

Soybean growth and related soil N in a sandy soil under chemical fertilizer, poultry manure, and bentonite additions

Vuthipun Thongviang^{1*}, Viriya Limpinuntana¹, Sawaeng Ruaysoongnern¹
and Richard W. Bell²

ABSTRACT: The objectives of this research were to study the effects of bentonite, chemical fertilizer, and poultry manure, either sole or combined addition, on soybean growth and plant N uptake, and also to examine the related soil N content in a sandy soil. The column experiment was conducted in the glasshouse in Western Australia during May to August 2007. The experiment was laid out in a RCBD with three replications. Eight treatments were additions of chemical fertilizers (CF) at 200 kg/ha, poultry manure (PM) at 6.25 t/ha, bentonite (BN) at 50 t/ha, (CF+PM), (CF+BN), (PM+BN), and (CF+PM+BN). Soybeans (var. Hale) were planted and both plant and soil samples were collected at 42 days after planting for chemical analysis. From the results, the BN treatment did not increase soybean dry matter, plant N content (uptake) and concentration over the control. In contrast, the PM gave highest dry matter (growth) of soybean among all treatments. Any combined treatments with BN depressed the soybean growth except for CF+PM+BN. After adding the soil for 42 days, the soils in all treatments showed decreases in soil OM with CF+PM+BN treatment having the lowest content. There were no changes in total N and NH_4^+ contents in the soil when compared to the contents at beginning. At the same time, both BN and PM treatments had higher NO_3^- content than the control and CF treatment at 0-15 and 30-40 cm soil depths. At the harvesting time, it was found that addition of BN in fine powder form might have caused soil clogging and limited soybean root growth. Although this column study gave different results from other previous researches on BN it still showed possibility of BN to interact with other soil factors to produce soil N (NO_3^-) for crop growth.

Keywords: bentonite, sandy soil, soybean, ammonium (NH_4^+), nitrate (NO_3^-)

Introduction

Sandy soils are widespread in tropical regions and most of them become one of limiting factors in crop production due to soil degradation (FAO, 1983). From previous case studies on such sandy soil improvements, application of bentonite (BN), known as a smectite group mineral composed mostly of 2:1 alumino-silicate structure (Gate et al., 2002), is proved to be one of effective approaches for improving soil fertility and crop productivity (Noble et al., 2001). For examples, the addition of BN (50 t/ha) increased the biomass yield of forage sorghum grown in some degraded

sandy soils in field trial (Noble et al., 2004) and pot trials (Puttaso, 2003; Croker et al., 2004). The application of this montmorillonitic clay (50 t/ha) increased the biomass yield of sugarcane planted in a degraded sandy soil (Tangkoonboribun, 2006). Bentonite applied in a clay-loam soil also increased grain yield of maize (Mekuria et al., 2014). In a recent study, the addition of sole bentonite (50 t/ha) or combining with chemical fertilizers and/or tree leaf litters increased the growth and grain yield of soybean planted in an upland infertile-sandy soil (Thongviang, 2016).

Main effects of BN addition on crop growth in previously mentioned case studies included

¹ Department of Plant Science and Agricultural Resources, Faculty of Agriculture, Khon Kaen University, Khon Kaen 40002, Thailand

² School of Environmental Science, Murdoch University, Murdoch, Perth 6150, Western Australia

* Corresponding author: vthongviang33@gmail.com

increasing in available cation nutrients (e.g. Ca, Mg, and K), cation exchange capacity (CEC) and pH of amended sandy soils (Noble et al., 2001). Moreover, the BN addition increased the contents of soil organic matter (soil OM) and total nitrogen (total N) in the soil that positively related to sorghum plant N concentration (Puttaso, 2003; Croker et al., 2004). Positive relationship between total N in soil and plant N uptake (content) was also confirmed by another case study of using 2:1 silicate clay in sugarcane crop (Tangkoonboribun, 2006). Croker et al. (2004) suggested that increasing plant N uptake might relate to soil N coming from soil OM decomposition followed by N-mineralization in sandy soils as a result of BN added. However, most previous studies examined and reported only soil OM and total N but no such a study on the detail of N-mineralization and related products concerning crop growth in relation to the addition of BN. There is no study on NH_4^+ and NO_3^- , the final products of N-mineralization.

From a previous field study, BN additions also increased greater OM and total N contents in the soil than did the one without addition of BN (Thongviang, 2016). Moreover, the result of this study showed significantly high dry matter (and grain yield) of soybean as affected by BN-based additions even in the sandy soil with sole BN addition. However, the soybean in BN treated plot had been planted without inoculation and addition of any N fertilizer sources, except little N possibly coming with rain. Therefore, the question remains whether mineralization, the final process of soil OM transforming to inorganic nutrients (especially N) by soil microorganisms, really occurs and supplied available soil N to growing crop in the

case of BN-added plot.

Thus, the objectives of this study were to reaffirm the effects of BN addition on soybean growth and N uptake, and to examine the amounts of total N, ammonium-N (NH_4^+), and nitrate-N (NO_3^-) in sandy soil added with BN solely and in combination with CF and/or PM.

Materials and methods

A soil column experiment was conducted in the glasshouse at School of Environmental Science, Murdoch University, Western Australia (WA) during May to August 2007. The average soil and air temperatures during this experimental period were 14.4 and 14.0 °C, respectively. The experiment was laid out in a randomized complete block design (RCBD) with three replications. Eight treatments consisted of the additions of chemical fertilizers (CF) at 200 kg/ha equivalent to 0.34 g/column, poultry manure (PM) at 6.25 t/ha equivalent to 11.04 g/column, bentonite (BN) at 50 t/ha equivalent to 88.31 g/column and combinations of these materials including (CF+PM), (CF+BN), (PM+BN), and (CF+PM+BN). The bentonite used above is referred to the rate of 50 t/ha applied in a previous case study with successful improvement of the forage sorghum biomass yield in a degraded sandy soil of Northeast Thailand (Noble et al., 2004). Meanwhile, the rate of CF and PM used in this experiment as given above is referred to the research reports of Rattanarat (1999) for CF rate about 187.5-250 kg/ha and Panpruek et al. (2007) for PM rate about 6.25 kg/ha that both used rated were performed by soybean production in sandy soils.

Sandy soil used in the experiment was collected from 15 km north of Badgingarra, Western Australia (WA). The soil samples were collected separately from the 0-15 cm layer as topsoil and 15-30 cm layer as subsoil. Air-dried soil was sieved through a 4-mm stainless steel screen to select suitable granule/aggregate for planting crop in the soil column and 2-mm sieved screen for physical and chemical analysis as reported in **Table 1**. Soil pH and electrical conductivity (EC) were measured in suspensions of air-dried soil in distilled water using 1:5 ratio of soil: to water by using pH and EC meters, respectively. Cation exchange capacity (CEC) was determined by ammonium acetate (NH_4OAc ; pH=7) extraction method (Peech, 1945). Organic matter content was determined by Walkley and Black method (Black, 1965). Total N content was determined by micro-Kjeldahl method and using a flow injection analyzer (Black, 1965). Ammonium-N and nitrate-N were extracted with 1 N KCl (1: 10; soil: volume), shaking for 1 hour at 200 rpm and filtered using filter paper no.1, and then determined both N forms by using a flow injection analyzer. Available P content was determined by Bray II method and using spectrophotometer (Bray and Kurtz, 1945). Exchangeable K and Ca contents were determined by ammonium acetate (NH_4OAc ; pH=7) extraction method and using flame photometer (Black, 1965).

Chemical fertilizers with N (11.8%), P (6.0%), K (15.6%), Mg (1.0%), S (8.3%), Cu (0.05%), Zn (0.05%) and Mn (0.13%) and poultry manure (C:N ratio about 6.5) with N (3.2%), P (2.6%), K (1.3%),

Ca (7.7 %), Fe (0.1%), Mn (0.06%) and Zn (0.03%) were used in this study. Both materials were grounded finely and then uniformly mixed with the topsoil only. Bentonite in fine powder form was applied by mixing uniformly with the topsoil and some of its chemical properties are also given in **Table 1**.

Soil column was set up using polyvinylchloride (PVC) pipe, 15 cm in diameter and 50 cm in length. The column was split longitudinally into halves for soil sampling. The two halves of the PVC pipe were sealed and attached to PVC cap with draining hole at the bottom of the column. White sand was added at the capped bottom of the column (800 g/column). Then, 6 kg of sieved-subsoil with no amendments was placed over the white sand and followed by the sieved-topsoil of 3.8 kg thoroughly mixed with material with respect to each treatment added into the column above the sieved-subsoil.

Soybean seeds (var. Hale) were planted using 6 seeds per column of which soil moisture content inside was adjusted at field capacity (FC) by applying about 2 L of de-ionized water to dry soil in the column. Young soybean was thinned to have 2 plants left per column at 10 days after planting (DAP) along with supplying water about 400 mL every week until harvesting time. Soybean (2 plants per column) was harvested at 42 DAP, stem and leaf samples were dried in a hot-air oven at 70 °C for 24 hours, and dry weights were recorded. Dried stem and leaf samples were ground finely and combined for plant N analysis by micro-Kjeldahl method and using a flow injection analyzer (Black, 1965).

Table 1 Some physical and chemical properties of initial soil and bentonite used

	Top-soil (0-15 cm depth)	Sub-soil (15-30 cm depth)	Bentonite
<i>Physical properties</i>			
1) Sand (%)	97.9	98.9	4.7
2) Silt (%)	1.0	0.2	9.5
3) Clay (%)	1.1	0.9	85.8
Textural class	Sand	Sand	Clay
<i>Chemical properties</i>			
1) pH (H ₂ O)	5.61	5.85	8.03
2) Electrical conductivity; EC (dS/M)	0.019	0.010	0.348
3) Cation exchange capacity; CEC (cmol/kg)	6.98	5.20	34.26
4) Organic matter; OM (%)	1.07	0.46	0.07
5) Total N (%)	0.060	0.036	0.010
6) Ammonium-N (mg/kg)	4.15	2.22	5.18
7) Nitrate-N (mg/kg)	3.18	2.19	2.81
8) Available P (mg/kg)	1.55	0.99	59.50
9) Exchangeable K (mg/kg)	16	7	346
10) Exchangeable Ca (mg/kg)	200	110	5750

After harvesting soybean, each column was split vertically for soil sampling at 0-10, 10-15, 15-20, 20-30 and 30-40 cm depths. The soil samples taken from each depth interval were separately sieved through 0.75 cm screen for removing roots of soybean. Then, the soil samples were air-dried and sieved through 2-mm stainless screen for the analysis of soil chemical properties including soil OM, total N, ammonium, and nitrate as followed the analytical method above.

The analysis of variance (ANOVA) of the data based on the RCBD and comparison of treatment means with least significant difference (LSD) were undertaken using the Statistix8 program (version

2003) at the 95% probability ($p \leq 0.05$).

Results

Soybean dry weight and N uptake

At 42 DAP, the shoot dry weight of soybean was significantly different ($p \leq 0.05$) among treatments (**Figure 1**). Among sole additions, the soybean plants had highest shoot dry weight in sandy soil added by PM followed by CF, control, and BN. Meanwhile, the soybean shoot dry weight was depressed in the sandy soil with BN-treated compared to untreated except CF+PM and CF+PM+BN.

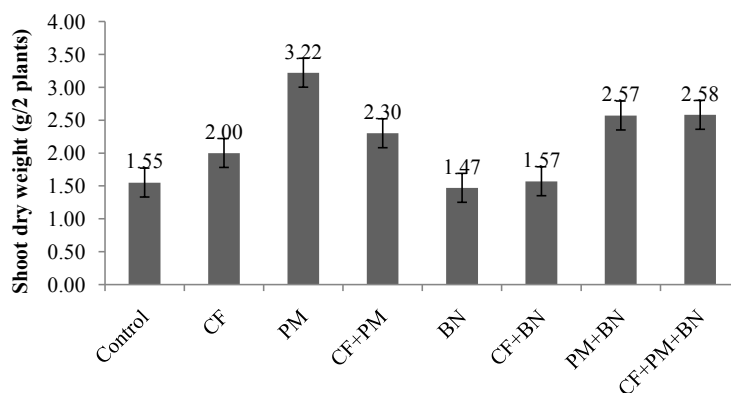


Figure 1 Shoot dry weight of soybean under chemical fertilizer (CF), poultry manure (PM), and bentonite (BN) additions at 42 DAP ($p \leq 0.05$)

The content and concentration of N in soybean shoots (stem and leaf parts) at 42 DAP were significantly different ($p \leq 0.05$) among treatments (Figure 2a and 2b). Soybean plants with the highest N content were in the treatment of PM for 0.077 g followed by the content in CF, CF+BN, PM+BN, CF+PM+BN, and CF+PM treatments for 0.067, 0.051, 0.047, 0.044, and 0.035 g. Meanwhile, the plant shoot N had lower

content in BN (0.027 g) and control (0.023 g) than in other treatments (Figure 2a). Soybean N concentration in shoot was the highest in sandy soil added with CF and CF+BN for 3.33 and 3.25% followed by the concentration in PM treatment for 2.40% while plant N concentration in PM+BN, control, CF+PM+BN, BN, and CF+PM treatments were 1.83, 1.72, 1.69, 1.58, and 1.52%, respectively (Figure 2b).

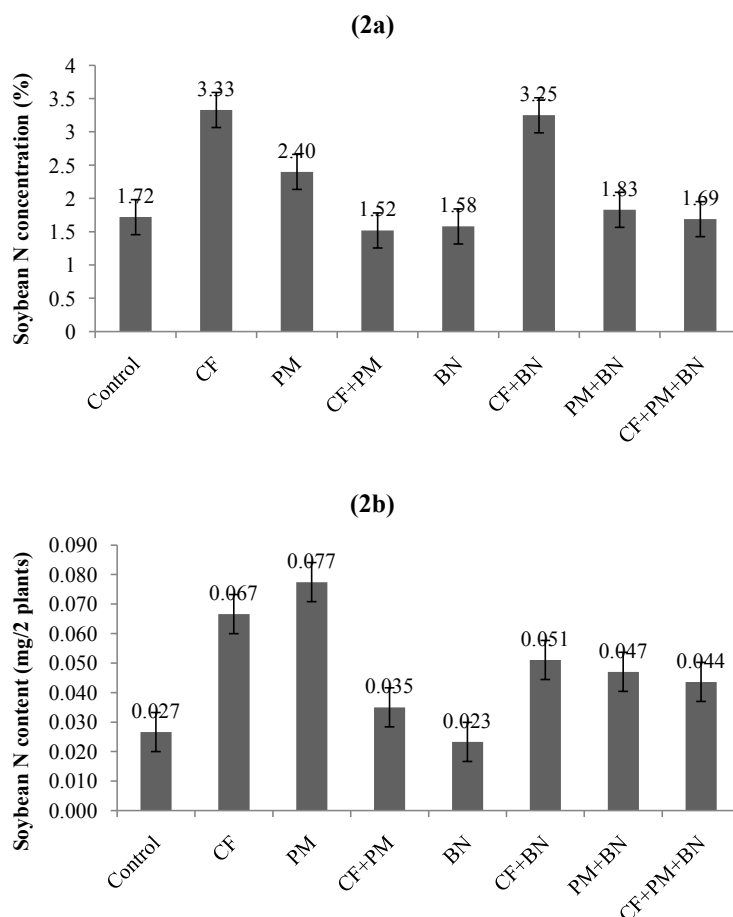


Figure 2a and 2b Concentration and content of N in above ground plant parts of soybean under chemical fertilizer (CF), poultry manure (PM), and bentonite (BN) additions at 42 DAP ($p \leq 0.05$)

Change of OM and total N in soil

At 42 DAP, both soil OM and total N contents decreased slightly from the beginning. Soil OM content was significantly different ($p \leq 0.05$) among treatments at 0-30 cm but not at 30-40 cm soil depth (**Table 2**). With variations among treatments, the soil OM contents at 0-10, 10-15, 15-20, 20-30, and 30-40 cm depths were lower than that of the initial levels. In treated topsoil (0-15 cm soil depth), soil OM from CF+PM+BN had the lowest content among all treatments.

However, total N contents were not significantly different ($p \leq 0.05$) among treatments at all soil depths (**Table 3**). Total N contents at 0-10, 10-15, 15-20, 20-30, and 30-40 cm depths were in the range of 0.047-0.056%, 0.048-0.054%, 0.026-0.034%, 0.022-0.030%, and 0.022-0.025%, respectively. Nevertheless, total N in the topsoil (0-15 cm depth) with BN-treated tended to have lower content than that in untreated soil (significantly different at $p \leq 0.10$).

Table 2 Effect of chemical fertilizer, poultry manure, and bentonite additions on soil organic matter (soil OM) at 0-40 cm soil depth at 42 DAP

Treatments	Soil OM (%)				
	0-10 cm	10-15 cm	15-20 cm	20-30 cm	30-40 cm
T1: Control	0.93 ab ^{1/}	0.91 a	0.49 ab	0.34 ab	0.35
T2: Chemical fertilizer (CF)	0.89 b	0.89 ab	0.37 ab	0.35 ab	0.35
T3: Poultry manure (PM)	0.94 ab	0.89 ab	0.39 ab	0.37 ab	0.32
T4: CF+PM	0.87 b	0.83 b	0.38 ab	0.34 ab	0.35
T5: Bentonite (BN)	0.96 a	0.90 ab	0.36 b	0.33 b	0.38
T6: CF+BN	0.91 b	0.88 b	0.40 ab	0.37 ab	0.37
T7: PM+BN	0.96 a	0.91 a	0.38 ab	0.39 ab	0.39
T8: CF+PM+BN	0.77 c	0.78 c	0.51 a	0.48 a	0.34
F-test ($p \leq 0.05$)	* ^{2/}	*	*	*	ns ^{3/}
CV. (%)	19.76	27.98	19.55	22.65	17.33

^{1/} Means in each column followed by the same letter are not significantly different as determined by LSD

^{2/} *Significant at $p \leq 0.05$ ^{3/} ns is non-significant at $p \leq 0.05$

Table 3 Effect of chemical fertilizer, poultry manure, and bentonite additions on soil total nitrogen (total N) at 0-40 cm soil depth at 42 DAP

Treatments	Total N (%)				
	0-10 cm	10-15 cm	15-20 cm	20-30 cm	30-40 cm
T1: Control	0.053 ^{1/}	0.051	0.033	0.023	0.024
T2: Chemical fertilizer (CF)	0.053	0.051	0.027	0.024	0.024
T3: Poultry manure (PM)	0.055	0.053	0.028	0.025	0.022
T4: CF+PM	0.052	0.050	0.027	0.023	0.024
T5: Bentonite (BN)	0.055	0.053	0.026	0.022	0.025
T6: CF+BN	0.054	0.052	0.028	0.024	0.024
T7: PM+BN	0.056	0.054	0.027	0.026	0.025
T8: CF+PM+BN	0.057	0.048	0.034	0.029	0.023
F-test ($p \leq 0.05$)	ns ^{2/}	ns	ns	ns	ns
CV. (%)	18.51	17.29	24.10	16.70	23.95

^{1/} Means in each column followed by the same letter are not significantly different as determined by LSD

^{2/} ns is non-significant at $p \leq 0.05$

Ammonium (NH_4^+) and nitrate (NO_3^-) contents in soil

At 42 DAP, NH_4^+ content was not significantly different ($p \leq 0.05$) among treatments at all soil

depths (**Table 4**). However, NH_4^+ content in each treatment decreased when compared to related initial level.

Table 4 Effect of chemical fertilizer, poultry manure, and bentonite additions on soil ammonium (NH_4^+) content at 0-40 cm soil depth at 42 DAP

Treatments	NH_4^+ (mg/kg)				
	0-10 cm	10-15 cm	15-20 cm	20-30 cm	30-40 cm
T1: Control	3.67 ^{1/}	2.38	1.73	2.09	1.69
T2: Chemical fertilizer (CF)	3.78	2.44	2.07	1.76	1.50
T3: Poultry manure (PM)	3.46	2.55	1.81	1.75	2.00
T4: CF+PM	3.31	2.78	1.75	1.60	1.95
T5: Bentonite (BN)	3.12	2.22	1.78	2.13	2.06
T6: CF+BN	3.87	2.02	1.73	2.05	1.53
T7: PM+BN	3.18	2.93	2.04	1.96	2.04
T8: CF+PM+BN	3.26	2.56	2.19	2.07	2.14
F-test ($p \leq 0.05$)	ns ^{2/}	ns	ns	ns	ns
CV. (%)	18.52	22.32	20.69	23.67	24.27

^{1/} Means in each column followed by the same letter are not significantly different as determined by LSD

^{2/} ns is non-significant at $p \leq 0.05$

In contrast, NO_3^- content was significantly different ($p \leq 0.05$) among treatments at all soil depths (**Table 5**). The NO_3^- content from any PM-added treatments was found to be higher in all soil depths (0-40 cm) when compared with that of BN, CF, and the control. It was also found that topsoil treated with CF+BN and BN had higher NO_3^- content at 0-15 cm depth than that added with CF and the control.

At 30-40 cm soil depth, the results also showed higher NO_3^- content in CF+BN and BN treatments when compared to CF and control treatments. Furthermore, at the same depth the NO_3^- content was higher in PM+BN than the content in PM, and CF+PM+BN also had higher NO_3^- content than did CF+PM.

Table 5 Effect of chemical fertilizer, poultry manure, and bentonite additions on nitrate (NO_3^-) content at 0-40 cm soil depth at 42 DAP

Treatments	NO_3^- (mg/kg)				
	0-10 cm	10-15 cm	15-20 cm	20-30 cm	30-40 cm
T1: Control	2.15 c ^{1/}	2.09 c	1.70 c	1.87 c	1.70 c
T2: Chemical fertilizer (CF)	1.94 c	1.97 c	1.70 c	1.78 c	1.75 c
T3: Poultry manure (PM)	5.35 ab	5.48 a	3.07 b	3.37 b	3.15 b
T4: CF+PM	4.73 b	5.35 a	5.04 a	5.88 a	3.47 b
T5: Bentonite (BN)	3.14 b	3.97 b	1.84 c	1.92 c	3.22 b
T6: CF+BN	2.84 bc	3.49 b	1.58 c	1.66 c	3.10 b
T7: PM+BN	6.39 a	4.87 ab	3.42 ab	3.68 ab	5.09 ab
T8: CF+PM+BN	5.82 a	5.57 a	3.03 b	5.35 a	6.01 a
F-test ($p \leq 0.05$)	* ^{2/}	*	*	*	*
CV. (%)	25.20	30.92	35.53	25.42	26.56

^{1/} Means in each column followed by the same letter are not significantly different as determined by LSD

^{2/} *Significant at $p \leq 0.05$

Discussions

Soybean biomass (growth) and plant N uptake

From the result of this column study, sole addition of BN for 42 days (without any N source added) produced the lowest soybean biomass (shoot dry weight), plant N content and concentration among all treatments in this WA sandy soil. Therefore, the result was quite opposite to several reports that showed the benefits of BN addition in enhancing growth of many crops accompanied with increasing plant N content and concentration (Puttaso, 2003; Croker et al., 2004; Thongviang, 2016). In this experiment, small soybean plants treated with BN alone also showed sign of N deficiency with lowest plant N concentration (1.58%), much lower than the critical N concentration of 4.2% for deficiency (Reuter and Robinson, 1997).

Adding CF alone only slightly increase soybean growth over the control. However, soybean plants treated with chemical fertilizers still had much higher plant total N and concentration than the control. We assumed that the soybean plants might have limited growth by soil N loss. Loss of both N cation and anion by leaching in medium and long terms could be another possibility, supported by the report of Sittthaphanit et al. (2009) on high loss of both NH_4^+ and NO_3^- from similar kind of sandy soil without added BN in during 3 weeks after chemical fertilizers addition. Under PM (narrow C:N ratio) addition, soybean had the highest growth and plant N content among all treatments. The PM is known to be easier decomposed by microorganism than crop residues (Khalil et al., 2005) and capable of regularly releasing mineral nutrients for crop growth (Eneji et al., 2002).

Combinations among treatments gave soybean growth, plant total N and concentration at medium levels. Here are some interesting results.

Firstly, combining BN with either PM or CF lower all soybean growth, plant total N and concentration when compared to the related sole addition treatments. Such findings imply that BN itself could retard N uptake and growth of soybean in these combinations and the reason why BN retarding soybean growth in the combined additions would be explained later on. Secondly, combining PM (narrow C:N ratio) with CF gave medium soybean growth with rather low plant total N and lowest N concentration. Low N in plant, starting at early growth, is most likely due to N-immobilization. During this process, growing microorganisms in soil successfully compete with young plants for mineral nutrients uptake and could last for 4 weeks after amendment (Vityakon et al., 2000).

Nitrogen in the soils

To find whether N supply from the soils is sufficient to support crop growth or not, we have to analyze the capability of these soil additions to supply N and relate with some soil properties including soil organic matter, total N, NH_4^+ and NO_3^- . Based on %N and the amount applied, PM can supply most N to the soil for plant uptake, followed by CF and BN. The latter is surely insufficient according to its initial N (0.01%).

For soil parameters measured after 42 DAP, soil OM at top soil decreased with time from the original value at 1.07%, implying that OM decomposition could be another soil N supplying source for plant to take up. Most treatments had soil OM ranging from 0.86-0.96% at 42 DAP, except CF+PM+BN that had the lowest amount (0.77%). This latter treatment result might imply having highest population of microorganism decomposing soil OM. Firstly, CF provides mineral nutrients for early activity of microorganism, then easily decomposed PM to provide food for increasing microorganism population and at the

same time it would be suggested the BN might accelerate closed-attraction between local OM and microorganisms that promote the N-mineralization. More than 85% of N mineralized comes from fine fraction in the clays and only 50% of this N comes from larger fraction in sandy soils (Blanchart et al., 2005).

For other related soil N parameters, there were no significant differences in total soil N and NH_4^+ among all treatments but not NO_3^- , the end product of mineralization. Both PM and BN treatments had the top soils (0-10 cm and 10-15 cm. depth) with significantly higher soil NO_3^- than other treatments resulting in all combined PM with BN treatments also having higher NO_3^- than that of other treatments. For supporting evidence, Sitthaphanit et al. (2010) also found high soil NO_3^- in non-plant soil treated with BN at 0-15 cm depth of soil column. In addition, soil NO_3^- from BN-added treatments was found to accumulate at 30-40 cm soil depth presumably due to BN structure with ample micro pores slowing the movement of NO_3^- down the soil profile (Berthelsen et al., 2007).

Relationships between soil N and soybean plant growth

In contrast to the results of previous field experiments on BN addition to other field crops, soybean grown in this column study under BN solely or combined treatments showed poor growth. It was found later, at harvesting (42 DAP), that unexpected limiting growth factor for soybean grown in BN-added treatments was soil clogging due to fine powder of BN blocking water flow through soil pores. Roots of growing soybean could not penetrate through soil peds of soil in the column they then extend down mostly along the inner side wall of the column. By observation, the roots of soybean grown in BN based treatments were much smaller and shorter than

soybean in other treatments and therefore the former might perform less nutrient uptake.

Soil compaction did not occur in the previously mentioned field experiments as BN applied was in coarser form than the BN used in this column study (Thongviang, 2016). Therefore, soybean plants never show root growth restriction in any BN treated field plots (Thongviang, 2016).

Conclusion

From this column experiment, BN alone or based amendments did not increase soil OM, N contents and related crop growth when compared to the previous findings in fields and pots. In contrast, all PM based treatments increased both soil N and soybean growth. However, we could identify increasing mostly in soil NO_3^- from sole BN or combined treatments at 0-15 cm depth. But at harvesting, it was found soil clogging caused by added fine powder BN could be the main crop growth limiting factor in this column study.

Acknowledgments

The research reported here was funded by the Royal Golden Jubilee (RGJ) Ph.D. Program and the Senior Research Scholar Project of Prof. Dr. Aran Patanothai under the Thailand Research Fund (TRF), Thailand.

References

- Berthelsen, S., A.D. Noble, S. Ruaysoongnern, H. Huan, and J. Yi. 2007. Addition of clay based ameliorants to light-textured soils to reduce nutrient loss and increase crop productivity, pp. 373-382. Management of tropical sandy soils for sustainable development. In: Proceedings of the International Conference on the Management of Tropical Sandy soils, Khon Kaen, Thailand (on November 2005). FAO Regional Office for Asia and Pacific, Bangkok, Thailand.

- Black, C.A. 1965. Methods of soil analysis. American Society of Agronomy, Madison (Eds.), Wisconsin, USA.
- Blanchart, E., A. Albrecht, M. Bernoux, J.L. Chotte, C. Feller, F. Ganry, E. Hien, R. Manlay, D. Masse, S. Sall, and C. Villenave. 2005. Organic matter and biofunctioning in implications for its management. In: 1st International Symposium on the Management of Tropical Sandy Soils for Sustainable Agriculture "A holistic approach for sustainable development of problem soils in the tropic". Khon Kaen, Thailand. November 27th - December 2nd 2005.
- Bray, R.H., and L.T. Kurtz. 1945. Determination of total organic available form of phosphorus in soil. *Soil Sci.* 59: 39-45.
- Crocker, J., R. Poss, C. Hartmann, and S. Bhuthorntharaj. 2004. Effects of recycled bentonite addition on soil properties, plant growth and nutrient uptake in a tropical sandy soil. *Plant and Soil.* 267(1-2): 155-163.
- Eneji, A.E., T. Honna, S. Yamamoto, T. Saito, and T. Masuda. 2002. Nitrogen transformation in four Japanese soils following manure plus urea amendment. *Comm. in Soil Sci. and Plant Anal.* 33: 53-66.
- FAO. 1983. Guidelines for the control of soil degradation. Rome, Italy: United Nations Environment Program and FAO.
- Gate, W.P., J.S. Anderson, M.D. Raven, and G.J. Churchman. 2002. Mineralogy of a bentonite from Miles, Queensland, Australia and characteristics of its acid activation products. *Appl. Clay Sci.* 20(4-5): 189-197.
- Khalil, M.I., M.B. Hossain, and U. Schmidhalter. 2005. Carbon and nitrogen mineralization in different upland soils of the subtropics treated with organic materials. *Soil Bio. and Biochem.* 37(8): 1507-1518.
- Mekuria, W., A. Noble, O. Sengtaheuanghoung, C.T. Hoanh, D. Bossio, N. Sipaseuth, M. Cartney, and S. Langan. 2014. Organic and clay-based soil amendments increase maize yield, total nutrient uptake, and soil properties in Lao PDR. *Agro-eco. and Sustain. Food Syst.* 38: 936-961.
- Noble, A.D., G.P. Gillman, S. Nath, and R.J. Srivastava. 2001. Changes in the surface charge characteristics of degraded soils in tropics through the addition of beneficiated bentonite. *Aust. J of Soil Res.* 39: 991-1001.
- Noble, A.D., S. Ruaysoongnern, F.W.T. Penning de Vries, C. Hartmann, and M.J. Webb. 2004. Enhancing the agronomic productivity of degraded soils in Northeast Thailand through Clay-base Interventions, pp. 147-160. In: V. Seng, E. Craswell, S. Fukai, and K. Fischer, Water and Agriculture, ACIAR Proceeding No.116.
- Panpruek, P., K. Paisanchoen, A. Nunthakhid, and T. Kaewkongka. 2007. Effect of compost, chemical fertilizer and lime for soybean production in Satuk soil series. *Thai J of Soil and Fert.* 29: 145-152. (in Thai).
- Peech, M. 1945. Determination of exchangeable cations and exchange capacity of soils: rapid micro method utilizing centrifuge and spectrophotometer. *Soil Sci.* 59: 25-48.
- Puttaso, A. 2003. Effect of clay materials, soil amendment substances and compost on improvement of degraded sandy soil. M.Sc. Thesis, Department of Soil Science, Faculty of Agriculture, Khon Kaen University, Khon Kaen, Thailand. (in Thai).
- Rattanasat, S. 1999. Research summary in soil and fertilizer for soybean. Research report of soybean, pp. 86-96. Department of Agriculture, Thailand. (in Thai).
- Reuter, D.J., and J.B. Robinson. 1997. Plant analysis: An interpretation manual. CSIRO (2nd eds.), Melbourne and Sydney, Australia.
- Sithaphanit, S., R.W. Bell, and V. Limpinuntana. 2010. Effect of clay amendments on nitrogen leaching and forms in sandy soil. In: 19th World Congress of Soil Science, Soil Solutions for a Changing World, 1-6 August 2010, Brisbane, Australia. Published on DVD.
- Sithaphanit, S., V. Limpinuntana, B. Toomsan, S. Panchaban, and R.W. Bell. 2009. Fertilizer strategies for improved nutrient use efficiency on sandy soils in high rainfall regimes. *Nutr. Cycl. in Agroeco.* 85:123-139.
- Tangkoonboribun, R. 2006. Effects of organic and clay material amendments on sugarcane production in a degraded sandy soil of Northeast Thailand. Ph.D. Thesis, Department of Soil Science, Faculty of Agriculture, Khon Kaen University, Khon Kaen, Thailand.
- Thongviang, V. 2016. Effects of bentonite clay and soil amendments on soybean growth and yield in a degraded-sandy soil of Northeast Thailand. Ph.D. Thesis (Agronomy), Department of Plant Science and Agricultural Resources, Faculty of Agriculture, Khon Kaen University, Khon Kaen, Thailand.
- Vityakon, P., S. Meepech, G. Cadisch, and B. Toomsan. 2000. Soil organic matter and nitrogen transformation mediated by plant residues of different quality in sandy acid upland and paddy soils. *Neth. J of Agri. Sci.* 48: 75-90.