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Soil and water table management effects on aluminum dynamics in an acid sulphate soil in Vietnam

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Abstract

Understanding the process of toxicity accumulation in the root zone is important in improving the quality of acid sulphate soils. The effect of straw mulching, soil surface ploughing and water table depths on aluminum dynamics during the dry season and the first three weeks of the rainy season 1994 were studied in field and lysimeter conditions in an acid sulphate soil, in Mekong Delta, Vietnam. More acidity was produced in the subsoil when the water table was maintained at 60 and 90 cm compared with 30 cm deep. The amount of aluminum that accumulated in the topsoil during the dry season was linearly proportional to the cumulated evaporation. Straw mulching significantly lowered the dry season aluminum accumulation (0.6 cmol(+) kg^{-1}) in comparison with nonmulching treatment (2.0 cmol(+) kg^{-1}). Surface ploughing also reduced aluminum accumulation, but the reduction was not statistically significant compared with nonploughed plots. Rains at the beginning of the rainy season raised the water table rapidly to the topsoil layer. Aluminum brought up with the rising water table greatly increased the toxicity level in the topsoil and nullified the positive effects of dry season soil treatments. Controlling groundwater level to below the topsoil and enhancing the leaching effects at the beginning of the rainy season are important for retaining the effects of the dry season treatments. © 1998 Elsevier Science B.V.

Keywords: Water management; Capillary; Leaching; Macropores; Mulching

1. Introduction

In acid sulphate soils acidity originates from the oxidization of pyrite and results mostly from lowering of the groundwater level (Dent, 1992; Ritsema et al., 1992). Subsequently, evaporation from the soil surface may cause accumulation of toxic salts in surface horizons by upward capillary movement (Sen, 1988a). These salts may be leached in the rainy season, creating environmental hazards to the surroundings.

The rate of capillary rise is controlled by climatic conditions, water table depth, and physical properties of the soil (Bloemen, 1980). In saline soils, capillary rise plays a key role in the transport of salt from the groundwater to the topsoil (Nakayama et al., 1973; Hassan and Ghaibeh, 1977; Hellwig, 1979; Sharma et al., 1985; Lal, 1989; Bastiaanssen et al., 1990; Tuong et al., 1991). Evaporation, accumulation of salts and measures to reduce it in acid sulphate soils have also been studied. Using soil cores, Tuong et al.

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(1991) investigated the effects of water table depth on accumulation of soluble aluminum at the top layer of a bare acid sulphate soil during the dry season in the Mekong delta, Vietnam. Li et al. (1989) reported that in China tillage, groundwater level control, and mulching techniques were applied to acid sulphate soils to reduce evaporation and accumulation of toxicity. Other authors (e.g., Manuelpillai et al., 1986) demonstrated positive effects of mulching on the yields of several crops in acid sulphate soils such as yam (*Dioscorea esculanta*), pineapple (*Ananas comosus*), soybean (*Glicine max*) and peanut (*Arachis hypogaea*). Previous investigators, however, did not quantify the toxicity transport process in acid sulphate soils, nor the effects of different land management and water table depth on the accumulation of toxic substances in acid sulphate soils under field conditions. Duong et al. (1986) postulated that water management measures such as maintaining a shallow water table and minimizing capillary rise could be useful for reducing the accumulation of toxicity in the topsoil during the dry season. This hypothesis, however, has not been tested.

At the beginning of the rainy season, rainfall redistributes the amount of aluminum that has accumulated on the topsoil to the lower layers and may raise the water table to near the soil surface. It is possible that these occurrences modify the effects of soil and water table management during the dry season. Understanding these processes would benefit management strategies for increasing agricultural productivity and reducing the environmental effects of acid sulphate soils.

The objectives of this study were to quantify the process of aluminum transport from the groundwater to the topsoil in acid sulphate soils during the dry season and at the beginning of the rainy season. The relationship between the amount of accumulated aluminum and evaporation as influenced by straw mulching, ploughing the surface soil and water table depths was investigated in field and lysimeter conditions.

2. Methodology

2.1. Experimental site

The study was conducted at Hoa An station (10°10 N, 106°15 E), in the Mekong delta, Vietnam. It has two distinct seasons: a dry season from January to May and a rainy season from June to December accounting for 90% of the 1800-mm annual rainfall. Average evaporation rate varies from 4 mm d^{-1} in the rainy season to 6.5 mm d^{-1} in the dry season.

According to soil taxonomy (Soil Survey Staff, 1992) the soil is classified as a very fine Typic Sulfaquept with a high organic matter content in the top 30 cm. There is a compacted layer, with low saturated hydraulic conductivity at 30–40 cm (Table 1). The sulfuric horizon, with yellow mottles of jarosite, runs from 40 cm to 120 cm. From 120-cm depth, a grey permanently reduced sulfidic horizon is found. The soil was originally uncultivated and covered by *co nang* reed (Chinese water chestnut, *Eleocharis dulcis*). Tables 1 and 2 shows some important chemical and physical characteristics of the soil.

2.2. Field experiment

2.2.1. Field layout

The field experiment started at the beginning of the dry season, February 1994. The water table depth

Table 1
Bulk density and saturated hydraulic conductivity (mean ± standard deviations of three measurements) of the study soil

Horizon	Depth (cm)	Bulk density (Mg m^3)	Hydraulic conductivity ($\times 10^{-6}$ m s^{-1})
Topsoil	0–30	0.65 ± 0.07	0.640 ± 0.23
Compacted layer	30–40	1.04 ± 0.09	0.015 ± 0.02
Sulfuric horizon	40–120	0.81 ± 0.07	0.059 ± 0.03
Sulfidic horizon	> 120	0.88 ± 0.07	0.044 ± 0.02

Table 2
Exchangeable and soluble aluminum and pH (mean ± standard deviation of four measurements) of 10-cm topsoil before the experiment

Parameters	Field		Lysimeter	
	Aluminum (cmol(+) kg^{-1})	pH	Aluminum (cmol(+) kg^{-1})	pH
Exchangeable[a]	16.67 ± 3.81	3.66 ± 0.4	14.70 ± 3.31	3.80 ± 0.3
Soluble[b]	1.94 ± 0.61	3.83 ± 0.4	1.46 ± 0.82	3.92 ± 0.3

[a]Extracted by 1 M KCl (1:2.5).
[b]Saturation extraction (1:1.5).

was 15 cm and water content of the topsoil was high (0.55 m^3 m^{-3}). The treatments were arranged in a split-plot design with four replications. The main plot was the land preparation treatments: with ploughing (P_1) and without ploughing (P_0). Ploughing was carried out at the beginning of the experiment by hoeing to a depth of 10 cm, breaking the soil into clods of approximately 10 cm by 15 cm. Each 12-m × 16-m main plot was divided for the sub treatments: with mulching (M_1) and without mulching (M_0). The M_1 subplots were covered with 15 cm thick mulch made of dry *co nang* straw. All plots were separated by compacted bunds (0.4 m high and 0.5 m wide) constructed with topsoil materials taken from outside the experimental field.

2.2.2. Soil physical properties

Bulk density of different soil layers was determined at the beginning of the experiment with three undisturbed soil cores sampled by 15 cm long and 20 cm diameter PVC tubes. The large size of the cores was necessary to take into account the heterogeneity of the macropore-dominated soils, especially the top layer (Minh et al., 1997). Similar soil cores were used for determining the saturated hydraulic conductivity following the constant head method described by Booltink and Bouma (1991).

Each week, soil tension at depths of 5, 15, 25, 30, and 40 cm was measured using tensiometer cups (2 cm in diameter and 8 cm long) and a digital transducer. The battery of tensiometer cups was installed at the center of each sub-plot. Daily rainfall and evaporation rates were measured by a rain gauge and a class-A evaporation pan.

2.2.3. Soil and groundwater chemical measurements

Sampling of soil and groundwater for chemical analysis was carried out at the start of the experiment (designated week 0), at the end of the dry season (week 8), and in the first part of the rainy season (week 11). One composite soil sample was taken from each subplot, by mixing five 10-cm topsoil samples taken randomly over the subplot. Groundwater was sampled using 27-mm diameter groundwater tubes installed to 1-m depth at the center of each subplot. About 1 h before sampling, the amount of water that had previously accumulated in the tubes was pumped out, using a hand pump. Groundwater was then sucked into pre-vacuumed bottles as described by Tuong et al. (1993). Soil pH (measured in 1:2.5 saturation extract) and pH of groundwater were measured by digital meters. Exchangeable aluminum (extracted by 1 M KCl, 1:2.5), soluble aluminum (in 1:1.5 saturation extract) in soil and aluminum in the groundwater were measured by colorimetry (Begheijn, 1980). The amount of aluminum accumulation in the topsoil layer during the dry season was considered as the difference between soluble aluminum concentrations at week 8 and 0, and during the experiment between week 11 and week 0. Accumulation during the beginning of the rainy season (between week 8 and 11) were derived from the above.

2.3. Lysimeter experiment

The lysimeter experiment was carried out from week 0 to week 10 at the same site as the field experiment. Each lysimeter was a 1 m long × 0.4 m diameter PVC tube. The tubes were inserted into the soil by gradual hammering, after sharpening the tube-end and greasing the tube-walls. The soil outside the core was removed after every 5 cm of insertion. At the 95-cm insertion depth, the tube was lifted up using a hoist and a heavy duty tripod. The lower end of each tube was filled with coarse sand and covered by an asphalt-coated iron cap connected to a Mariotte bottle. The tubes were lowered in a trench so that the soil core surfaces were at the same level as the natural soil surface.

To prevent direct sunlight reaching the exposed side wall of the tube, nipa palm (*Nipa fructicans*) leaves were used to cover the opening between the tubes and the trench surface. At night and during rain events, the tubes were sheltered by a roof made of transparent nylon sheet.

Soil in the tube received similar management treatments (P_0, P_1, M_0 and M_1) as the field experimental plots. In addition, different water table depths (30, 60, and 90 cm from the soil surface) were imposed on the tubes. Altogether, there were 12 lysimeters, i.e., there was no replication. The groundwater levels in the tubes were controlled by the water level in the Mariotte bottles. Each day, the bottles were refilled to the predetermined treatment levels. The daily evaporation loss from the lysimeter (E) was taken as the volume of the refilling water divided by the surface area of the lysimeter. A linear regression function $E = a \cdot E_0$ was used to relate E and daily Class-A pan evaporation E_0, where a is the slope of the regression curve.

Soil samples (0–10 cm depth) were taken from each lysimeter, using a 5-cm diameter soil auger at the start (week 0) and end (week 10) of the experiment for soluble aluminum analysis (in soil saturation extract, 1:1.5). Similar to the field experiment, aluminum accumulation was taken as the difference in soluble aluminum concentrations measured in week 10 and week 0.

2.4. Statistical analysis

IRRISTAT (IRRI, 1992) was used to perform standard analysis of variance, mean comparison and correlation analysis of parameters measured in the field experiment. Least significant differences at 5% and 1% levels of significance were used for pair-wise comparisons of the means.

3. Results and discussion

3.1. Evaporation rate

The evaporation rate from each lysimeter reduced steadily as the soil dried out, and reached steady values from week 3. This steady-state evaporation rate was reduced by soil surface treatments (Fig. 1). The reduction was more pronounced when the water table depth was at 30 cm. At this level, the lowest evaporation rate (2.4 mm d^{-1}) occurred when both mulching and ploughing (i.e., treatment P_1M_1) were applied. The effects of mulching agreed with Sen (1988b) who found that thin peat layers on top of soil columns reduced the evaporation rate by 50% compared with columns without peat layer. In absolute terms, the reduction of evaporation was greater in this study than that found by Sen (1988b), possibly because of the differences in potential evaporation, which were 3.0 mm d^{-1} in the report of Sen and 6.5 mm d^{-1} in this study. Tillage reduced evaporation and capillary rise by forming a ‘self-mulch’ layer (Mwendera, 1992) and creating a discontinuity in the capillary system, reducing water transmission properties (Benoit and Khirkham, 1963; Papendick et al., 1973).

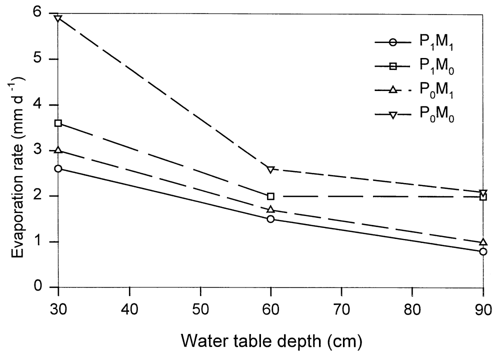

Fig. 1. Steady-state evaporation rate from lysimeters as affected by water table depth and soil management treatments. P_0 = nonploughing, P_1 = ploughing; M_0 = nonmulching, M_1 = mulching.

The steady-state evaporation rates also decreased with increasing groundwater depths (Fig. 1). Evaporation rates decreased more sharply when water table depth increased from 30 cm to 60 cm and only slightly when water table depth increased further to 90 cm. The mean evaporation rates of all treatments were 3.7, 1.9, and 1.4 mm d^{-1} when water table depths were 30, 60, and 90 cm, respectively.

Over the experiment period, there was a significant correlation ($r = 0.89$) between daily lysimeter evaporation (E) and Class-A pan evaporation (E_0)

Table 3
Correlation coefficient (r) and coefficient a of the linear regression $E = a \cdot E_0$ under different treatments in the lysimeters. E = evaporation (mm d^{-1}) from lysimeters; E_0 = Class-A pan evaporation (mm d^{-1})

Coefficients	Treatment[a]			
	P_0M_0	P_0M_1	P_1M_0	P_1M_1
Water table depth = 30 cm				
a	−0.81	−3.34	0.60	−0.69
r[b]	0.89**	0.64 ns	0.39 ns	0.47 ns
Water table depth = 60 cm				
a	0.92	−0.22	0.98	0.37
r	0.48 ns	0.51 ns	0.48 ns	0.42 ns
Water table depth = 90 cm				
a	2.13	1.06	0.83	0.78
r	0.17 ns	0.14 ns	0.2 ns	0.17 ns

[a] M_0 = nonmulching, M_1 = mulching, P_0 = nonploughing and P_1 = ploughing.
[b],** = Significant at 1% level.
ns = not significant.

in treatment P_0M_0 when water table depth was kept at 30 cm. Under other soil surface treatments and water table depths, the correlation became insignificant (Table 3). This implied that evaporative demand strongly dictated the actual evaporation of untreated soil under a shallow groundwater level. Under the deeper groundwater levels, and with soil mulching and/or ploughing, other factors like soil moisture content, the continuity of the pore system might have played more important roles in controlling the actual evaporation rate (Unger and Stewart, 1983).

3.2. Water table depth and groundwater quality in the field

Fig. 2 shows the changes of the water table in the field during the experiment. Water table depth dropped rapidly from 15 cm to about 60 cm during the first week of the experiment. After this rapid decline, the water table slowly declined to 85 cm depth at week 8. Following several consecutive rains after week 8, it rose rapidly and reached the 0–10 cm topsoil. Though there were significant differences in evaporation among different soil management treatments (Fig. 1), differences in groundwater levels among treatments were negligible. This was because

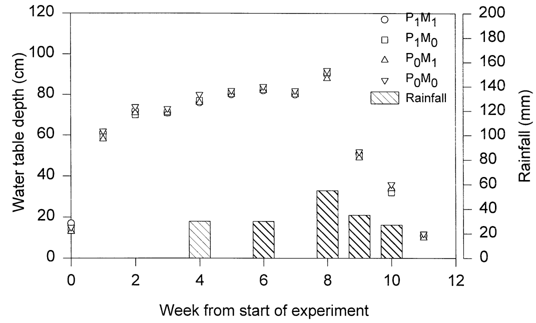

Fig. 2. Rainfall and water table depth during the field experiment. P_0 = nonploughing, P_1 = ploughing; M_0 = nonmulching, M_1 = mulching. For clarity, standard deviations of the mean values (ranged from 5 to 11 cm) were not plotted.

there was no attempt to isolate groundwater in different experimental plots and in part from the relatively high saturated conductivity of the sulfuric and sulfidic horizons (Table 1).

Aluminum concentration in the groundwater in the field experiment remained rather constant during the dry season, but increased at beginning of the rainy season (i.e., week 8 to 11, Fig. 3). This increase might be the result of toxicity leached down from the top layers by rainfall. Additional acidity might have been generated by acidification of the sulfuric horizon when the water table was lowered during the dry season (Duong et al., 1986).

3.3. Soil water tension

Soil water tensions increased in all measuring depths and soil management treatment in the first

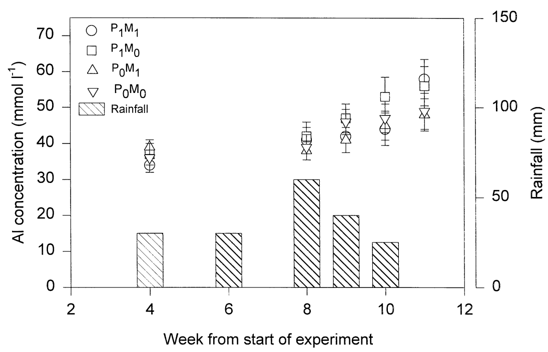

Fig. 3. Groundwater Al^{3+} concentration (mean ± standard deviation) and rainfall during the field experiment. P_0 = nonploughing, P_1 = ploughing; M_0 = nonmulching, M_1 = mulching.

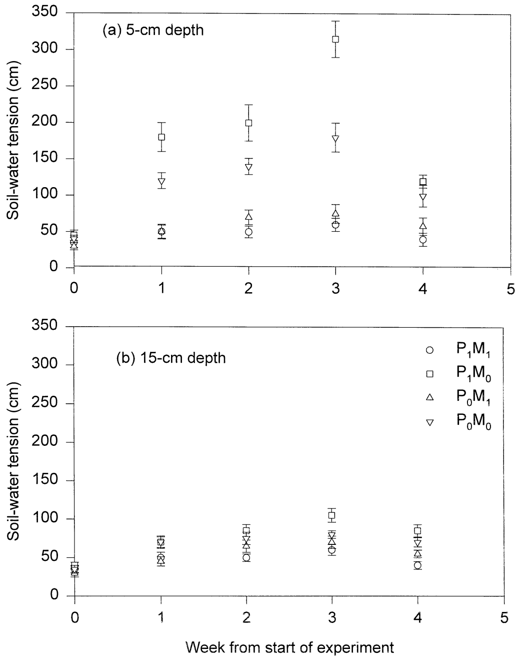

Fig. 4. Soil water tension (mean ± standard deviation) at (a) at 5-cm depth, and (b) at 15-cm depth as affected by soil management treatments in the field. P_0 = nonploughing, P_1 = ploughing; M_0 = nonmulching, M_1 = mulching.

three weeks of the experiment. A 24-mm rain in week 4 slightly reduced soil water tensions in the top two layers (Fig. 4). Thereafter, soil water tension was not monitored because the tensiometers installed at 5-cm depth reached air entry values. At the lower measuring depths (below 25 cm), soil water tensions were low (less than 75 cm of water) and the differences among soil management treatments were small (data not shown). Soil management treatments significantly affected soil water tension of the topsoil layers (Fig. 4). The P_1M_0 treatment had the highest soil water tensions (310 cm in week 3 at 5-cm depth, followed by P_0M_0 (190 cm), P_0M_1 (80 cm) and P_1M_1 (61 cm). Mulching effectively reduced evaporation from the top layer and kept the soil moist. This conformed with the lower evaporation rate of P_0M_1 and P_1M_1 measured in the lysimetric experiment (Fig. 1). Ploughing when not combined with mulching dried out the top layers more rapidly than the control treatment. At the same time, it reduced the evaporation loss from the soil column (Fig. 1), indicating capillary rise could not make up the evaporative loss from the topsoil and confirming the observations of Benoit and Khirkham (1963) and Papendick et al. (1973) that ploughing created a discontinuity in the capillary system reducing water transmission.

3.4. Aluminum accumulation in topsoil in lysimeters

The accumulation of aluminum in the topsoil of the lysimeter was linearly correlated with the cumulative evaporation (E_{cu}, Fig. 5). The slope of the Al–E_{cu} regression line was lower when water table depths were maintained at 30 cm compared with that corresponding to water table depths of 60 cm and 90 cm. This implied that aluminum concentration in the capillary water was higher when the water table was lowered. Probably the 30-cm water table depth prevented further formation of acidity during the dry season, which could occur during the oxidation of the sulfuric horizon when the water table was further lowered (Duong et al., 1986).

3.5. Accumulation of toxicity in topsoil in the field

Table 4 lists data on Al^{3+} accumulation in the 0–10 cm soil layer at weeks 8 and 11 in different soil management treatments of the field experiment. At week 8, this varied from 0.59 to 2.02 cmol(+) kg^{-1}, similar to the range of Al^{3+} accumulation obtained in the lysimeter study (Fig. 5). This indi-

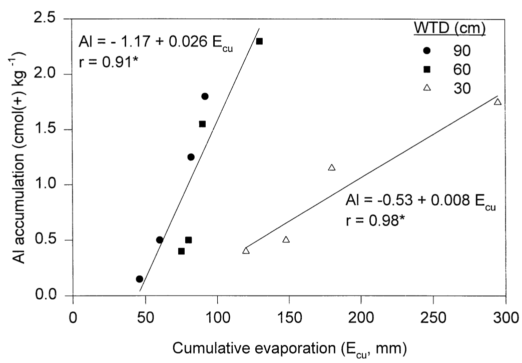

Fig. 5. Relationship between Al^{3+} accumulation in topsoil of lysimeters and cumulative evaporation (E_{cu}) in the dry season as affected by different soil treatments and water table depths (WTD). P_0 = nonploughing, P_1 = ploughing; M_0 = nonmulching, M_1 = mulching.

Table 4
Al^{3+} accumulation (cmol(+) kg^{-1}) in the 0–10 cm topsoil after 8 and 11 weeks of experiment under different soil management treatments in the field condition. M_0 = nonmulching, M_1 = mulching, P_0 = nonploughing, and P_1 = ploughing. Al^{3+} accumulation was the difference between the soluble aluminum concentration at the sampling time and at the start of the experiment

Treatment[a]	P_0	P_1	Difference[b]
Week 8			
M_0	2.02	0.64	1.38 ns
M_1	0.59	0.63	−0.04 ns
Difference	1.43*	0.01 ns	
Week 11			
M_0	3.78	2.02	1.76 ns
M_1	2.53	2.29	0.24 ns
Difference	1.25 ns	−0.17 ns	

[a] M_0 = nonmulching, M_1 = mulching, P_0 = nonploughing and P_1 = ploughing.
[b], * = significant at 5% level.
ns = not significant.

cates that field conditions were satisfactorily simulated in the lysimeters.

From the beginning to week 8 of the field experiment, mulching significantly reduced the accumulation of aluminum in topsoil when the soil was not ploughed. However, the reduction due to mulching was insignificant when the soil was ploughed (Table 4). Ploughing also helped reduce aluminum accumulation but differences between ploughing and nonploughing treatments were not statistically significant. The nonsignificance was probably because of high spatial variability of the surface soil in the ploughed treatment. The field results agree with the findings of Sen (1988b) that a layer of peat on top of soil columns reduced the accumulation of toxic substances in the topsoil of an acid sulphate soil. Li et al. (1989) found reduction of toxicity in the topsoil of an acid sulphate soil by covering the soil surface with sugar cane leaves, presumably as a result of reduced evaporation.

The Al^{3+} accumulation in the topsoil of all treatments at week 11 was greater than that at week 8 (Table 4). In some treatments, the accumulation during weeks 8–11 was even greater than that during weeks 0–8. The differences among treatments were not statistically significant. The findings indicated that aluminum continued to be brought up to the topsoil layer and the positive effect of soil treatments (mulching and ploughing) during the dry season could be eliminated during the first weeks of the rainy season. The additional aluminum was probably brought up to the surface layer by the contaminated groundwater (Fig. 3) which reached within 10 cm from the soil surface (Fig. 2). Hanhart and Ni (1993) also found that raising the water table was the main cause of surface soil acidification at the beginning of the rainy season. Some aluminum might also have been brought to the topsoil by capillary rise which could take place during dry spells between the rains.

4. Conclusions

Evaporation and Al^{3+} concentration in the capillary water dictate the rate of Al^{3+} accumulation in topsoil in acid sulphate soils during the dry season. Mulching and surface tillage help reduce evaporation and therefore are effective means of reducing Al^{3+} accumulation. Maintaining a shallow water table (at 30 cm depth) during the dry season might help prevent further formation of acidity, which was generated by oxidation of the sulfuric horizons when the water table is further lowered. Thus, keeping a shallow water table, combining with mulching or surface ploughing are recommendable measures to prevent dry season Al^{3+} accumulation. The positive effect of the dry season management on Al^{3+} accumulation can, however, be diminished at the beginning of the rainy season when the water table rises and brings aluminum in the groundwater to the soil surface. To utilize the effects of dry season treatments, it is essential to control the water table such that it will not reach the topsoil layers at the beginning of the rainy season.

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