications of fertilizers are made to assure high yields. More than 50% of applied N fertilizer is subject to potential leaching or runoff losses. Therefore, excess nutrients that are not utilized by the crop are a potential source of surface water and/or ground water contamination.

Leaching is the physical process of the downward movement of dissolved constituents in soil solution. As the soil solution is displaced through soil profile by rainfall or irrigation in excess of the water-holding capacity of the soil, the dissolved ions move with the wetting front. The study of NO<sub>3</sub><sup>-</sup> movement, which is both a nutrient and possible contaminant, has intensified in recent years (Spalding and Exner, 1993) and remains a growing concern due to application of N fertilizers (Tan et al., 2002) and climatic conditions (Di and Cameron, 2002). Being an anion, NO<sub>3</sub><sup>-</sup> is not adsorbed by most soils (Nikolla et al., 2000); whereas ammonium leaching occurs in soils amended with sewage and other sludge (Medalie et al., 1994).

Copper is commonly used as a major component of fungicides for vegetable and citrus crops. On annual basis, the removal of accumulated Cu in soils by harvested portion of the citrus trees is insignificant. Copper is one of the least mobile trace elements in soils; however, transport of Cu through surface runoff into surface water could be considerable (Zhang et al., 2003). Management actions should be taken to reduce N and other nutrient (such as Cu) losses from soils. Adding soil amendments is considered one of the promising ways to reduce N loss. The effectiveness of amendments is influenced by soil and watershed characteristics. Practical considerations such as amendment availability, optimal rate, and cost must also be accounted for. Loss of other nutrients such as Mg, K, Cu, and Zn must be also considered to ensure that solving the N problem does not lead to loss of other nutrients or other water quality problems (O'Connor et al., 2005). Liming acid soils improves citrus yield and quality due to improved soil environment for root development. Liming also decreases losses of nutrients and metals in surface runoff by increasing soil holding capacity for these elements. Lime has been used as soil amendment to increase soil pH. Many other amendments [such as CaCl<sub>2</sub>, Al(OH)<sub>3</sub>, etc.] and industry byproducts (such as sugarcane mill mud) have been suggested to reduce N, P, and metal leaching in sandy soils. However, no systematic studies have been conducted in the Indian River area to demonstrate the effectiveness of these materials in reducing N and other nutrient losses into surface waters. The objective of this study was to evaluate the effectiveness of some commonly used organic and inorganic amendments in reducing leaching losses of N and other nutrients in typical sandy soils in the Indian River area.

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**Table 1. Relevant properties of the Ankona sand soil.**

Soil Depth	pH (H <sub>2</sub> O)	Electrical Conductivity	Organic Matter	KCl extractable N		
				Mehlich 3-P	NO <sub>3</sub> <sup>-</sup> -N	NH <sub>4</sub> <sup>+</sup> -N
- cm -		μS cm <sup>-1</sup>	g kg <sup>-1</sup>		mg kg <sup>-1</sup>	
0-15	6.3	326	4.0	95.7	26.5	23.7
15-30	6.5	405	2.4	98.5	25.8	28.0

**Table 2. Relevant properties of the tested sugarcane mill mud.**

Element	Na	K	Ca	Mg	B	Cd	Cr	Cu	Fe	Mn	Mo	NH <sub>4</sub> -N	Ni	NO <sub>3</sub> -N	P	Pb	Zn
mg kg <sup>-1</sup>	295	2472	78600	5042	11.3	<1.00	10.5	138	5302	445	<1.00	56.0	8.20	286	9280	<5.00	235

## MATERIAL AND METHODS

### Soil and Amendments

Soil samples were collected at 0- to 15-cm and 15- to 30-cm depths from a representative commercial farm (Ankona sand: sandy, siliceous, hyperthermic, ortstein Arenic Haplaquods) in the Indian River area. The soil samples were air dried and ground to < 2 mm prior to physical and chemical analysis. Some properties of the soil are presented in Table 1. Total organic carbon in the soil samples was determined by combustion using a Macro Elemental Analyzer (Vario MAX CN, Elementar Analysensysteme GmbH, Germany). Electrical conductivity (EC) and pH of the soil samples were measured in slurry with deionized water at a soil: water ratio of 1:2 and 1:1, respectively, using a pH/ion/conductivity meter (Model 220, Denver Instrument, Denver, CO). Labile N (NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N) was determined by shaking a 2.5 g air-dried sample in 25 ml of 2 M KCl for 1 h and the concentrations of NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N in the filtrate were analyzed using a N/P Discrete Autoanalyzer (EasyChem, Syntex Scientific LLC, Oak Brook, IL). Available P was determined by extracting the samples with Mehlich III solution and measuring the concentration by inductively coupled plasma atomic emission spectrometry (ICPAES, Ultima, J Y Horiba, Edison, NJ).

The soil amendments tested in this study included CaCl<sub>2</sub>, CaCO<sub>3</sub>, cellulose, Al(OH)<sub>3</sub>, and mill mud. They were all commercial products except for mill mud (pH 6.88), which was provided by the USDA, Sugarcane Field Experiment Station, Canal Point, FL. This material is an organic waste from sugar industry, containing approximately 24% organic C, 1% N, 0.9% P, 0.02% K, and trace amounts of metals (Table 2).

### Column Leaching Study

Air-dried soil (1.0 kg) was thoroughly mixed with chemical fertilizer and one or two of the amendments, depending on treatment. There were two levels of P, N, and K (0 and 100 mg kg<sup>-1</sup> P as KH<sub>2</sub>PO<sub>4</sub> and 0 and 200 mg kg<sup>-1</sup> N and K as KNO<sub>3</sub>/NH<sub>4</sub>NO<sub>3</sub>) and three replicates for each treatment. Fertilizer levels were equivalent to 112.5 kg ha<sup>-1</sup> for P and 225 kg ha<sup>-1</sup> for N and K, which were close to the field application rate for major crops in south Florida. There were seven amendment treatments: (1)

CaCl<sub>2</sub>, (2) CaCO<sub>3</sub>, (3) CaCl<sub>2</sub> + CaCO<sub>3</sub>, (4) cellulose, (5) Al(OH)<sub>3</sub>, (6) mill mud, and (7) mill mud plus Al(OH)<sub>3</sub>. Soil samples receiving neither amendment nor inorganic fertilizer were used as the control. The application rate of soil amendment was 15 g kg<sup>-1</sup> for a single amendment and 7.5 g kg<sup>-1</sup> each if two amendments were applied together. Deionized water was added to maintain soil moisture at 70% field-holding capacity. The mixtures were then incubated at 25 °C for 10 d, prior to being placed in a column leaching study, to ensure adequate equilibrium of chemical reactions between soil and the amendment.

Column leaching study was conducted using 6.6-cm inner diameter and 30.5-cm-long plastic columns (soil depth for 1 kg soil was approximately 20 cm) with leaching solution delivered by a peristaltic pump (Pump- Pro MPL, Watson-Marlow, Inc., Wilmington MA, UK). After incubation, the soil was packed into each column and two disks of filter paper (Whatman # 42) were placed on the top of each soil column to prevent disturbance by water droplets during leaching. The soil columns were slowly saturated by placing the bottom of each column in a shallow pan containing deionized water and maintained at room temperature for 3 d to allow the soil to compact naturally and allow equilibrium of chemical and biological reactions to occur prior to leaching. Leaching (250 ml of deionized water, equivalent to 90 mm of rainfall or two pore volume of the soil column) was conducted every four days for 32 d. A total of 2000 ml of water was leached, which was equivalent to a half year's rainfall (720 mm) in the Indian River area. Leachate samples were filtered through a Whatman # 42 filter paper, and pH and EC of the leachates were measured within 8 h after sample collection using the pH/ion/conductivity meter. Filtration of leachates with 0.45-μm membrane was performed on the same day. The concentrations of dissolved macro- and micro-elements in leachate were determined using the ICPAES following EPA method 200.7. Concentrations of NH<sub>4</sub><sup>+</sup>-N and NO<sub>3</sub><sup>-</sup>-N in the leachate samples were measured using the Discrete Autoanalyzer following EPA method 350.1 and 353.2, respectively.

### Statistical Analyses

Separation of means for leachate concentrations of Mg, K, Cu, Fe and Zn among different treatments was conducted by the Duncan multiple range test procedure of the Statistical Analysis System release 8.2 (SAS Institute,

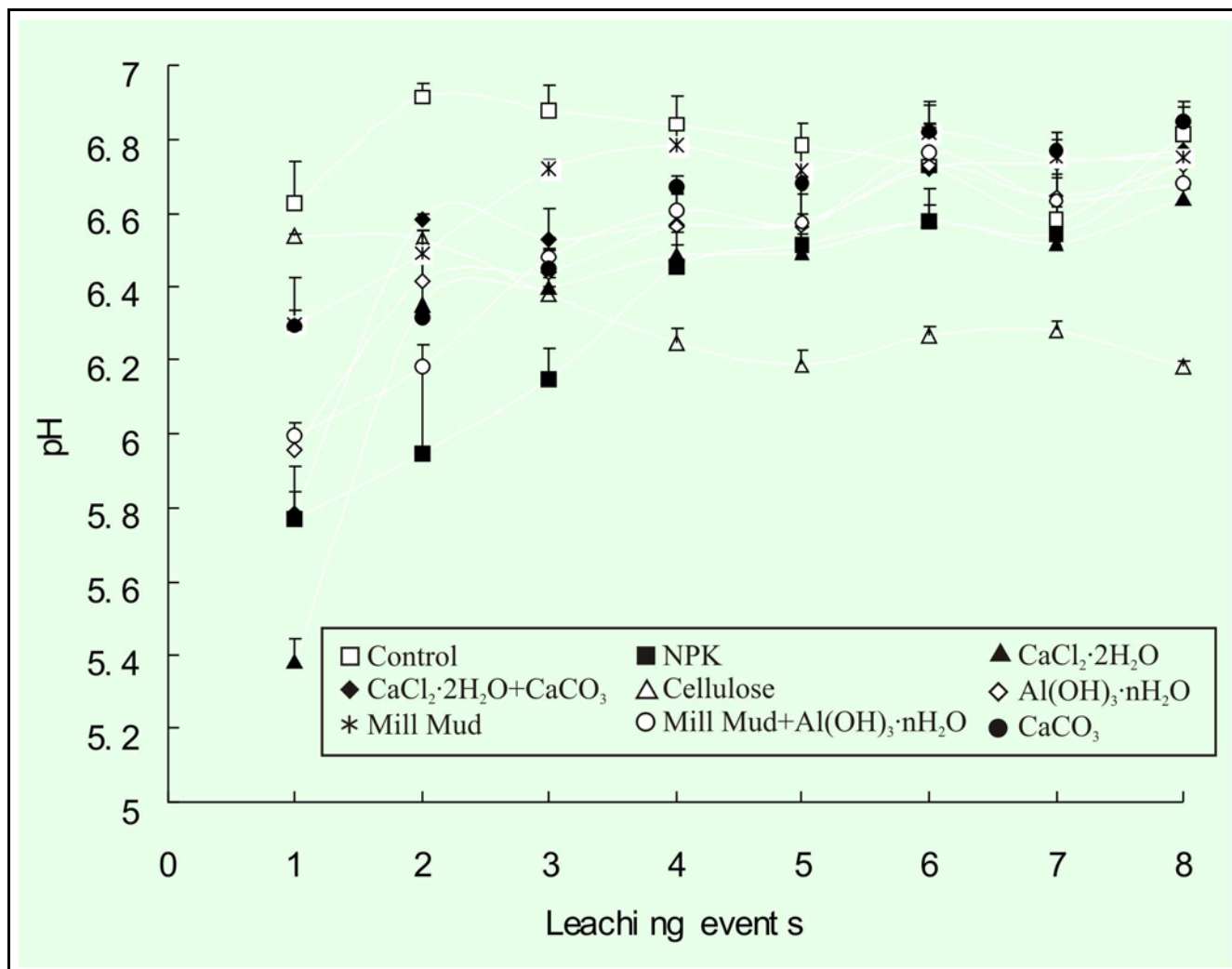


Figure 1. Effect of different soil amendments on leachate pH of the eight successive leaching events. Error bars indicate standard deviation.

2001). Each variable of pH, electrical conductivity, leachate concentrations of NO<sub>3</sub>-N and NH<sub>4</sub>-N was expressed as means plus standard error.

## RESULTS AND DISCUSSION

### Effects on Leachate pH and EC

Fertilization affects the mobility of ions by changing the ionic strength of soil solution and input of cations to replace sorbed metals on exchange sites and by changing soil pH. In this study, addition of fertilizer alone decreased leachate pH. Compared with application of fertilizer alone, application of soil amendment together with fertilizer generally increased leachate pH except that a decrease in leachate pH (0.39 units) of the first leaching event occurred in the columns amended with CaCl<sub>2</sub> or cellulose (Fig. 1). Application of CaCO<sub>3</sub> and mill mud increased leachate pH by 0.53 units. Leachate pH values from the first two leaching events were generally lower and then increased gradually with leachings except that leachate pH

values did not change significantly for the cellulose-amended column. The effect of soil amendments on leachate pH diminished with further leaching events and leveled off at 6.2 to 6.9 in later leaching events, probably due to depletion of H<sup>+</sup> and/or Al<sup>3+</sup>.

The variation of leachate EC with different amendments was similar to pH (Fig. 2). The EC values in leachates of the control soil were lower than those receiving chemical fertilizer alone. The increase in leachate EC was most with CaCl<sub>2</sub> among the seven treatments, which was 9.2 times greater than that of the control. For all the leachate water samples, leachate EC of the amended soils was high in the first leaching event, but rapidly declined from the second and third leaching events. By the fourth leaching event, EC values were similar among the different treatments and similar to the control level. Leachate EC of the third leaching was only 4.6% to 15.6% of the first leaching, indicating that soluble salts are readily leached out from the sandy soils. There were no differences in leachate EC among the samples from the

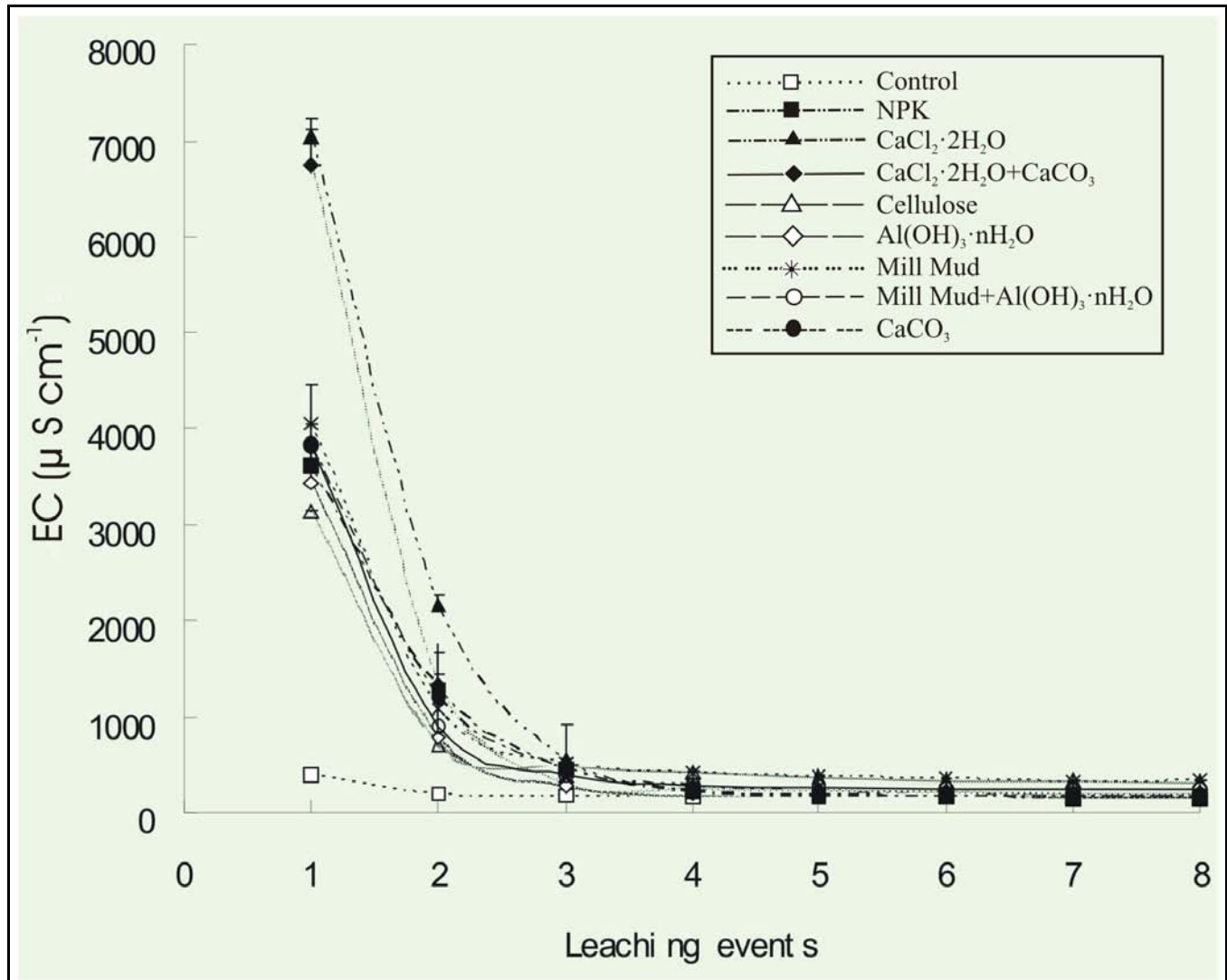


Figure 2. Effect of different soil amendments on leachate electrical conductivity (EC) of the eight successive leaching events. Error bars indicate standard deviation.

third to eighth leaching event. The elevated EC value from the addition of chemical fertilizer alone or application of soil amendment together with chemical fertilizer was caused by the input of soluble salts from the fertilizer or amendments.

#### Effects on Nitrogen Leaching

The total amount of leached  $\text{NO}_3^-$ -N from the control soil was  $7.86 \text{ mg kg}^{-1}$ . Application of chemical fertilizer alone markedly increased the leaching of  $\text{NO}_3^-$ -N by 20.9 times. The variation curves of  $\text{NO}_3^-$ -N in leachate as a function of leaching events were similar for different amendment treatments (Fig. 3). The concentration of leachate  $\text{NO}_3^-$ -N decreased markedly in the first three leaching events and dropped to a minimal level afterwards, which implied that most of the leachable  $\text{NO}_3^-$ -N was released from the soil during the first 12 days. Nitrate concentration in the first two leaching events greatly exceeded the drinking water standard ( $10 \text{ mg L}^{-1}$ )

(USEPA, 1994) indicating that leachate  $\text{NO}_3^-$ -N in a fertilized soil can be a potential source of non-point pollution. The high rate of leaching is undoubtedly due to the input of N fertilizer and the sandy nature of the tested soil. In the third leaching event, the concentration of  $\text{NO}_3^-$ -N in leachate decreased to lower than  $10 \text{ mg L}^{-1}$  except for those applied with chemical fertilizer alone or chemical fertilizer plus  $\text{CaCO}_3$  amendment. After the initial rapid declines, the concentration of  $\text{NO}_3^-$ -N in leachate was similar for all the treatments by the fourth leaching event, which was 0.06% ( $\text{CaCl}_2$  treatment) to 0.82% (chemical fertilizer alone) of the first leaching. The leachate  $\text{NO}_3^-$ -N concentrations decreased to below the surface water limit ( $1.5 \text{ mg L}^{-1}$ ) after the fifth leaching event. This indicates that the release of  $\text{NO}_3^-$ -N is a fast process. With different soil amendments, the concentration of  $\text{NO}_3^-$ -N released in the second leaching event ranged from  $5.9$  to  $75.4 \text{ mg L}^{-1}$ . The corresponding values for the third, fourth, and 8th (last) leaching events were  $0.8$  to  $9.4 \text{ mg L}^{-1}$ ,  $0.1$  to  $2.3 \text{ mg L}^{-1}$ , and  $0.0$  to  $1.2 \text{ mg L}^{-1}$ , respectively, except for the

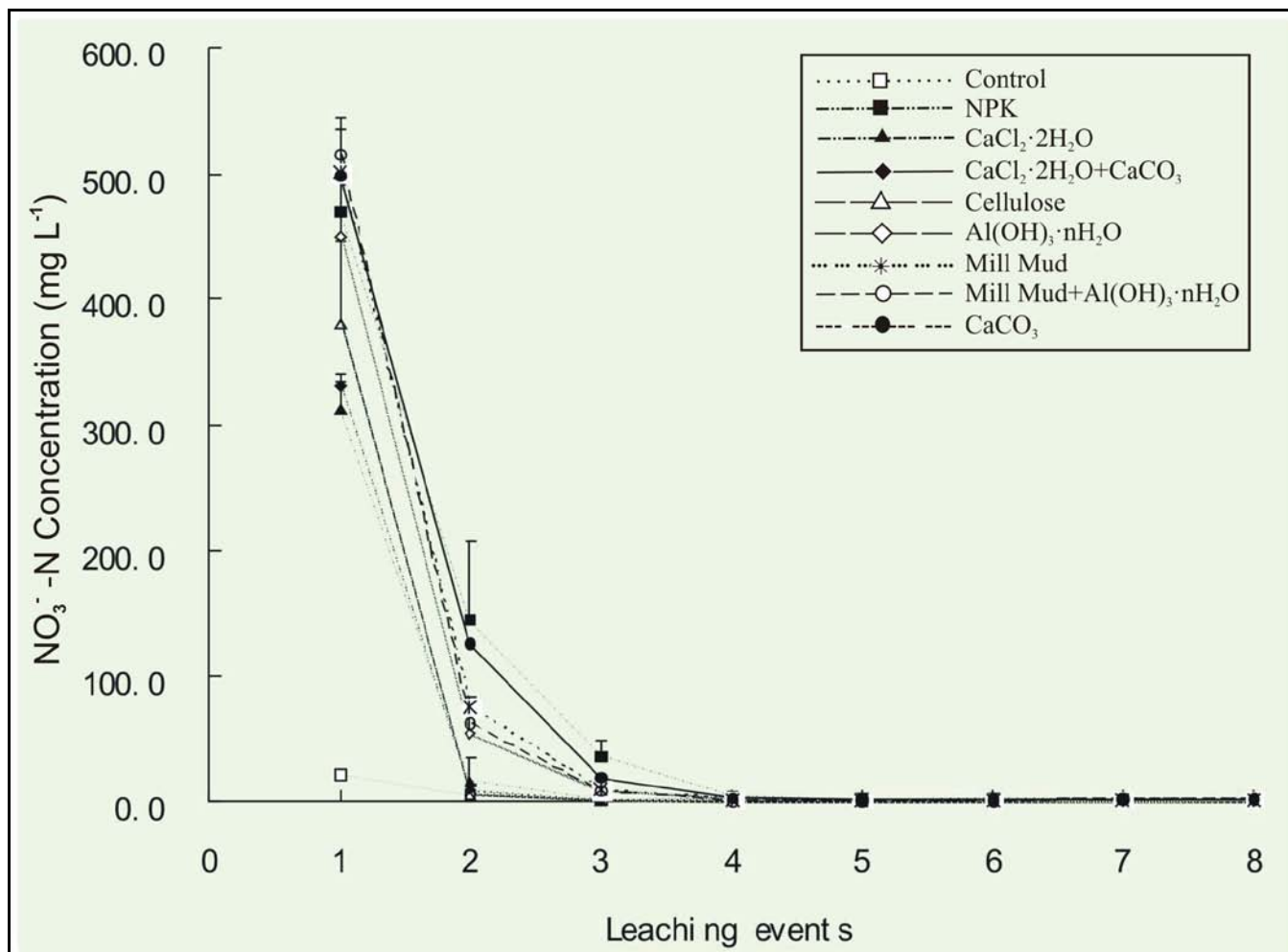


Figure 3. Effect of different soil amendments on NO<sub>3</sub><sup>-</sup>-N concentrations in leachate from the eight successive leaching events. Error bars indicate standard deviation.

columns with CaCO<sub>3</sub> amendment which showed no considerable effect of time on NO<sub>3</sub><sup>-</sup>-N leaching. Leachate NO<sub>3</sub><sup>-</sup>-N concentration of the control columns remained relatively low for the entire leaching period except for the first leaching event. In the first leachate, NO<sub>3</sub><sup>-</sup>-N concentration was 20.9 mg L<sup>-1</sup>, which exceeded the drinking water standard. These results indicate that fertilization practices in the Indian River Area may cause potential N contamination to ground water. Leaching loss of NO<sub>3</sub><sup>-</sup>-N was reduced by 50%, 47%, 41%, and 21%, respectively, by CaCl<sub>2</sub>, CaCl<sub>2</sub> + CaCO<sub>3</sub>, cellulose, or Al(OH)<sub>3</sub> amendment, all which were significantly less than with chemical fertilizer alone. The mechanisms of reduced NO<sub>3</sub><sup>-</sup>-N leaching by above amendments are not fully understood. The inputs of CaCl<sub>2</sub> or Al(OH)<sub>3</sub> reduce the negative charges on soil surface by Ca<sup>2+</sup>, Al<sup>3+</sup> sorption, thus decreasing NO<sub>3</sub><sup>-</sup>-N leaching, whereas the addition of cellulose enhanced microbial incorporation of NO<sub>3</sub><sup>-</sup>-N into organic fractions (He et al., 2002). Mill mud and mill mud + Al(OH)<sub>3</sub> did not have significant effects on NO<sub>3</sub><sup>-</sup>-N leaching loss, and the high NO<sub>3</sub><sup>-</sup>-N background in the mill mud could be a factor. The cumulative losses of NO<sub>3</sub><sup>-</sup>-N decreased among the different amendments in the order of

chemical fertilizer alone = CaCO<sub>3</sub> = Mill mud = Mill mud + Al(OH)<sub>3</sub> > Al(OH)<sub>3</sub> > cellulose > CaCl<sub>2</sub> + CaCO<sub>3</sub> > CaCl<sub>2</sub>. With soil amendments, the cumulative losses of NO<sub>3</sub><sup>-</sup>-N ranged from 83 to 164 mg kg<sup>-1</sup> which was 41-82% of total applied N. This result agrees with the previous report that NO<sub>3</sub><sup>-</sup> is not adsorbed by soil components and therefore, readily moves downward or laterally (Nikolla, 2000). The high concentration of NO<sub>3</sub><sup>-</sup>-N in surface water often causes suffocation disease (Panichsakpatana, 1997) or eutrophication if other factors (such as phosphorus and potassium) are adequate (Sukreeyapongse et al., 2001).

The mean NH<sub>4</sub><sup>+</sup>-N concentration in leachate varied among the leaching events. The cumulative loss of NH<sub>4</sub><sup>+</sup>-N from the control soil was 2.34 mg kg<sup>-1</sup>. Application of chemical fertilizer alone increased the amount of NH<sub>4</sub><sup>+</sup>-N in leachate by 25.5 times (Fig. 4). With soil amendments, the cumulative losses of NH<sub>4</sub><sup>+</sup>-N in leachate ranged from 25.5 to 69.5 mg kg<sup>-1</sup>, which was much lower than those of NO<sub>3</sub><sup>-</sup>-N leaching. Leaching N in the form of NH<sub>4</sub><sup>+</sup>-N was 13-33% of total applied N. After the first leaching event, the NH<sub>4</sub><sup>+</sup>-N concentration decreased markedly until the third leaching event and thereafter the NH<sub>4</sub><sup>+</sup>-N concentration was close to zero for all the treatments. The

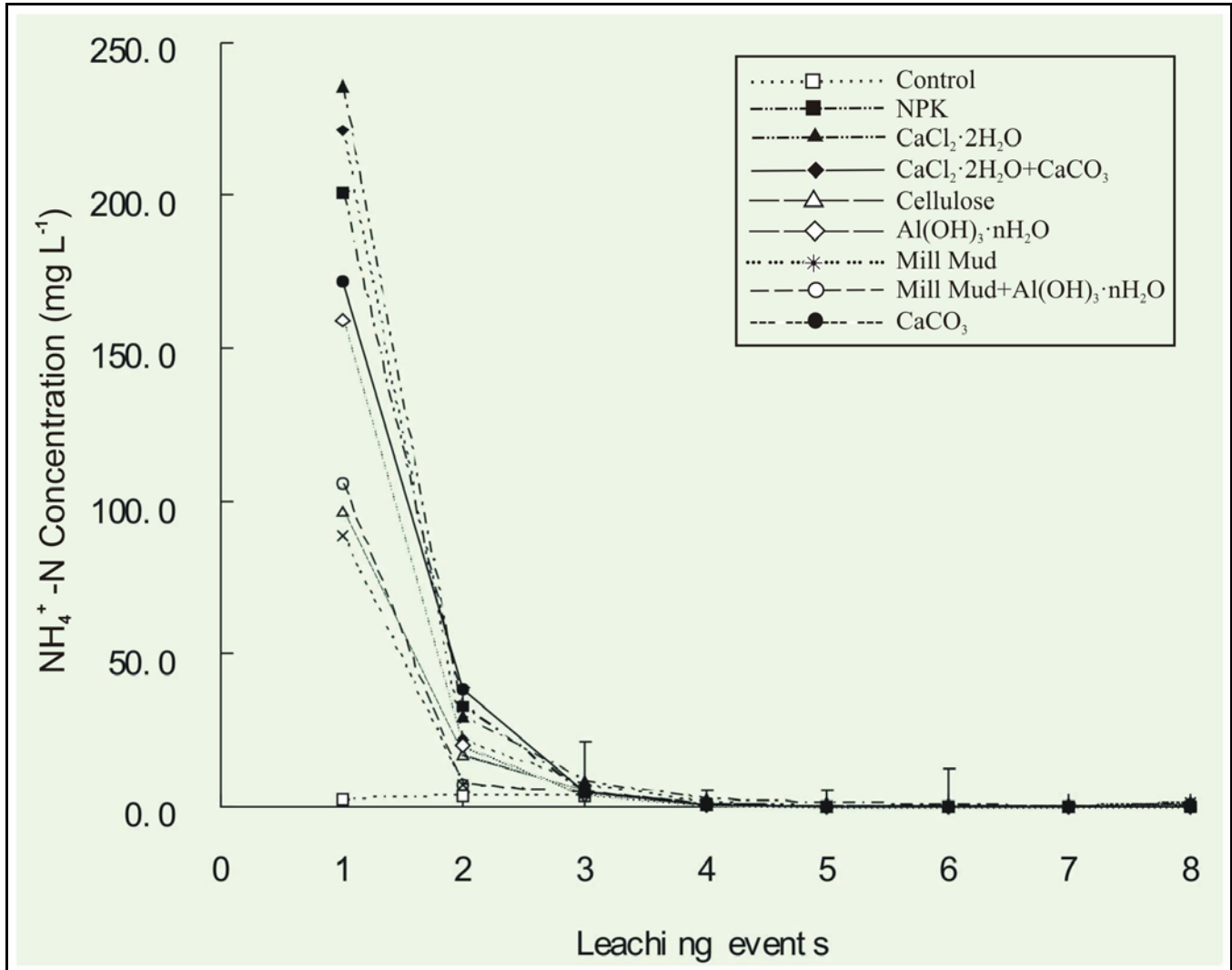


Figure 4. Effect of different soil amendments on  $\text{NH}_4^+$ -N concentrations in leachate from the eight successive leaching events. Error bars indicate standard deviation.

highest  $\text{NH}_4^+$ -N concentration in leachate generally occurred in the first leaching event, which accounted for 80% to 89% of the total leached  $\text{NH}_4^+$ -N. In the second leaching event,  $\text{NH}_4^+$ -N concentration of all the leachate samples was below  $29.4 \text{ mg L}^{-1}$  except for soils amended with  $\text{CaCO}_3$  ( $38.3 \text{ mg L}^{-1}$ ) or chemical fertilizer alone ( $32.9 \text{ mg L}^{-1}$ ). It has been reported that high concentration of  $\text{NH}_4^+$ -N ( $\geq 29.4 \text{ mg L}^{-1}$ ) can cause fish kills (Ghosh and Bhat, 1998). Cellulose, mill mud, and mill mud +  $\text{Al}(\text{OH})_3$  decreased  $\text{NH}_4^+$ -N leaching from the soil, but  $\text{CaCl}_2$ ,  $\text{CaCO}_3$ , and  $\text{CaCl}_2 + \text{CaCO}_3$  had no significant effect on  $\text{NH}_4^+$ -N leaching. Application of cellulose increases the microbial biomass, which probably was responsible for immobilization of inorganic N (He et al., 2002), thus decreasing leaching loss of  $\text{NH}_4^+$ -N. With the different amendments, N loss by leaching in the form of  $\text{NO}_3^-$ -N was 1.2-5.8 times more than that of  $\text{NH}_4^+$ -N. Nitrate with its negative charge can easily move through the root zone and transport to deep soil or groundwater. Ammonium, in contrast, has a positive charge and can be retained by

negatively charged surfaces of the soil. This may explain why the average N leaching in the form of  $\text{NO}_3^-$ -N was greater than  $\text{NH}_4^+$ -N (Sukreeyapongse et al. 2001). This finding is in agreement with previous studies, which indicated that N in leachate was mostly in the form of nitrate (Cabrera, 1997; Sukreeyapongse, 2001). Total inorganic N ( $\text{NO}_3^-$ -N +  $\text{NH}_4^+$ -N) losses by leaching were 57-96% of the total N applied in chemical fertilizer. Reduction in total inorganic N leaching was most significant when the soil was amended with cellulose,  $\text{CaCl}_2$ , or  $\text{CaCl}_2 + \text{CaCO}_3$ , which reduced N leaching by 43, 32, and 33% respectively. The effects of mill mud,  $\text{Al}(\text{OH})_3$ , and mill mud +  $\text{Al}(\text{OH})_3$  on N leaching were moderate (23, 22, and 21%, respectively), whereas  $\text{CaCO}_3$  had no effect.

#### Effects on Other Nutrients Leaching

Trace metals were analyzed because they can be transported to water by leaching or surface runoff if they are accumulated in soils due to repeated application. The concentrations of macro-elements and micro-elements in

the leachate decreased with leaching events, and most leaching loss occurred in the first two leaching events (Tables 3-4). The effects of soil amendments on the leaching of K, Mg, and heavy metals including Cu, Zn, and Fe were different. Application of  $\text{CaCl}_2$  and  $\text{CaCl}_2+\text{CaCO}_3$  significantly decreased K, Mg, Cu, and Fe concentrations, but increased Zn concentration in leachate, though the extent of decrease varied with individual elements.

The leaching of Mg decreased in the soils amended with  $\text{CaCl}_2$  and  $\text{CaCl}_2+\text{CaCO}_3$ , as compared to the control. Magnesium concentration was high at the beginning of leaching, but decreased quickly and was minimal at the end of leaching. In the first leaching event, Mg concentration in leachate from the  $\text{CaCl}_2$  and  $\text{CaCl}_2 + \text{CaCO}_3$  amended soils were 55.6 and 65.1  $\text{mg L}^{-1}$ , respectively, but it decreased to 4.7 and 2.8  $\text{mg L}^{-1}$ , respectively, in the second leaching event. Thereafter, Mg concentration remained below 1.0  $\text{mg L}^{-1}$ . Cumulative Mg loss by the eight leaching events in columns amended with  $\text{CaCl}_2$  and  $\text{CaCl}_2 + \text{CaCO}_3$  were 71% and 81%, respectively, of the columns amended with chemical fertilizer alone. There were no significant differences in Mg loss between columns with chemical fertilizer alone and chemical fertilizer combined with  $\text{CaCO}_3$  or  $\text{Al}(\text{OH})_3$ . Cellulose, mill mud, and mill mud +  $\text{Al}(\text{OH})_3$  increased total leachate Mg by 24%, 120%, and 60%, probably due to mill mud containing considerable amount of Mg. Leaching pattern of K was similar to that of Mg.

The concentrations of leached K were very high in the first leaching event for all the treatments, but decreased sharply in the second event, especially in the  $\text{CaCl}_2$  and  $\text{CaCl}_2 + \text{CaCO}_3$  treatments, which were only 11% and 9% of the first leaching event. Leachate-K concentrations declined with time, but were higher than the unamended soil at the end of the experiment except for the  $\text{CaCl}_2$  and  $\text{CaCl}_2 + \text{CaCO}_3$  treatments, which were similar to the unamended soil. Reduction in leachate-K concentration was most significant when the soil was amended with  $\text{CaCl}_2$ , or  $\text{CaCl}_2 + \text{CaCO}_3$ . Total amount of K loss from the tested soils during the entire experiment period was 174, 133, and 128  $\text{mg kg}^{-1}$ , respectively, for chemical fertilizer alone,  $\text{CaCl}_2$  or  $\text{CaCl}_2 + \text{CaCO}_3$  amendments. The effects of cellulose and  $\text{Al}(\text{OH})_3$  on reduced K leaching were moderate, and the amount of K loss were 155.9 and 152.2  $\text{mg kg}^{-1}$ , respectively. Total amount of K loss from mill mud and mill mud +  $\text{Al}(\text{OH})_3$  treatment were much higher compared to the chemical fertilizer alone and the unamended soil (6.1  $\text{mg kg}^{-1}$ ), likely due to the input of K from the amendment. Theoretically, Mg and K leaching can be increased by amendment of  $\text{CaCl}_2$  or  $\text{CaCl}_2 + \text{CaCO}_3$ , due to the replacement of  $\text{Ca}^{2+}$ . In this case, the large amount of Ca from these two Ca-containing amendments would precipitate water-soluble P, and therefore, during the formation of less water-soluble

The effect of fertilization on the transport of trace metals varied among the different individual elements. Copper is one of the least mobile trace elements in soils. However, transport of Cu through surface runoff has been reported as a major pathway of Cu from land to surface water and has caused increasing concern in South Florida (Zhang et al., 2003). In this study, among all the 72 leaching water samples, 5.6% of the samples exceeded the highest value (280  $\mu\text{g L}^{-1}$ ) of Cu observed in a published assessment of natural surface waters of the USA (Manahan, 1991), while 56.9% of the samples had dissolved Cu < 100  $\mu\text{g L}^{-1}$ , a limit value for Cu in surface water (USEPA, 1994). Mean dissolved Cu concentration of leaching water samples during the whole leaching process were 83  $\mu\text{g L}^{-1}$  (control), 120  $\mu\text{g L}^{-1}$  (chemical fertilizer alone), 70  $\mu\text{g L}^{-1}$  ( $\text{CaCl}_2+\text{CaCO}_3$ ), 82  $\mu\text{g L}^{-1}$  ( $\text{CaCl}_2$ ), 91  $\mu\text{g L}^{-1}$  ( $\text{CaCO}_3$ ), 138  $\mu\text{g L}^{-1}$  (mill mud), 143  $\mu\text{g L}^{-1}$  ( $\text{Al}(\text{OH})_3$ ), 147  $\mu\text{g L}^{-1}$  (mill mud +  $\text{Al}(\text{OH})_3$ ), and 150  $\mu\text{g L}^{-1}$  (cellulose). All these values were higher than the average (15  $\mu\text{g Cu L}^{-1}$ ) for natural surface waters in the USA (Manahan, 1991). Among the seven treatments,  $\text{CaCl}_2+\text{CaCO}_3$  had the greatest effect on reduced Cu leaching from soil, which reduced 42% of Cu loss, as compared with chemical fertilizer alone. Calcium chloride or  $\text{CaCO}_3$  alone reduced Cu leaching by 32% and 24%, respectively. The effects of these amendments on reduced  $\text{Cu}^{2+}$  leaching are likely related to flocculation of dissolved organic matter at elevated salt concentration as evidenced by the increased EC value and raised pH by  $\text{CaCO}_3$ . The transport of Cu from soil to water is realized mainly through chelation with dissolved organic matter (He et al., 2006).

The mean concentrations of Zn in leaching water for all samples except that from columns amended with  $\text{CaCl}_2$  and  $\text{CaCl}_2+\text{CaCO}_3$  were below 45  $\mu\text{g L}^{-1}$ . This mean value is below the average (64  $\mu\text{g L}^{-1}$ ) of natural surface waters in the USA (Manahan, 1991). All samples had Zn < 5000  $\mu\text{g L}^{-1}$ , the maximum permissible value for Zn in U.S. drinking water (United States Public Health Service, 1962). Addition of  $\text{CaCl}_2$  and  $\text{CaCl}_2+\text{CaCO}_3$  significantly increased Zn concentration in the first leaching event, which were 32 and 8 times, respectively, greater than that of the chemical fertilizer treatment. After the first leaching event, Zn concentration in those treatments decreased from the second to third event and was similar to the level of all the other treatments. The increased leaching of Zn might be attributable to the replacement of retained Zn by the fertilizer cations such as  $\text{Ca}^{2+}$ ,  $\text{K}^+$ , and  $\text{NH}_4^+$ .

The effect of different amendments on Fe was very similar to that of Cu. The  $\text{CaCl}_2+\text{CaCO}_3$  treatment had the greatest effect on reducing Fe leaching from soil, which reduced Fe loss by 76% as compared with chemical fertilizer alone. Amendment of  $\text{CaCl}_2$  or  $\text{CaCO}_3$  reduced Fe leaching by 71% and 46%, respectively. It was reported that in the Riviera fine sand, Fe is in the amorphous oxides forms (Zhang et al., 1997) and the dissolution of the

**Table 3. Concentrations of total dissolved Mg and K in leachate from the eight successive leaching events (L1 to L8).**

Treatments	Concentrations, mg L <sup>-1</sup>								
	L1	L2	L3	L4	L5	L6	L7	L8	
Mg	Control	11.0e <sup>†</sup>	6.33c	6.07cd	5.74d	5.00cde	5.58c	5.34c	5.31c
	N P K	36.5d	19.6ab	7.95bc	4.89de	4.32def	5.11c	5.30c	5.16c
	N P K +CaCl <sub>2</sub>	55.6c	4.74c	0.74e	0.48f	0.35f	0.32e	0.31e	0.28e
	N P K +CaCO <sub>3</sub>	43.0d	19.9ab	6.24cd	3.86e	3.09ef	3.12d	3.45d	3.24d
	N P K +CaCl <sub>2</sub> + CaCO <sub>3</sub>	65.1b	2.78c	0.83e	0.86f	0.68ef	0.63e	0.57e	0.47e
	N P K +Cellulose	38.9d	11.4bc	13.0a	11.8b	9.67b	9.02b	8.25b	8.01b
	N P K +Al(OH) <sub>3</sub>	38.2d	11.4bc	4.64d	4.51de	7.72bed	5.15c	5.42c	5.18c
	N P K +Mill Mud	89.4a	25.2a	14.6a	13.6a	17.1a	12.6a	12.0a	11.3a
	N P K +Mill Mud + Al(OH) <sub>3</sub>	70.7b	20.1ab	10.3b	8.92c	8.95bc	7.87b	7.72b	7.25b
	K	Control	7.37c	4.76e	3.66e	2.47c	2.00c	1.70c	1.43c
N P K		413b	164abc	61.0abc	26.1b	14.0b	9.17b	6.05b	4.50b
N P K +CaCl <sub>2</sub>		462b	50.7de	10.6e	4.14c	2.57c	1.54c	1.16c	1.02c
N P K +CaCO <sub>3</sub>		435b	213a	64.6ab	25.7b	14.0b	7.31b	5.85b	4.51b
N P K +CaCl <sub>2</sub> + CaCO <sub>3</sub>		447b	40.3de	10.6e	4.15c	2.59c	1.77c	1.71c	1.52c
N P K +Cellulose		399b	121bc	47.0cd	22.4b	13.5b	8.69b	6.81b	5.28b
N P K +Al(OH) <sub>3</sub>		413b	98.6cd	39.9d	21.9b	14.2b	9.58b	6.58b	5.12b
N P K +Mill Mud		615a	174ab	69.5a	35.3a	21.0a	13.8a	9.28a	7.40a
N P K +Mill Mud + Al(OH) <sub>3</sub>		541a	130bc	48.8bcd	24.1b	14.3b	9.31b	6.57b	4.96b

<sup>†</sup> Values within a column with the same letter(s) are not significantly different at  $P < 0.05$  based on Duncan's Multiple Range Test.

**Table 4. Concentrations of total dissolved Cu, Fe, and Zn in leachate from the eight successive leaching events (L1 to L8).**

Treatments	Concentrations (mg L <sup>-1</sup> )								
	L1	L2	L3	L4	L5	L6	L7	L8	
Cu	Control	0.15cd <sup>†</sup>	0.11b	0.07c	0.07b	0.06cd	0.07bc	0.06bc	0.08abc
	N P K	0.27b	0.19a	0.11abc	0.11ab	0.08bcd	0.08bc	0.07abc	0.07abc
	N P K +CaCl <sub>2</sub>	0.18c	0.10b	0.07c	0.08b	0.07bcd	0.05c	0.04c	0.06bc
	N P K +CaCO <sub>3</sub>	0.17cd	0.14ab	0.09bc	0.09b	0.06bcd	0.05c	0.06bc	0.06bc
	N P K +CaCl <sub>2</sub> + CaCO <sub>3</sub>	0.11d	0.10b	0.08c	0.08b	0.06d	0.04c	0.05c	0.05c
	N P K +Cellulose	0.34a	0.20a	0.16a	0.16a	0.08bcd	0.09bc	0.10a	0.07abc
	N P K +Al(OH) <sub>3</sub>	0.29ab	0.21a	0.13abc	0.09ab	0.11a	0.11ab	0.09ab	0.10a
	N P K +Mill Mud	0.34a	0.18a	0.11abc	0.09ab	0.09b	0.11ab	0.09ab	0.09ab
	N P K +Mill Mud + Al(OH) <sub>3</sub>	0.31ab	0.18a	0.15ab	0.10ab	0.09bc	0.16a	0.09ab	0.10a
	Fe	Control	0.03a	0.04b	0.04bc	0.05b	0.04b	0.02b	0.03b
N P K		0.02a	0.03b	0.02bc	0.03b	0.05b	0.07b	0.03b	0.04b
N P K +CaCl <sub>2</sub>		0.00b	0.00b	0.00c	0.01b	0.02b	0.02b	0.01b	0.02b
N P K +CaCO <sub>3</sub>		0.01b	0.01b	0.03bc	0.03a	0.03b	0.02b	0.01b	0.01b
N P K +CaCl <sub>2</sub> + CaCO <sub>3</sub>		0.00b	0.01b	0.01c	0.02b	0.02b	0.01b	0.01b	0.00b
N P K +Cellulose		0.03a	0.48a	0.16a	0.67a	0.92a	0.69a	0.51a	0.69a
N P K +Al(OH) <sub>3</sub>		0.03a	0.18b	0.11ab	0.05b	0.07b	0.04b	0.03b	0.03b
N P K +Mill Mud		0.04a	0.04b	0.04bc	0.02b	0.03b	0.03b	0.06b	0.07b
N P K +Mill Mud + Al(OH) <sub>3</sub>		0.03a	0.08b	0.03bc	0.03b	0.03b	0.10b	0.04b	0.06b
Zn		Control	0.03c	0.01b	0.01c	0.00a	0.01b	0.02ab	0.03b
	N P K	0.09c	0.06ab	0.04a	0.01a	0.01b	0.01b	0.03b	0.02bc
	N P K +CaCl <sub>2</sub>	2.75a	0.11a	0.03ab	0.01a	0.01b	0.02ab	0.02b	0.02bc
	N P K +CaCO <sub>3</sub>	0.07c	0.04b	0.02abc	0.00a	0.00b	0.01b	0.03b	0.03bc
	N P K +CaCl <sub>2</sub> + CaCO <sub>3</sub>	0.69b	0.03b	0.02bc	0.01a	0.01b	0.01b	0.02b	0.01c
	N P K +Cellulose	0.08c	0.02b	0.02abc	0.02a	0.02ab	0.04a	0.05a	0.05a
	N P K +Al(OH) <sub>3</sub>	0.10c	0.07ab	0.03ab	0.01a	0.04a	0.02ab	0.04ab	0.02bc
	N P K +Mill Mud	0.06c	0.02b	0.02bc	0.01a	0.02b	0.02ab	0.03b	0.04ab
	N P K +Mill Mud + Al(OH) <sub>3</sub>	0.06c	0.03b	0.02abc	0.01a	0.02ab	0.04a	0.03b	0.02bc

<sup>†</sup> Values within a column with the same letter(s) are not significantly different at  $P < 0.05$  based on Duncan's Multiple Range Test.

amorphous Fe oxides was lower in the leaching solution containing high salt concentration (He et al., 2000a). In this study, Fe concentration was low in the leachate with high EC value. The mean EC value in the leachate of CaCl<sub>2</sub>, CaCO<sub>3</sub>, CaCl<sub>2</sub> + CaCO<sub>3</sub> amended, and chemical fertilizer treated columns was 1352, 805, 1194, and 772 •S cm<sup>-1</sup>, respectively. Cellulose, Al(OH)<sub>3</sub>, mill mud, and Al(OH)<sub>3</sub> + mill mud significantly increased Fe leaching from soils. But the control columns leached as much Fe as those that were amended with chemical fertilizer alone. All of the samples had dissolved Fe < 1000 µg L<sup>-1</sup>, a limit

value for Fe in surface water (USEPA, 1994). Further work is needed to understand the mechanisms of interactions between the applied macronutrients and the micronutrients present in the soil in relation to the potential leaching of the latter.

## CONCLUSIONS

The Ankona soil in South Florida is sandy with minimal holding capacities for moisture and nutrients. Repeated application of fertilizers for sustaining high yield of vegetable crops has caused potential contamination to



surface and ground water. The benefits and effectiveness of soil amendments in reducing N losses from vegetable cropping systems while sustaining desired vegetable yield need to be demonstrated. Results from this study indicated that  $\text{CaCl}_2$  and  $\text{CaCl}_2 + \text{CaCO}_3$  are most effective in reducing N leaching from sandy soil and decrease the concentrations of K, Mg, Cu, and Fe in leachate. Amendment of  $\text{CaCl}_2$  and  $\text{CaCl}_2 + \text{CaCO}_3$  should be more closely studied for their contribution to nutrient cycling within soil-water ecosystem, especially where soil pH is low, before use of these amendments is put into practice and considered in the development of BMPs for the sandy soil regions.

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