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High soil Mn and Al, as well as low leaf P concentration, may explain for low natural rubber productivity on a tropical acid soil in Vietnam

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ABSTRACT
The aim of the current study was to identify major soil and leaf factors accounting for low natural rubber (NR, *Hevea brasiliensis*) productivity on tropical acid Acrisols in Vietnam. Twenty NR plots were measured with NR productivity, leaf factors (N, P, K, Ca, Mg, Mn, Cu, Fe, and Zn), soil factors (pH, particle size distribution, total C, N, P, K, exchangeable K, Ca, Mg, Al, Mn, Fe, Zn, available P). Cluster analysis showed that NR productivity could be separated into three clusters with low (23.2), medium (38.2), and high (61.3 g tree^{-1} harvest^{-1}) yield. High-yield cluster had higher leaf P concentration and soil pH, while low-yield cluster had higher leaf Mn, soil exchangeable Al, and Mn concentration. Simple and multiple linear regression analysis applied with backward elimination procedure suggested that leaf and soil toxic concentration may be responsible for low NR productivity in the study soil.

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KEYWORDS
acid soil; tropical soil; soil toxicity; nutrient deficiency; natural rubber

1. Introduction

Acid soils (pH lower than 5.5) occupy a large portion of the arable land worldwide. It is estimated that around 30% of world's total land area (excluding the ice occupied regions) and as much as 50% of world's arable soils are acidic (von Uexküll and Mutert 1995). Soils could become acidic for many reasons (Sumner and Noble 2003). Positive correlations between soil pH and growth of spring and winter wheat (Mohebbi and Mahler 1989) and Eucalyptus urophylla seedlings (Aggangan, Dell, and Malajczuk 1996) indicate that soil acidity is an important factor determining crop productivity. The effects of soil acidity may be associated with nutrient deficiencies of some elements such as potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), and zinc (Zn), while the biological toxicity of aluminum (Al) and manganese (Mn). According to Brady and Weil (2002) K, Mg, Ca, and P availability tends to increase, whereas iron (Fe), zinc (Zn), Al, and Mn become less available with a rise in soil pH.

The nutrients, becoming less available when pH decreasing, result in nutrient deficiency to plants. A typical example is soil phosphorous, which is highly adsorbed by Al and Fe oxides in acidic soils, resulting in P deficiency when soil pH descends. Leaf P concentration is a good indicator of soil P status due to a positive relationship between leaf and soil P concentrations (He et al. 2014). Similarly, Mulligan (1989) found that as much as 60% of leaf P concentration in seedlings of Eucalyptus Grandis was reduced by low-P treatment applied to study soil. Nevertheless, plant develops mechanisms to acquire

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more P for growth (Kochian, Hoekenga, and Pineros 2004). Therefore, in many cases, the relationships between soil and leaf nutrient concentration as well as with plant growth and yield may be hardly observed.

In contrast, those inversely related to soil pH may become toxic to plants in acidic soils. For example, high aluminum concentration has been found to influence elongation of rice root (Watanabe and Okada 2005), wheat yield (Carr, Ritchie, and Porter 1991), and the development of coffee tree roots (Rodrigues et al. 2001). Manganese toxicity was also reported to affect the growth of canola (Moroni, Scott, and Wratten 2003), and ryegrass and white clover (Rosas et al. 2007; Mora et al. 2009) when excessive concentrations are present in soils. Those above indicate that a combination of negative effects of toxic and deficient factors determines crop growth and productivity on acid soils.

However, such the combination effects on plants typically natural rubber (NR, *Hevea brasiliensis Müll. Arg*) plantations are limitedly reported from acid soils. The NR trees are native to South America, and currently, there is a large portion of the world's NR plantations located on tropical soils, which normally have low pH and high exchangeable Al concentration (Bolan, Adriano, and Curtin 2003). Moreover, NR cultivation may further acidify soil (Oku, Iwara, and Ekukinam 2012) and deplete soil nutrient concentrations (Cheng, Wang, and Jiang 2007) with a magnitude dependent on individual elements, locations, and growth duration. Nevertheless, there are very few studies pointing out any significant potential nutritional factors responsible for reduced NR productivity in tropical acidic soils. Therefore, the current study was conducted on NR plantations grown on tropical acid Acrisol soils in southeastern Vietnam. The objective of the current study was to identify major factors including soil and leaf nutrients accounting for low NR productivity in the study soil.

2. Materials and methods

2.1. Study area

The current study was conducted in Tan Thanh rubber plantation, Dong Phu Rubber company, the southeastern region of Vietnam, located at 108° 49′ 55″E, 11° 31′ 59N. The region had a high annual rainfall regime (1500–2000 mm) and high mean air temperature (26–28°C). There were two distinct seasons (dry and rainy seasons) in the region. The study area was located on a Haplic Acrisols (FAO/UNESCO) with low soil pH, and the altitude varied from 70 to 110 m above sea level. Inorganic fertilizers were applied to the study soil annually, while organic fertilizers were applied to the study soil for the immature period of NR trees (the first 7 years), and were not applied when the trees became mature. Some basic properties of the study soil such as particle size distribution, total organic carbon, total nitrogen, phosphorous, and potassium are shown in Table 1.

2.2. Experimental design

Natural rubber trees: The current study was based on 10 NR blocks making up 200 ha grown with clone PB 235. Plant density was 555 trees ha^{-1}, with a spacing of 6 × 3 m. About 70% of NR trees were harvested, and the other 30% of the trees were either dead or underdeveloped. The rubber trees

Table 1. Basic properties of the study soil.

	Particle size distribution (%)			Total contents (g kg^{-1})			
	Clay	Silt	Sand	Organic C	Nitrogen	Phosphorous	Potassium
Mean	60.7	15.4	23.9	16	1.5	0.4	2.8
Minimum	47.5	8.3	15.3	14	1.3	0.3	0.5
Maximum	75.6	24.3	34.6	19.3	2	0.5	8.1
Std. Dev.	11.2	5.8	8.7	1.16	0.17	0.06	2.07

were planted in 1990 and first harvested in 1997. At the time current study was conducted (2011), NR trees were in the 14th year of harvest.

Experimental setup: From the 200 ha of 10-block NR plantations selected for the current study, we further selected and marked 20 small plots for the current study. The 20 plots selected were well located within the 200 ha of NR plantation and had similar topography and soil slope. The size of each plot was around 0.18 ha, including 100 harvested trees (5 rows and 20 trees per row). The 20 examined plots had the same NR clone and harvest age and were located in relatively flat areas (slope within individual plots was less than 1%).

2.3. Soil and leaf sampling and NR productivity measurements

Soil and leaf samples were taken in July and October 2011 on individual plots. An auger was used to sample soil to 0.3 m depth from the surface. Soil material, collected from 10 drilled points evenly distributed over each plot, was mixed well. One half of each sample was air-dried and ground to pass a 2-mm sieve before chemical analyses (total carbon, total nitrogen, total phosphorus, and total potassium) and particle size distribution. The other half was rapidly transported to the laboratory at Rubber Research Institute of Vietnam (RRIV) for measurements of exchangeable concentrations. Leaf samples were collected from terminal whorls of low branches exposed to sunlight from 10 to 15 random harvested trees from each plot (three to four basal leaves for one tree). One or two leaflets from one basal leaf were detached, combined into one sample for each plot and transferred to the laboratory for chemical analyses.

The NR productivity was also measured in July and October 2011 at the same time of soil sampling. Because there were about 10 harvest days per month in the studied NR plantations, we randomly selected 4 harvests to collect NR latex data. At about 10 am of the harvest day fresh latex of 100 trees within each plot was measured volumetrically. Additionally, the fresh latex was sampled from 20 trees selected randomly from 100 trees in each plot and combined into one mixed sample per plot. The latex samples were transferred to the laboratory for measurement of dry rubber content (in percentage), following the Standard Laboratory Method of acid coagulation (Danwanichakul, Lertsurasakda, and Wiwattanasit 2012). Briefly, the collected fresh latex was coagulated using acetic acid and the coagulum was dried at 70°C overnight in an oven. The dried rubber was obtained, and dry rubber content was reported as ratio of dried rubber weight to total weight of fresh latex. The NR productivity (gram-dried latex per tree per harvest) was calculated by multiplying dry rubber content by fresh latex weight, and productivities from four harvest days for each month were averaged. Thus, two averaged productivities for July and October were processed and reported.

2.4. Chemical analysis of soil and leaf samples

The air-dried and ground soil samples were chemically analyzed for pH in water, total C, total N, total P, total K in g kg^{-1} and available P (mg kg^{-1}), following methods used in (Nguyen et al. 2011). Soil particle size distribution of the air-dried samples were analyzed using the pipette method (Kroetsch and Wang 2008). Exchangeable K, Ca, Mg, Zn, and Al in (cmol (+) kg^{-1}) and exchangeable Fe and Mn in mg kg^{-1} in field soil samples (no air-drying samples) were extracted using $0.1M$ barium chloride solution (Rao 2005). Leaf tissue analyses for N, P, K, Ca, Mg, Mn, Fe, Cu, and Zn concentration in g kg^{-1} was carried out following the method reported in Suchartgul, Maneepong, and Issarakrisila (2012).

2.5. Statistical analysis

The whole data were measured at two series. Thus, the current study had repeated observations from which data were processed. Cluster analysis (CA) was applied to NR yield data to classify the productivity into clusters based on their similarity, following procedure used in study by (Singh et al. 2004). Hierarchical agglomerative CA was applied withWard's method, and Euclidean distance was calculated and used as a measure of similarity. Analysis of variance (ANOVA) was performed on the measured data to test the difference of means of different clusters. The current study was considered as a completely randomized design with single factor (cluster) and varying replicates (seven replicates for cluster 1, nine for cluster 2, and four for cluster 3, based CA results). ANOVA model was $y_{ij} = \mu + \alpha_i + \omega_{ej}$, where y_{ij} is data of j^{th} experimental plot classified into cluster i; μ is overall mean; α_i is an effect due to cluster i; and ω_{ej} is a random error (Ott and Longnecker 2011). When ANOVA indicated a significant difference at $P \leq 0.05$, the Tukey honestly significant difference test was used to test for significant differences among cluster means. In order to examine the simple linear relationship of any two variables, ex. NR productivity and exchangeable Al, a scatterplot was made using Sigmaplot 12 (Systat Software Inc, California, USA). For most cases except for the soil and leaf Mn relationship (Figure 5a), the linear regression model, f = b + ax (where f and x are independent and dependent variables, respectively; b is an intercept and a is a slope), was fitted using the least square approach. The fitted model and coefficient of determination (r^2) as well as probability (P) were included in the relationship panel if the regression statistics showed P value smaller than 0.05. Multiple linear regression analysis was conducted to investigate the dependency of NR productivity on soil and leaf nutrient concentration. The full model used for the multiple linear regression analysis is $f = \beta + \beta_1 x_1 + \beta_2 x_2 + .. + \beta_n x_n + \varepsilon$, where f is NR yield; β is intercept; $\beta_1, \beta_2, \beta_n$ are partial slopes; x_1, x_2, x_n are leaf and soil factors and ε is random error (Ott and Longnecker 2011). In addition, a stepwise procedure with backward elimination was conducted to find a reduced equation describing the multiple linear regression relationship, using JPM 10 (SAS Institute Inc, North Carolina, USA). All figures reported from the current study were made from the same scatterplots by the Sigmaplot 12.

3. Results

3.1. Classification of natural rubber productivity

A Dendrogram resulted from cluster analysis showed that NR productivity could be classified into three groups (Figure 1). Cluster 1 had the lowest productivity, 23.2; cluster II had a medium value, 38.2; and cluster III had the highest value, 61.3 g tree^{-1} harvest^{-1} (Table 2). NR productivity of the three clusters was significantly different from the other. There were 14 data grouped into cluster I, 18 data into cluster II, and 8 data into cluster III. The next step is to test the difference in leaf and soil nutrient concentration of the three clusters.

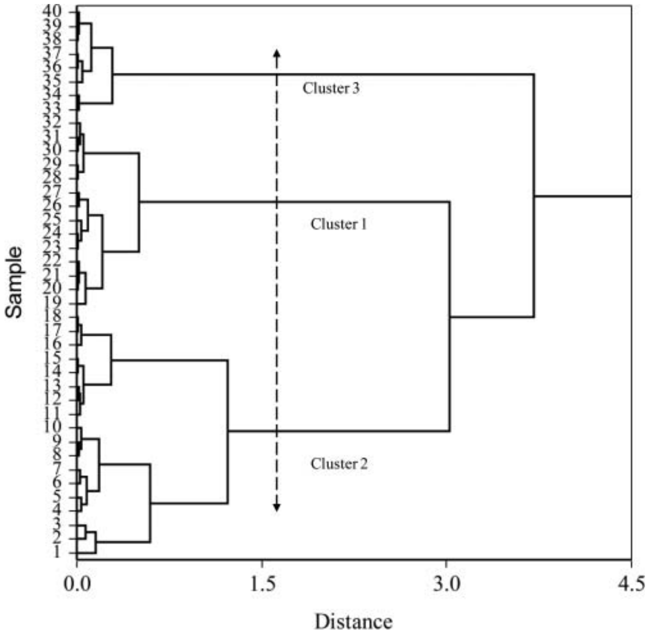

Figure 1. Dendrogram showing clusters of the NR yield data.

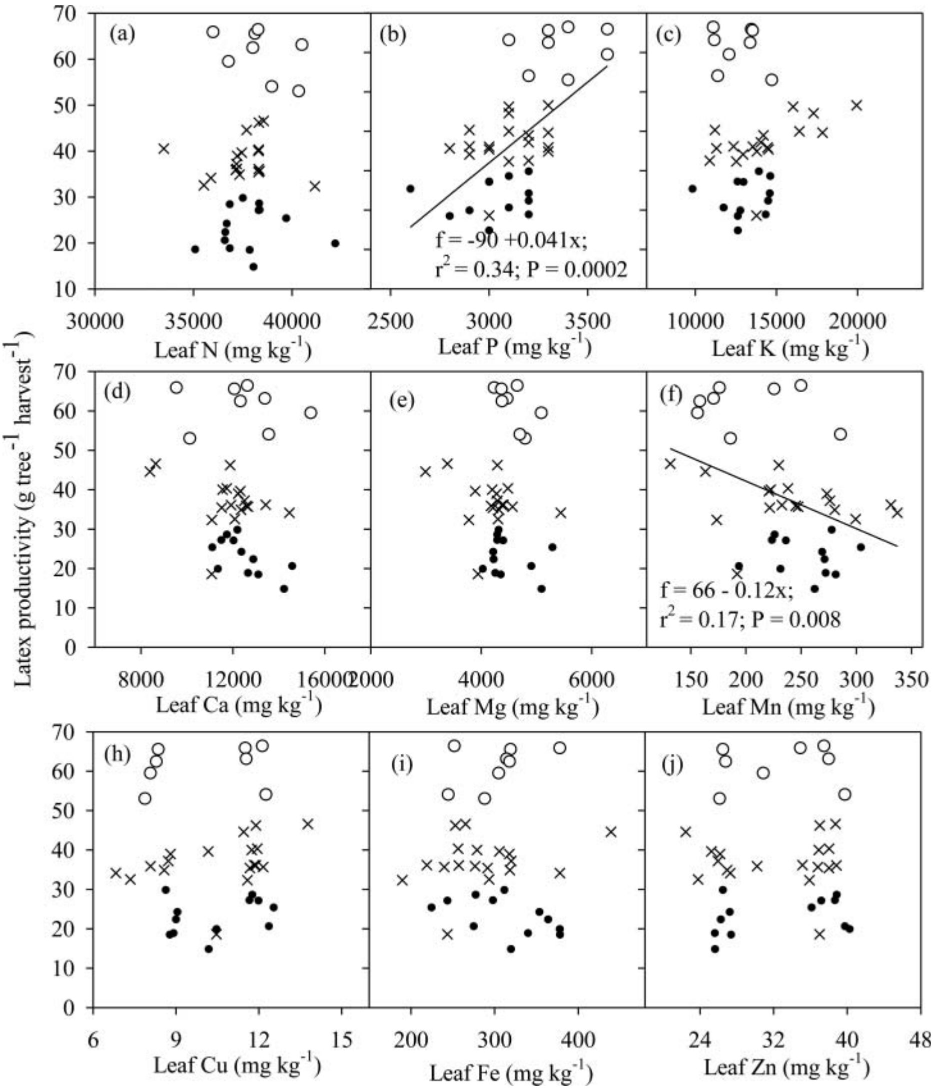

Figure 2. Relationship between leaf factors and NR productivity. The solid circles were data of cluster I; thin Xs were data of cluster II, and the opened circles were data of cluster III.

3.2. Difference in leaf and soil factors among three clusters

Of the nine leaf nutrients analyzed in the current study, there were two nutrients, leaf P and Mn having concentrations significantly different among the three clusters. The lowest-yield cluster (cluster I) had a

Table 2. Average NR yield and leaf macro- and micronutrients of three clusters. Data in the same column attached with different letters were significantly different from the other. Numbers in parenthesis were standard deviations of the mean. (No. of data averaged for cluster 1 was 14; cluster 2 was 18; and cluster 3 was 8.).

		Leaf macronutrients (mg kg^{-1})					Leaf micronutrients (mg kg^{-1})			
Cluster	NR yield (g tree^{-1} harvest^{-1})	N	P	K	Ca	Mg	Mn	Cu	Fe	Zn
I	23.2^{c}	37,778	3,043^{b}	13,243	12,356	4,415	251^{a}	10	310	32
	(4.7)	(1,693)	(187)	(1,367)	(1,068)	(395)	(34)	(1)	(51)	(6)
II	38.2^{b}	37,540	3,106^{b}	14,473	11,996	4,148	246^{a}	10	288	32
	(4.3)	(1,561)	(159)	(2,529)	(1,568)	(546)	(55)	(2)	(57)	(6)
III	61.3^{a}	38,370	3,363^{a}	12,600	12,374	4,583	201^{b}	10	302	33
	(5.3)	(1,566)	(177)	(1,344)	(1,879)	(279)	(47)	(2)	(42)	(6)

Table 3. Average values of soil pH and nutrient concentration of three clusters. Data in the same column attached with different letters were significantly different from the other. Numbers in parenthesis were standard deviations of the mean. (No. of data averaged for cluster 1 was 14; cluster 2 was 18; and cluster 3 was 8.).

		cmol(+) kg^{-1}					mg kg^{-1}		
Cluster	pH	K	Mg	Ca	Al	Zn	Fe	Mn	P
I	4.63^{b}	0.08	0.49	0.60	2.14^{a}	0.0007	1.00	3.87^{a}	9.0
	(0.18)	(0.06)	(0.20)	(0.32)	(0.32)	(0.0003)	(0.54)	(0.76)	(7.1)
II	4.68^{b}	0.12	0.38	0.46	2.02^{a}	0.0008	1.33	3.21^{b}	7.4
	(0.15)	(0.11)	(0.23)	(0.26)	(0.34)	(0.0003)	(0.91)	(0.60)	(4.6)
III	4.97^{a}	0.10	0.49	0.61	1.64^{b}	0.0008	1.56	3.00^{b}	14.5
	(0.28)	(0.10)	(0.38)	(0.45)	(0.41)	(0.0002)	(1.74)	(0.61)	(11.4)

leaf P concentration 3043 mg kg^{-1} similar to that of cluster II 3106 mg kg^{-1} (Table 2). The cluster III had a significantly highest leaf P concentration 3363 mg kg^{-1}. In contrast, cluster III had a lowest leaf Mn concentration 201 mg kg^{-1}, while clusters I and II had significantly lower leaf P concentrations, 251 and 246 mg kg^{-1}, respectively.

The three clusters also showed a significant difference in some soil factors including soil pH, exchangeable Al and exchangeable Mn (Table 3). Soil pH of clusters I and II was similar, 4.63 and 4.68, respectively, and was significantly lower than that of cluster III, 4.97. In contrast, soil Al was significantly lowest in cluster III 1.64 cmol (+) kg^{-1}, while highest in clusters I and II 2.14 and 2.02 cmol (+) kg^{-1}, respectively. Soil Mn was highest in cluster I 3.87 mg kg^{-1}, and lowest in clusters II and III, 3.21 and 3.00 mg kg^{-1}, respectively. The other soil factors were not significantly different among the three clusters.

3.3. Simple relationships between NR productivity and leaf and soil factors

Of the eighteen leaf and soil factors investigated in the current study (Tables 2 and 3), NR productivity was linearly and significantly correlated with leaf P, leaf Mn, soil pH, soil Al, and soil Mn.. NR productivity was positively correlated with leaf P concentration with a slope of 0.041 mgP g^{-1} (latex). The linear relationship explained for 34% of total NR yield variance. In contrast, NR productivity was negatively correlated with leaf Mn concentration with a slope of −0.12 mgMn g^{-1} (latex). The Mn based linear regression line explained for 17% of total NR yield variance.

The studied soil was acidic with pH values ranging from 4.2 to 5.4 and a mean of 4.7. Based on the linear regression, for every increasing pH unit, NR productivity increased by 34 gram dried latex per tree per harvest. This positive linear relationship can explain for 29% of total NR yield variance (Figure 3a). In contrast, NR productivity was significantly and negatively correlated with soil exchangeable Al and exchangeable Mn (Figures 3i, 3j). Based on the linear regression, NR yield decreased significantly with a reducing rate of 17 g latex per tree per harvest for every cmol(+) per kg rise in Al and 9 g latex per tree per harvest for every mg kg^{-1} rise in Mn. The each of the two simple relationships explained for 23% and 25% of total NR yield variance, respectively.

Simple linear regression analysis was also applied to examine pH dependency of soil available P, exchangeable Al and Mn (Figure 4). While available P was positively correlated with soil pH with a slope 20.8, exchangeable Al and Mn were negatively correlated with soil pH with slopes −1.0 and −1.3, respectively. Based on simple linear regression equations shown within Figure 4, when soil pH changed from 4.3 to 5.4, available P increased from 1.14 to 24.02 mg kg^{-1}, Al changed from 2.5 to 1.4 cmol(+) kg^{-1}, and exchangeable Mn decreased from 3.7 to 2.3 mg kg^{-1}.

Because Mn is an essential nutrient, which is taken up by plant for growth, we examined the relationships between leaf Mn and soil Mn (Figure 5). The Figure showed a significant correlation ($r^2 = 0.23$) between leaf Mn concentration and soil exchangeable Mn concentration. The dependence of leaf Mn on soil Mn was an exponential function; that is, leaf Mn increased rapidly for soil - Mn concentrations less than 3 mg kg^{-1} and leveled off afterward. Because soil P was significantly correlated with pH,

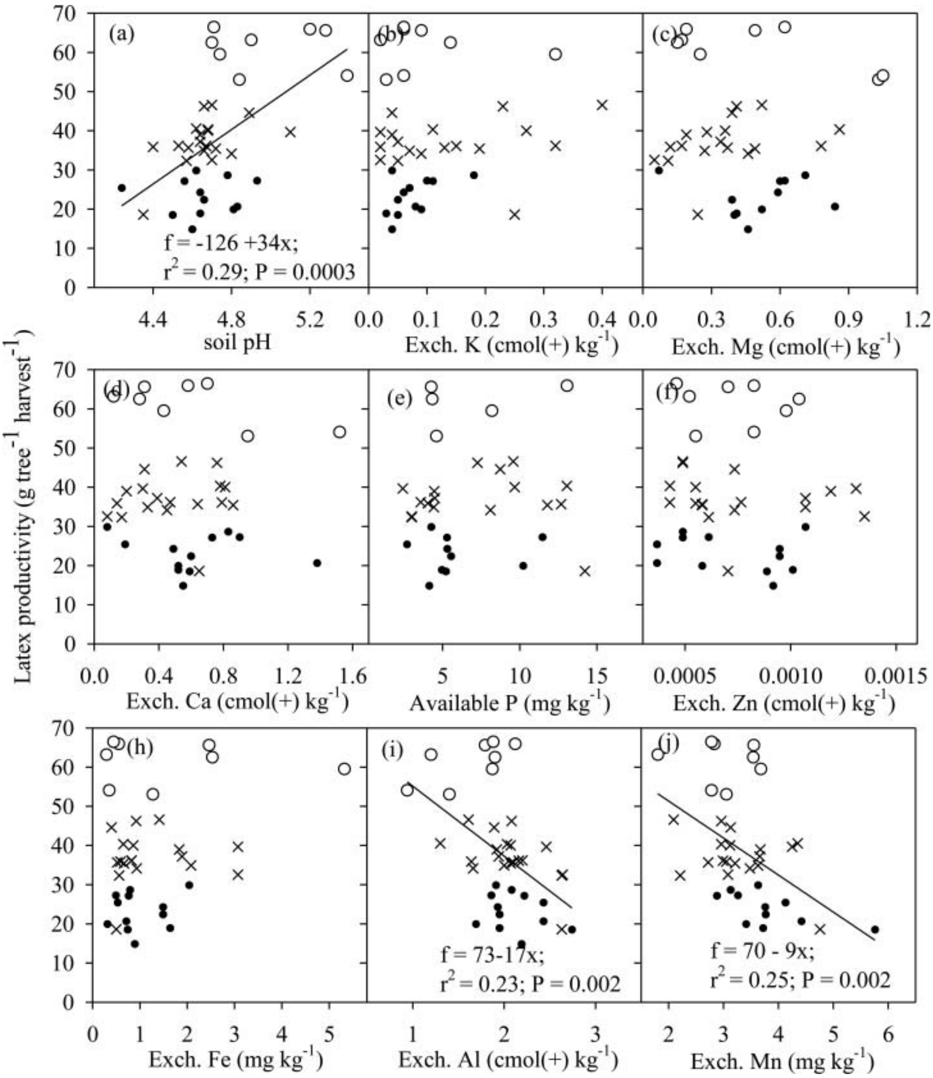

Figure 3. Relationship between soil factors and NR productivity. The solid circles were data of cluster I; thin Xs were data of cluster II, and the opened circles were data of cluster III.

and leaf P was significantly correlated with NR productivity, we also examined the relationship between soil P and leaf P (Figure 4). However, this relationship was not significant.

3.4. Multiple relationships between NR productivity and soil and leaf factors

Multiple linear regression analysis was conducted to examine dependency of NR productivity on multiple soil and leaf factors, although simple linear regressions showed that NR productivity was significantly correlated with leaf P, leaf Mn, soil pH, soil Al and soil Mn. A stepwise regression procedure was performed to eliminate the less-significant factors and retain the most significant factors constituting the multiple regression equation. To begin with the multiple regression 18 factors analyzed from leaf and soil samples were fully added to a multiple model and then the stepwise regression was applied. As a result, leaf P and soil exchangeable Mn were statistically retained to make up the final multiple regression equation (NR yield $= -55.6 + 0.038$ leaf P - 8.1 Mn), which could be used to forecast NR productivity (Table 4). This equation can explain for 49% variance of NR yield.

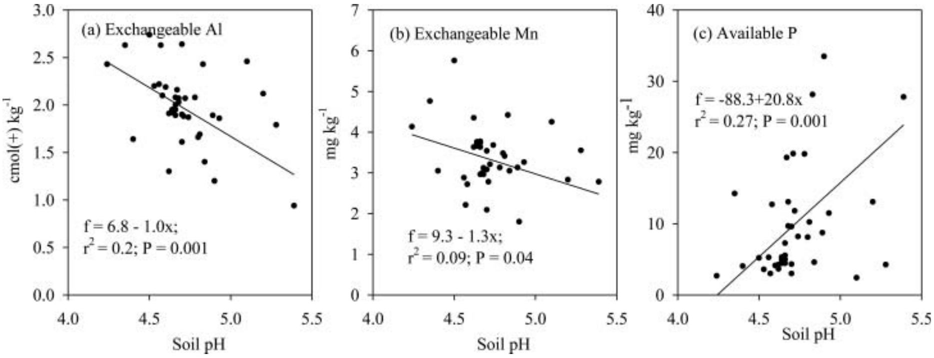

Figure 4. Relationship between soil pH and soil exchangeable Al, Mn, and available P.

4. Discussion

4.1. NR productivity in relation with leaf and soil factors

The current study was a part of a research project to examine soil and leaf factors governing NR productivity in the tropical acid Acrisol soil in Southeastern Vietnam. Significant differences in leaf P and Mn concentrations and in soil pH, Al, and Mn concentrations among the three yield-based clusters, coupled with significant relationship between NR productivity with leaf P, Mn, soil pH, Al, and Mn may suggest that high soil exchangeable Al and Mn concentrations and low leaf P concentration were the important factors accounting for the low productivity of NR plantations in the studied area. Negative effects of Al and Mn to various crops has been widely reported when their exchangeable forms were present at high levels (Mora et al. 2009; Rosas et al. 2007; Watanabe and Okada 2005; Moroni et al. 2003; Rodrigues et al. 2001; Carr, Ritchie, and Porter 1991).

There should be two expected trends of plants in response to the changing concentration of soil Mn. At low concentrations Mn is an essential micronutrient for plant growth resulting in a positive relationship between soil Mn and plant yield, while at high concentrations Mn is more likely toxic to plant resulting in a negative trend. The current study showing the linear and negative relationship (Figure 3) indicated that the observed soil Mn concentrations could be high enough to cause negative effects to NR trees. The negative effect could be induced by increasing Mn concentration in leaf tissue, which restricted photosynthetic processes (Mukhopadhyay and Sharma 1991). Again, because Mn is an essential nutrient, plant absorbs Mn for their growth, and the absorbed Mn is transferred to shoot/leaf to build up, resulting in a positive relationship between soil and plant Mn concentration as reported by

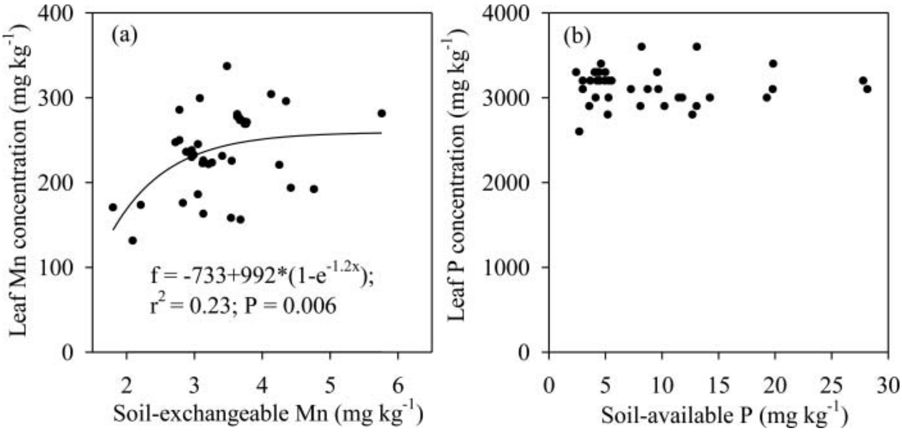

Figure 5. Relationships of soil Mn - leaf Mn and soil P - leaf P.

Table 4. Result of backward elimination from multiple linear regression analysis. The bald rows indicate significant factors contributing to a reduced equation used to forecast NR productivity. Leaf P and soil-exchangeable Mn together explained for 49% variance of NR yield. The reduced equation is: NR yield = −55.6 + 0.038 leaf P - 8.1 Mn.

Factors	Estimate	P	Factors	Estimate	P
Intercept	**−55.6**	**1.00**			
Leaf N	0.0	0.66	Soil K	0.0	0.87
Leaf P	**38.4**	**0.00**	Soil Ca	0.0	0.77
Leaf K	0.0	0.41	Soil Mg	0.0	0.57
Leaf Ca	0.0	0.55	**Soil Mn**	**−8.1**	**0.00**
Leaf Mg	0.0	0.31	Soil Fe	0.0	0.98
Leaf Mn	0.0	0.37	Soil Zn	0.0	0.31
Leaf Cu	0.0	0.78	Soil Al	0.0	0.13
Leaf Fe	0.0	0.78	Soil P	0.0	0.15
Leaf Zn	0.0	0.88	pH	0.0	0.13

Wright, Baligar, and Wright (1988) on switchgrass and subterranean clover. The positive but exponential trend describing the relationship between soil and leaf Mn in the current study (Figure 5a) could be explained by an initial linear increase in plant uptake with increasing concentration of soil Mn at low levels. However, as soil Mn concentration further increased the NR trees may develop mechanisms to restrict Mn uptake to prevent further negative effect. The negative and significant relationship between leaf Mn and NR productivity (Figure 2f) as well as significantly higher leaf Mn concentration in lower-yield cluster (Table 2) may indicate a negative effect due to accumulated Mn in leaves. Other studies also reported a negative relationship between leaf Mn concentration and dry weight of sweet potato (Mortley 1993) and of soybean yield (Bethlenfalvay and Franson 1989). However, plants can develop mechanisms to ameliorate the detrimental effects of the high Mn concentration such as symbiotic association with mycorrhiza (Nogueira, Magalhaes, and Cardoso 2004; Bethlenfalvay and Franson 1989). Limited Mn uptake and translocation from root to shoot (El−Jaoual and Cox 1998) are among the adaptation mechanisms for plants to grow in the excessive-Mn soils. Those mechanisms could be present with NR trees and thus provide additional explanation of the exponential pattern between soil and leaf Mn as shown in Figure 5a.

Aluminum is not an essential nutrient but is well recognized as a phototoxic element (Pax et al. 2015; Rout, Samantaray, and Das 2001), which is typically associated with root damage and suppression of plant uptake of other nutrients (Pax et al. 2015; Menzies 2003). A strong correlation between soil exchangeable Al and plant growth is rarely found (Delhaize and Ryan 1995). However, the current study showed that NR productivity was negatively correlated with soil Al (Figure 3i) and that soil Al concentration of high-yield cluster was lower than that of low-yield cluster (Table 3), indicating that exchangeable Al concentration may be important in determining NR productivity in the study soils. According to Cronan and Grigal (1995) Ca to Al ratios (>1, >0.5, and >0.2) were suggested to use as indicators of Al stress. The ratios in the current study varied from 0.23 in cluster II to 0.25 in cluster I, and 0.35 in cluster III, indicating that the study soil could be at least 75% risk of Al stress. Moreover, in a solution study from Brazil, Bueno et al. (1988) reported toxic effects of Al at $>$ 15-mg kg^{-1} concentrations on young-NR growth. The current study observed a much higher exchangeable Al concentration in extracted soil solution, from 84 to 246 mg kg^{-1}, again confirming that Al levels in the study soils were high and possibly accounting for the low yields by inducing negative effects on the trees.

Phosphorous is a macronutrient to plant and thus there is more likely a positive relationship between leaf P and plant yield. The current study also found the same pattern for NR productivity (Table 2 and Figure 2b). However, there was no relationship between soil P and leaf P concentration (Figure 5b) as well as soil P and NR productivity (Figure 3e). Previously Damrongrak, Onthong, and Nilnond (2015) reported that 2 years after application of fertilizer and dolomite to NR plantation, soil P and leaf P concentration was improved significantly, compared to the control. Feng et al. (2005) reported that NR yield was positively correlated with soil available P, but negatively correlated with leaf P concentration, which is opposite to the finding in the current study. The real reasons are still unclear and thus need more study. One possibility could be that NR trees additionally developed mechanisms to acquire more P in the low-P soil, such as formation of arbuscular mycorrhizal symbiosis (Ikram, Mahmud, and Othman 1993) and enhanced root system (George et al. 2009). This can explain for (1) no relationship between soil available P and leaf P and (2) no relationship between soil available P and NR productivity as found in the current study.

4.2. pH dependence of exchangeable Al, Mn, and available P

Soil pH was well correlated with soil exchangeable Al, Mn (negative trend), and available P (positive trend), which are similar to those reported by Hamilton, Takashi, and Fernando (2003). These authors found negative correlation between soil pH and Al saturation on tropical acidic soils in Brazil. The positive relationship between soil pH and available P reported in the current study (Figure 4) was similar to that reported by Sato and Comerford (2005). The authors reported that P sorption decreased with a consequent increase in soil pH, indicating that an increasing pH resulted in greater P availability. In addition, available P is normally low in acid soils due to fixation with Al and Fe (Ch'ng et al. 2014).

In contrast, Al and Mn were more exchangeable with decreasing pH in the study soil (Figure 4). Chemically, both Al and Mn become more exchangeable at pH below about 6, and the exchangeable quantity increases significantly when pH drops below 5.5. Soil pH in the current study varied from 4.2 to 5.4, which is well below the critical point and consequently increased changeable Al and Mn concentration were found. Previously, exchangeable Al and Mn were found to be inversely correlated with soil pH (Millaleo et al. 2010; Manrique 1986). The current study was conducted on Acrisols, which were acidic, and thus a similar negative relationship between Al, Mn, and soil pH was found.

4.3. Acidified soils with NR plantations

For the reasons discussed in section 4.1, the current study showed a positive linear relationship between soil pH and NR productivity (Table 2 and Figure 3). Other studies reported similar relationships between soil pH and growth of wheat (Mohebbi and Mahler 1989) and of Eucalyptus urophylla seedlings (Aggangan, Dell, and Malajczuk 1996). With a long lifecycle, soil properties including organic matter, N, K, and P concentrations in NR plantations were found to decrease in Hainan Island, China (Cheng, Wang, and Jiang 2007). After 41 years of NR cultivation, soil significantly decreased in pH in Nigeria (Oku, Iwara, and Ekukinam 2012). The current study did not examine the same trends but found low soil concentration of total C, N, P, and K (Table 1) after 20-year of growth. Those findings suggest that soils under NR plantations in Vietnam are more likely to be acidified with NR-cultivation age, possibly due to (1) frequent inorganic fertilizer application, (2) almost no organic fertilizer application during mature stages, (3) basic cations such as Ca, K, and Mg and other elements removed with frequently harvested latex, and (4) high rainfall in Vietnam resulting in nutrient leaching and/or erosion (Damrongrak et al. 2015; Cai et al. 2011). The findings from the current study may also suggest that soil acidity might be an important primary factor controlling over NR yield in the study area. Therefore, bringing soil pH to neutral levels should be a high priority in NR cultivation in Vietnam and possibly other countries.

5. Conclusions and suggestions

The studied soil is acidic with pH lower than 5.4. Leaf P concentration and soil pH were significantly higher in high-yield cluster, while leaf Mn, soil exchangeable Al, and Mn concentrations were significantly higher in low-yield cluster. NR productivity was significantly correlated with leaf P (positive trend), Mn (negative trend), soil pH (positive trend), exchangeable Al and Mn (negative trend). These indicated that NR productivity in the current study could be mainly controlled by these factors. Multiple regression analysis showed that NR productivity can be forecasted with a reduced equation: NR yield $= -55.6 + 0.038$ leaf P - 8.1 soil Mn. Soil pH was negatively correlated with soil exchangeable Al and Mn. These suggest that the current acidic soil needs to be improved to raise soil pH to neutral levels to improve NR yield. Liming the acidic soils could be considered for short-term management, but soil fertility improvements including building organic matter and improving basic cations concentrations should be long-term goals.

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