Pol. J. Environ. Stud. Vol. 22, No. 6 (2013), 1669-1676

Original Research

Effects of Bentonite on Sandy Soil Chemistry in a Long-Term Plot Experiment (II); Effect on pH, CEC, and Macro- and Micronutrients

Janusz Czaban[1]*, Grzegorz Siebielec[2]

[1]Agricultural Microbiology Department,
[2]Department of Soil Science, Erosion, and Land Protection
Institute of Soil Science and Plant Cultivation – State Research Institute,
Czartoryskich 8, 24-100 Puławy, Poland

Received: 23 April 2013
Accepted: 25 September 2013

Abstract

Microplots (0.8 m^2) were filled with a subsoil of a very poor, acidic sandy soil. This soil was enriched with bentonite (BNT) at rates of 0, 3, 6, and 12 kg/m^2. For 30 years the microplots were planted with different crops and regularly enriched with mineral and organic fertilizers. For the next eight years the microplots were left barren. After that time, the soils with added BNT had higher pH and content of available Mg than the control soil (CS) in the whole studied 5-80 cm soil profile. The soil with the highest dose of added BNT contained more total Ca, Mg, Zn, and Mn, as well as available P and K in 5-30 cm layer than the other soils. Furthermore, in comparison to CS, the soil with 12 kg/m^2 of BNT had higher cation exchange capacity (CEC).

Keywords: bentonite, soil pH, CEC, macronutrients, micronutrients

Introduction

The low content of clay in sandy soils usually limits humus accumulation, nutrients, and water availability as well as buffering capacity, which is a reason that many of these soils become acidified. Low crop yields from sandy soils are due, *inter alia*, also to easy and intensive leaching of fertilized-supplied nutrients from the upper soil horizon into deeper soil layers. These, for instance, cause light soils to be inherently deficient in micronutrients [1-6].

It has been found that the addition of an adequate amount of clay substance to a sandy soil can greatly improve its agricultural value. A relative comparison of kaolinite, illite, and montmorillonite has revealed that the latter clay mineral was most efficient with regard to nutrient retention in soil [6]. Bentonite – a rock containing mainly montmorillonite (a smectite group clay mineral) – has been recognized in many countries as a very good material to improve the properties of such infertile sandy soils [6-16]. However, all of these studies were of short-term character. Therefore, it was difficult to evaluate how permanent would be the improvement of fertility and buffering capacity of sandy soils by bentonite addition.

Such evaluation can be taken from a 38-year microplot experiment with a poor acidic sandy soil enriched with bentonite (BNT), conducted at the Institute of Soil Science and Plant Cultivation in Puławy, in eastern Poland (51º 24’ N, 21º 57” E).

The purpose of the study was to investigate whether the BNT addition to the sandy soil affects its chemical properties after such a long time. The present paper is the second part of a two-paper set on the effect of BNT on soil chemical properties. The first part describes the effect of BNT on accumulation of organic C (OC) and total nitrogen (ToN) in

*e-mail: czaban@iung.pulawy.pl

the soils, as well as on distribution of OC in humic fractions [17]. The present part concerns the influence of BNT on soil pH, CEC, and contents of various nutrients – both total and available.

Experimental Procedures

Experimental design and history of the plots are presented in part I of the two-paper set [17].

Soil Sampling

Soils were sampled in May 2009 from layers 5-30, 30-55, and 55-80 cm with the use of a soil auger (1 m long). CEC was determined only in the soil layers of 5-30 and 30-55 cm, sampled with a sampling stick (0.7 m long) in June 2010 from series amended with 0 kg/m^2 and 12 kg/m^2 of BNT. The uppermost layer 0-5 cm of the soils was removed before sampling because of intensive and irregular growth of algae on the surface, which would hamper the analysis of various soil parameters. The samples were placed in airtight containers for transport to the laboratory. At the laboratory the samples were stored at 4ºC in hermetically sealed containers until required. Then they were sieved (<2 mm) and homogenized. For determining the total contents of macro- and micro-elements the soil samples were air dried.

Soil Analyses

Soil pH was measured with a glass electrode in a slurry made by mixing 10 g of soil and 25 cm^3 of deionized water (active acidity) or 1 M KCl (exchangeable acidity).

Cation exchange capacity (CEC) of a soil at its real pH was determined by modified Gillman's method using a barium chloride solution, according to Polish Standard PN-ISO 11260:1999.

The total contents of calcium (ToCa), magnesium (ToMg), zinc (ToZn), manganese (ToMn), and iron (ToFe) in the soil samples were determined by atomic absorption spectroscopy, and the total contents of potassium (ToK) by atomic emission spectroscopy, after the hot digestion of soil samples with aqua-regia (according to McGrath and Cunliffe) [18].

The contents of available forms of phosphorus (AvP) and potassium (AvK) were determined by Egner-Riehm's method (extraction with lactic acid buffered with calcium lactate to pH 3.55), whereas available magnesium (AvMg) by Schachtschabel's method (extraction with 0.0125 M $CaCl_2$) [19].

All the mentioned soil variables were determined in three replicates. All data were based on dry weight of the soils.

Additionally, annual mean values of soil pH(H_2O) in 0-30 cm soil layers, determined during a period 1973-85 and 1990, are presented. In the 1991-2008 period this parameter was not measured. The other variables listed in this section were not determined during the period 1973-2008.

Statistical Analysis

For statistical evaluation, the obtained results were subjected to one-way analysis of variance (at $P = 0.05$) and the means were separated with Tukey's HSD test (with $P = 0.05$ level of significance). In the figures, the data presented as columns or as the numbers presented inside the legends marked with the same letters are not significantly different.

For estimation of the various relationships between the variables discussed in the present paper (Part II) and between these variables in Part II and the contents of OC, ToN, and texture (which were presented in Paper I [17]), the simple Pearson's correlation analysis was used. Together with correlation coefficients (r), level of probability (P) and number of data pairs (n) are presented in the text.

Results and Discussion

Soil pH

The initial pH of the control soil (CS) after enrichment with the mineral fertilizers in July 1973 was 5.9. At that time, an amendment of the soil with BNT (containing almost 5% of Ca and Mg and 1% of Na and K in forms soluble in 10% HCl [17], which were more readily dissolvable minerals, e.g. carbonates, as well as these elements bound in the interlayer space or the surface of clay minerals [20, 21]) shifted soil pH to 8.3, 8.7, and 8.9 for 3, 6, and 12 kg/m^2 of the BNT rates, respectively. During the 17-year period (1974-1990), pH of the bentonite soils (BNTSs) was decreasing more rapidly until 1977, and more slowly since 1978, to 6.6, 6.8, and 7.1 in 1990, for soils enriched with 3, 6, and 12 kg/m^2 of BNT, respectively (Fig 1A). Only temporary increases in pH were observed in some years, e.g. after fertilizing the soils with farmyard manure in 1975, 1983, and 1990. Since 1975, pH of CS was maintained at approximately 6.5 by occasional $CaCO_3$ fertilization. Therefore, the differences in pH between BNTSs (where base substances originated from BNT were subjected to leaching downward soil profiles) and CS were gradually diminishing (Fig. 1A). In the subsequent period of 1991-2002, when the soils were regularly cultivated, pH of the soils was not measured.

Since 2003 the plots were left fallow with no fertilization and with removal of weeds. The bare fallowing (2003-09) caused distinct acidification of the upper soil layers compared to the period 1975-1990 (Figs. 1A, 1B). Dzienia et al. [22] and Sienkiewicz et al. [23] also reported a distinct soil pH decrease under the influence of 5- and 6-year fallowing.

In 2009 pH of the upper layers of the soils was very low, on the level of most acidified Polish soils in 2010, measured in 0-20 cm horizons [24]. In these soil layers the differences in pH between the treatments were very small, and only pH of the soil with the highest BNT rate (12-BNTS), both determined in H_2O and KCl, differed significantly from those of CS and a soil with 3 kg/m^2 BNT rate (3-BNTS). Soil pH increased significantly with raising soil depth, especially for BNTSs, therefore the differences in pH (both measured in H_2O and KCl) between CS and BNTSs significantly raised with the increase of soil depth and the BNT dose (Fig.1B). It shows that greater amounts of soluble base substances accumulated in deeper soil layers of BNTSs than in those of CS.

Total Contents of Macro- and Micro-Elements and CEC

Total Ca (ToCa) and total Mg (ToMg) – important metals for soil properties and plant nutrition [21] – were present in BNT at the beginning of the experiment in significant amounts [17]. As Fig. 2 shows, after the long period of destructive bare fallowing the contents of ToCa (228-558 mg/kg) and ToMg (132-205 mg/kg) in the upper soil layers was on the lowest levels of the ranges of these variables in Polish soils in 2010 [24]. Within the whole soil horizon (5-80 cm), ToCa content increased with increasing BNT rate,

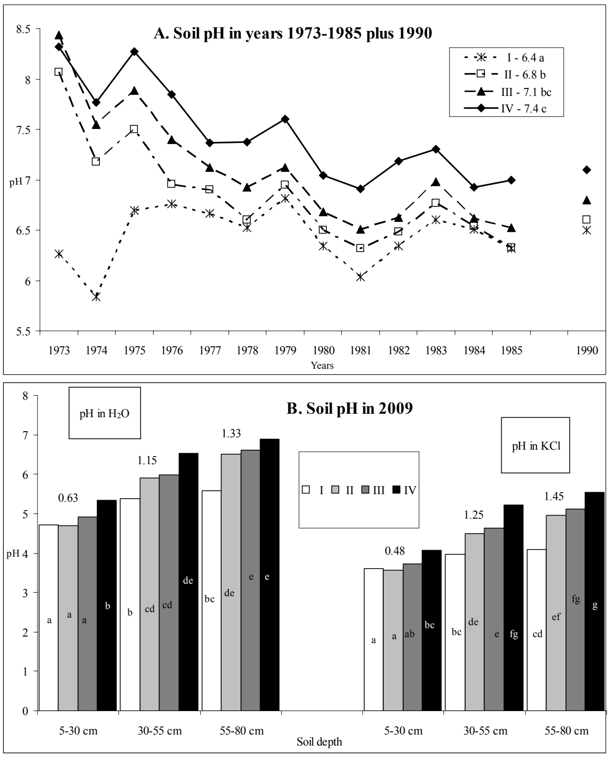

Fig. 1. Effect of the sandy soil amendment with 0 kg/m² (I), 3 kg/m² (II), 6 kg/m² (III), and 12 kg/m² (IV) of BNT on pH (both in H_2O and KCl) of the soils.

(A) Annual means of soil $pH_{[H_2O]}$ in the 0-30 cm soil layers during the period 1973-85 plus 1990. Inside the legend the means of soil pH for the whole presented period are placed. Means marked with different letters are statistically different at P = 0.05;

(B) Active (pH in H_2O) and exchangeable (pH in KCl) acidities of the soils in 5-30 cm, 30-55 cm, and 55-80 cm layers. Above the bars the differences in pH units between 12-BNTS and CS are presented; Different letters on the bars indicate significant differences between the treatments at P = 0.05.

I – the control soil without BNT added; II , III, and IV – soils with the addition of 3, 6, and 12 kg/m² of BNT, respectively.

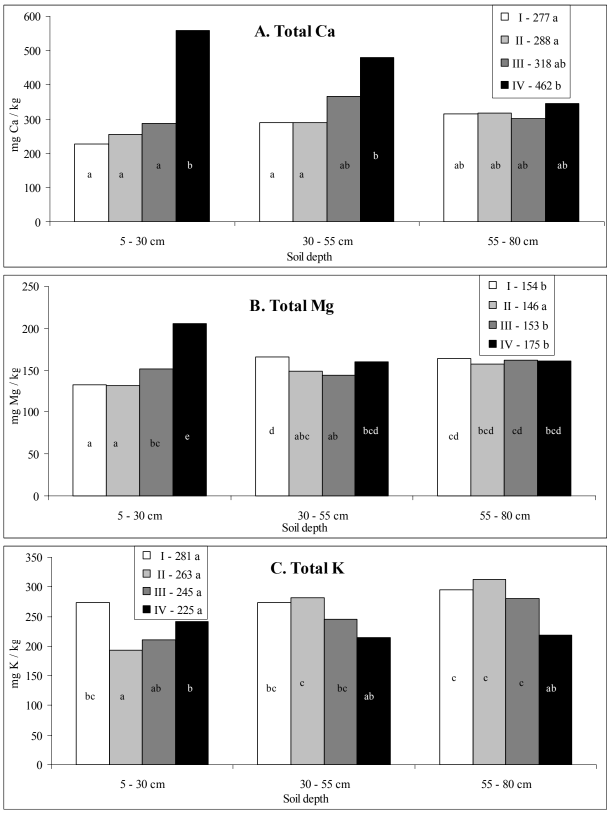

Fig. 2. Effect of the sandy soil amendment with 0 kg/m² (I), 3 kg/m² (II), 6 kg/m² (III), and 12 kg/m² (IV) of BNT on total contents of Ca (A), Mg (B), and K (C) in 5-30 cm, 30-55 cm, and 55-80 cm soil layers and, presented inside the legends (in mg/kg), the means for the whole 5-80 cm soil profiles. Different letters on the bars or placed in the legends indicate significant differences between the treatments at P = 0.05.

I – the control soil without BNT added; II , III, and IV – soils with addition of 3, 6, and 12 kg/m² of BNT, respectively.

achieving about 70% greater contents in 12-BNTS than that of CS. The differences between 12-BNTS and CS were the highest (145%) in the upper soil layer, moderate in the 30-55 cm layer (66%) and the least significant in the deepest layer (10%). In comparison, the soil amendment with BNT increased (up to 55%) the total Mg (ToMg) content only in the upper layer (Figs. 2A, 2B).

In CS and 3-BNTS the contents of both elements were higher in the deeper layers than those in the upper layer, contrary to 12-BNTS, where the contents of both metals were lower in deeper soil layers (Figs. 2A, 2B). When we take into consideration the results of all treatments, the total contents of both metals were significantly positively correlated (at $P < 0.01$, n = 48, results from all soil layers) with contents of finer soil particles, which originated from BNT [see Part I, 17]: ToCa with soil particles < 0.1 mm [PRT < 0.1] (r = 0.40) and ToMg with PRT < 0.05 (r = 0.38). For the individual experimental series the correlation coefficients (ToCa with PRT < 0.1 and ToMg with PRT < 0.05) gradually changed from negative in the case of CS (r = -0.12, -0.17, n = 12 for ToCa and ToMg, respectively) to significantly positive (r = 0.51 at P < 0.1 and 0.82 at $P < 0.01$ n = 12) for 12-BNTS. Also, only in the case of 12-BNTS was ToMg correlated with OC (r = 0.78 at $P < 0.01$, n = 12). Such gradual strengthening of the correlations from CS to the soil with the highest BNT rate prove that ToCa and ToMg in BNTSs were mainly connected with fractions originating from BNT. Contrary to this, the contents of both metals were significantly (at $P < 0.01$) strongly positively correlated with soil pH only in the case of CS (r = 0.80 and 0.71 for ToCa and ToMg, respectively, n = 12), but for all 48 experimental series no correlation between pH and contents of ToCa and ToMg (r = 0.24 and 0.19) was found. The following significant (at $P < 0.05$, n = 48) correlations (r = 0.37 and r = 0.32) suggest that ToCa was present mainly in BNTSs in the smallest sand fraction (PRT = 0.05-0.1, that partially migrated into 30-55 cm layer [Part I, 17]) and clay (PRT < 0.002), whereas ToMg occurred mostly in silt (r = 0.33) and clay (r = 0.37), the particle fractions localized predominantly in the upper layer.

The total content of K (ToK) – a major plant nutrient present in fairly significant amounts in BNT introduced into the soils [17, 21] – in the studied soils in the upper layer (194-274 mg/kg) was on the lowest level of the range for Polish soils in 2010 [24]. ToK in all the soil profiles (5-80 cm) gradually decreased with increasing bentonite dose (Fig. 2C) and it was positively correlated with the main particle fraction of CS – the sand fraction 0.5-0.1 mm (r = 0.57 at P < 0.01, n = 48) and negatively correlated with PRT < 0.1 (r = -0.54 at P < 0.01, n = 48) originating from BNT [17]. This suggests that ToK was mainly a component of minerals originating from the basic soil [see Part I, 17], and ToK present in BNT at the beginning of the experiment was taken up by plants and/or leached out from the soils.

Contents of total Zn (ToZn), total Mn (ToMn), and total Fe (ToFe) were studied because they were presented in the literature data as the main trace nutrients of various animal and green manures [25-29]. In the present microplot experiment, organic fertilizers were systematically introduced into soils during plant cropping [17]. It should enrich the upper layer of the soils in these micronutrients (from the external source as animal manure and from the deeper soil layers as green manure). Therefore, the role of BNT in accumulation of these micronutrients, which are related to each other in soils [21, 30, 31], was interesting.

ToZn (65-140 mg/kg) and ToMn (23-34 mg/kg) in the upper layer of CS, 3-BNTS and 6-BNTS were on the mean level, and that of 12-BNTS on the high level characteristic for uncontaminated Polish soils [24]. Strong correlations (at P < 0.01, n = 48) with contents of OC (r = 0.89), ToN (r = 0.89), and PRT < 0.05 (r = 0.77) suggest that ToZn was mainly bound with the organo-mineral complexes built on the structure of fine particles originating from BNT. Although the contents of ToZn in the whole soil profiles (5-80 cm) were on similar levels for CS and BNTSs, the proportions of this trace metals in the upper soil layer were distinctly higher in the case of BNTSs (64, 66 and 82% for 3, 6, and 12 kg/m² BNT dose, respectively) than those for CS (49%) (Fig. 3A). Limited leaching of zinc, both natural and introduced with fertilizers, in such a BNT soil system is important due to frequent Zn deficiency in plants grown on sandy soils [32].

Total Mn (ToMn) was on the lowest level recorded for Polish agricultural soils in 2010 [24]. It shows a similar pattern to that of ToZn. The contents of ToMn in the whole soil profiles were similar in all experimental series, but the proportions in the upper soil layers were highest for the soils with two highest BNT rates (46 and 48% in comparison to 29 and 32% in CS and 3-BNTS) (Fig. 3B). The content of ToMn also was correlated with contents of OC, ToN and PRT < 0.05 (r = 0.47, 0.45, and 0.54 at $P < 0.01$, n = 48), but the correlations were not as strong as those for ToZn. Likely in the case of BNTSs, Zn and Mn originating from farmyard manure, mineral fertilizers, and partly from BNT were concentrated in the upper soil layer through plant biomass mixed with topsoil. De Vries et al. [33], Graber et al. [34], and Dortzbach et al. [35] reported on accumulation of Zn and Mn in the upper layers of soils fertilized with animal manures. They stressed the positive impact of OM, clay, and higher pH on the accumulation of the metals in the upper soil layers. The soil's ability to retain trace metals is attributed to CEC and the specific surface area. The CEC of a soil depends upon its OM content and clay type and content. The type and quantity of clay also determines the specific surface. It increases with clay content, particularly when the clay contains a high proportion of 2:1 lattice-type minerals, e.g., montmorillonite – a main

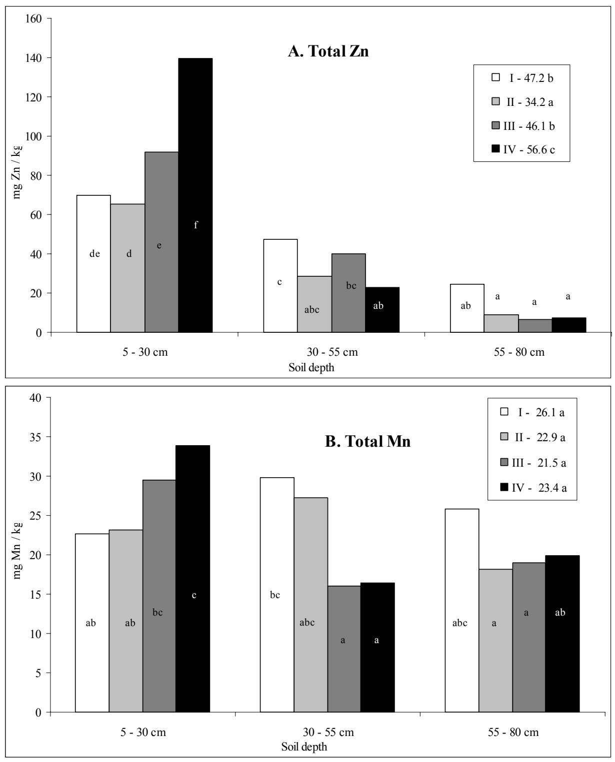

Fig. 3. Effect of the sandy soil amendment with 0 kg/m² (I), 3 kg/m² (II), 6 kg/m² (III), and 12 kg/m² (IV) of BNT on total contents of Zn (A) and Mn (B) in 5-30 cm, 30-55 cm, and 55-80 cm soil layers and, presented inside the legends, the means (in mg/kg) for the whole 5-80 cm soil profile; Different letters on the bars or placed in the legends indicate significant differences between the treatments at P = 0.05.
I – the control soil without BNT added; II , III, and IV – soils with the addition of 3, 6, and 12 kg/m² of BNT, respectively.

constituent of bentonite [30, 31]. Many authors have reported high potential of bentonites for sorption and retention of various metals, including Zn, from aqueous solutions [36-39]. Soil OM is known to be capable of binding Zn in stable forms, therefore a high proportion of Zn can be linked to OM in mineral soils [30].

Total content of Fe (ToFe) in the upper soil layer (1.91-2.10 g/kg) was on minimal level measured for Polish soils in 2010 [24]. The amendment of the soils with BNT did not have any significant effect on the content of ToFe. ToFe was slightly (significant at $P < 0.05$) higher (by approximately 10%) in the upper soil layer than in the other ones (results of ToFe content in various studied soil layers varying from 1.76 to 2.10 g/kg are not presented). Some part of the metal was probably bound to organo-mineral complexes of the soils because it was significantly correlated (at $P < 0.01$, n = 48) with OC (r = 0.58), ToN (r = 0.53) and PRT < 0.05 (r = 0.43). Kabata-Pendias [30] reported that Fe in soils occurs mainly in the forms of oxides and hydroxides, but in horizons rich in OM, Fe appears mainly in chelated forms.

ToZn and ToMn were significantly correlated (at $P < 0.01$, n = 48) with ToFe (r = 0.59 and 0.56 for Zn and Mn, respectively) and they were inter-correlated (r = 0.58). When the individual soil layers were evaluated, the correlations between OC and ToZn and ToMn occurred only in the upper soil layer (r = 0.82 and 0.84 at $P < 0.01$, n = 16). However, the correlations between contents of both metals and ToFe occurred only in the deepest soil layer (r = 0.51 at $P < 0.05$ and r = 0.68 at $P < 0.01$, n = 16 for ToZn and ToMn, respectively). Presumably, Mn and Fe occur in the deepest soil layer as oxides that have a high sorption capacity to bind Zn [30].

When inter-correlation between ToZn and ToMn and correlations between contents of these metals and OC, ToN, or PRT < 0.05 for the individual treatments were taken into consideration, the correlation coefficients usually distinctly rise with increasing BNT doses: between ToZn and ToMn 0.18, 0.22, 0.68, and 0.82 for 0, 3, 6 and 12 kg/m^2 BNT rates, respectively; between ToZn and OC: 0.83, 0.89, 0.94, and 0.96; between ToZn and ToN: 0.74; 0.78, 0.89, and 0.96; between ToZn and PRT < 0.05: 0.41, 0.69, 0.93, and 0.95; between ToMn and OC: -0.22, 0.10, 0.73, and 0.89; between ToMn and ToN: -0.11, 0.13, 0.69, and 0.76; between ToMn and PRT < 0.05: 0.43, 0.34, 0.67, 0.86. Such gradual strengthening of these relationships from CS to the soil with the highest BNT rate prove that BNT was a major factor responsible for the increase of silt and clay fractions, accumulation of OC and ToN onto the structures of these fine soil particles [17], and binding of the metals to the developed organo-mineral complexes.

The obtained results revealed that a combination of soil amendment with bentonite and agronomy factors (fertilization with organic and mineral substances, crop rotation) can serve as an effective measure enhancing contents of micronutrients (Zn, Mn) in sandy soils that are usually deficient in these elements due to soil pedogenesis and/or climatic conditions (water movement down in a soil profile) [6, 30, 32].

The total negative charge on soil, called the cation exchange capacity (CEC), is a good measure of soil ability to retain and supply nutrients to crops. CEC is the total amount of exchangeable cations that can be held by the soil is a general indicator of soil fertility. CEC is higher in soils with high amounts of clay and OM, and is lower in acidic soils [40]. CEC of the soil with a 12 kg/m^2 BNT rate, containing significantly more fine particles and OM than CS [17] as well having higher pH, was more than 70% larger than that of CS in both studied soil layers (Fig. 4). Other authors also found that application of bentonite into sandy soils significantly increased CEC of the soils [1, 13, 16, 41].

Contents of Available Mg, K, and P

The effects of BNT on the contents of soil-available phosphorus (AvP), potassium (AvK), and magnesium (AvMg) were studied because these variables were determined by many authors as very important parameters to estimate the soil pool of nutrients and optimize plant nutrition in terms of plant yield and crop quality [42-45].

The contents of AvMg (6-24 mg/kg) in the upper soil layers were on a low level of the range observed for Polish soils in 2010 [24]. AvMg content significantly and gradually increased with increasing soil depth and the BNT rate. In comparison to the other experimental series, the contents of AvMg in all soil layers were especially high in the soil enriched with the highest BNT rate (Fig. 5A). AvMg took a more significant share of ToMg in BNTSs (6-14% in soils with two lower BNT doses and 12-22% in 12-BNTS) than in CS (4.5-8%), and the proportion of AvMg in ToMg gradually increased with increasing soil depth in the case of all treatments. AvMg was significantly correlated (at $P < 0.01$, n = 48) with soil pH (r = 0.75 for pH both in H_2O and KCl). A larger part of AvMg in the 5-80 cm soil profile remained in the upper soil layer in the case of 12-BNTS (28.5%) than in the other soils (18.6-21.1%). All of these suggest that in comparison to the other treatments, 12-BNTS, containing

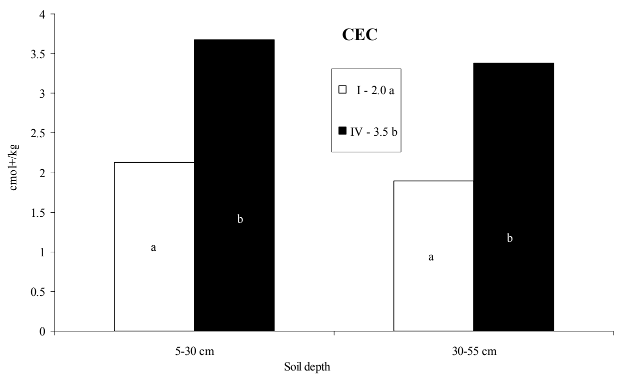

Fig. 4. Effect of the sandy soil amendment with 0 kg/m^2 (I) and 12 kg/m^2 (IV) of the bentonite on CEC in 5-30 cm and 30-55 cm soil layers and, presented inside the legend, the means (in cmol+/kg) for the whole 5-55 cm soil profile in 2010.
Different letters on the bars or placed in the legends indicate significant differences between the treatments at P = 0.05.
I – the control soil without BNT added and IV – soil with addition of 12 kg/m^2 of BNT, respectively.

more silt and clay, had stronger capability to bind AvMg in the upper layer. Siebielec et al. [24] also reported higher availability of Mg in soils with higher content of PRT ≤ 0.02.

The contents of AvK (34-73 mg K_2O/kg) in the upper soil layers were on rather the low level of the range for Polish soils in 2010 [24]. It had a tendency to increase with increasing soil depth. The differences between treatments in separate soil layers were not statistically significant at $P < 0.05$, excluding the value of 12-BNTS in the upper layer that was significantly higher than those of the other soils (Fig. 5B). 12-BNTS was also distinguishable from other soils by the highest proportion of AvK in the ToK pool (22-30% in comparison to 13-21%) throughout the whole soil profile. AvK was positively correlated (at $P < 0.01$, n = 48) with soil pH(H_2O), pH(KCl), and ToK (r = 0.56, 0.51, and 0.39, respectively).

The contents of AvP (114-161 mg P_2O_5/kg) in the upper soil layers measured in the present study were on the mean level observed for Polish soils in 2010 [24]. Significant correlations (at $P < 0.01$, n = 48) of AvP with OC (r = 0.70), ToN (r = 0.60), ToZn (r = 0.73), and PRT < 0.05 (r = 0.65) and its distribution in the soil profile (mainly in the upper soil layer) suggest that AvP was mainly connected with organo-mineral complexes of the soils. No clear influence of BNT on AvP was observed (Fig. 5C).

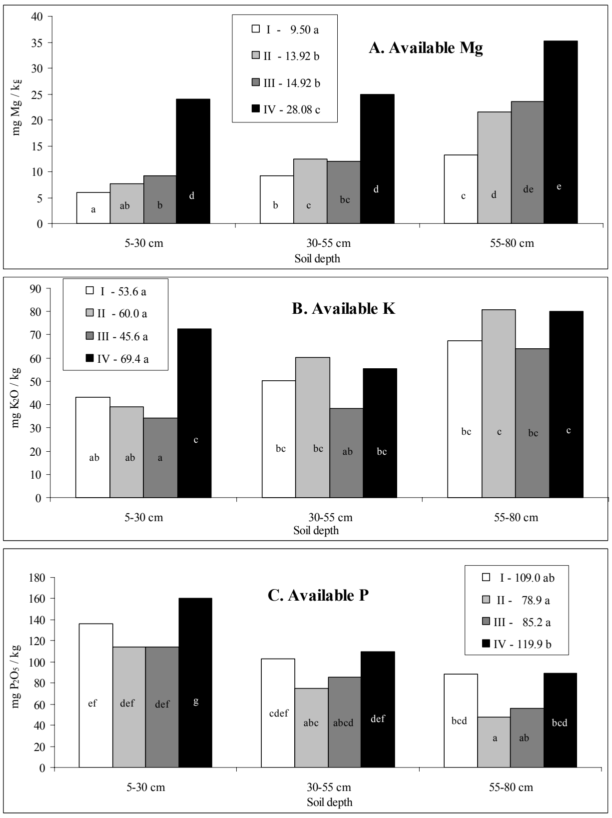

Fig. 5. Effect of the sandy soil amendment with 0 kg/m^2 (I), 3 kg/m^2 (II), 6 kg/m^2 (III) and 12 kg/m^2 (IV) of BNT on contents of available form of Mg (A), K (B), and P (C) in 5-30 cm, 30-55 cm, and 55-80 cm soil layers and, presented inside the legends, the means (in mg/kg) for the whole 5-80 cm soil profile. Different letters on the bars or placed in the legends indicate significant differences between the treatments at $P = 0.05$.
I – the control soil without BNT added; II , III, and IV – soils with addition of 3, 6, and 12 kg/m^2 of BNT, respectively.

From the other studies, Wyszkowski and Sivitskaya [46] have reported that bentonite addition into soil contaminated with fuel oil caused a large increase in the contents of available forms of Mg, K, and P.

Conclusions

The amendment of the sandy soil with bentonite (especially with its higher dose), containing substantial amounts of soluble in 10% HCl forms of Ca, Mg, Na, and K significantly reduced acidification of the soil during both the periods of plant cultivation and long-term fallowing.

The soil with the highest dose of the bentonite was characterized by significantly higher cation exchange capacity than the control soil, due to the formation of stable organo-mineral complexes on the structure of the fine bentonite mineral particles and higher pH. This soil, in comparison to all other treatments, strongly bound various elements in the upper layer, significantly enriching this horizon in total Ca, Mg, Zn, and Mn, as well as in available Mg, K, and P. The results confirm the potential effectiveness of bentonite addition in improving fertility of sandy soils.

Abbreviations

BNT – the bentonite used in the experiment; CS – the control soil without BNT added; BNTS and BNTSs – a soil or soils containing BNT; 3-BNTS, 6-BNTS and 12-BNTS – soils with addition of 3, 6 and 12 kg/m^2 of BNT, respectively; CEC - cation exchange capacity; PRT < 0.1 or PRT < 0.02 – soil particles with diameters < 0.1 mm or < 0.02 mm, respectively; OC – organic carbon; ToN – total nitrogen; ToCa – total calcium; ToMg – total magnesium; ToK – total potassium; ToZn – total zinc; ToMn – total manganese; ToFe – total iron; AvMg – available magnesium; AvK – available potassium; AvP – available phosphorus.

Acknowledgements

This paper was financed by 7FP project CATCH-C (Compatibility of Agricultural Management Practices and Types of Farming in the EU to enhance Climate Change Mitigation and Soil Health) No. 289782.

References

1. CROKER J., POSS R., HARTMANN C., BHUTHORNDHARAJ S. Effects of recycled bentonite addition on soil properties, plant growth and nutrient uptake in a tropical sandy soil. Plant Soil, **267**, 155, **2004**.
2. FILIPEK T. Natural and anthropogenic causes and effects of soil acidification. Nawozy i Nawożenie - Fertilizers and Fertilization, **3**, 5, **2001** [In Polish].

3. FOTYMA M., PIETRUCH C. The actual status of soil reaction and demand for limestone in Poland. Nawozy i Nawożenie - Fertilizers and Fertilization, **3**, 27, **2001** [In Polish].
4. KÁTAI J., TÁLLAI M., SÁNDOR ZS., OLÁH ZSUPOSNÉ Á. Effect of bentonite and zeolite on some characteristics of acidic sandy soil and on the biomass of a test plant. Agrokém. Talajtan, **59**, 165, **2010**.
5. NOBLE A.D., GILLMAN G.P., RUAYSOONGNERN S. A cation exchange index for assessing degradation of acid soil by further acidification under permanent agriculture in the tropics. Eur. J. Soil Sci., **51**, 233, **2000**.
6. LHOTSKÝ J., KREMER J., PODLEŠÁKOVÁ E., SHRBENÁ B., SKOKAN E., SKOKANOVÁ P. Theory of Bentonite Behaviour in Soils. Scientific monographs. Research Institute for Land Reclamation and Improvement, Zbraslav, Czech Republik, pp. 375, **1970**.
7. BENKHELIFA M., BELKHODJA M., DAOUD Y., TESSIER D. Effect of Maghnian bentonite on physical properties of sandy soils under semi arid Mediterranean climate. Pak. J. Biol. Sci., **11**, 17, **2008**.
8. KOBUS J. Influence of bentonite on the yield and chemical composition of some cultivated plants. Pamiętnik Puławski **55**, 57, **1972** [In Polish].
9. LAZÁNYI J. Effects of bentonite on the water budget of sandy soil. In: Technologii de Cultura Pentru Grau Si Porumb Sympozion International, Oradea-Romania, pp. 293-300, **2005**.
10. NOBLE A.D., SUZUKI S. Improving the productivity of degraded cropping systems in northeast Thailand: improving farmer practices with innovative approaches. In: Proceedings of the International Conference on Research Highlights and Vanguard Technology on Environmental Engineering in Agricultural Systems, Kanazawa, Japan, pp. 371-380, **2005**.
11. KÁTAI J., TÁLLAI M., LAZÁNYI J., LUKACSNÉ E.V., SÁNDOR Z. The effect of bentonite on specific soil parameters and microbial characteristics of the carbon cycle. In: Procedings of Joint International Conference on Long-term Experiments. Debrecen, Hungary. pp. 247-254, **2007** .
12. SALETH M., INOCENCIO A., NOBLE A., RUAYSOONGNERN S. Economic Gains of Improving Soil Fertility and Water Holding Capacity with Clay Application: The Impact of Soil Remediation Research in Northeast Thailand. IWMI Research Report 130, **2009**, http://www.iwmi.cgiar.org/Publications/IWMI_Research_Reports/PDF/PUB130/RR130.pdf.
13. SATJE A., NELSON P. Bentonite treatments can improve the nutrient and water holding capacity of sugarcane soils in the wet tropics. Proc. Aust. Soc. Sugar Cane Technol. 31, 166, **2009**.
14. SODA W., SUZUKI S., CHINABUT N., NOBLE A.D., SIMMONS R.W., SINDHUSEN L., BHUTHORNDHARAJ S. The role of clay based materials in the rejuvenation of degraded light textured soils from northeast Thailand: Changes in physical and chemical attributes associated with the application of these materials. LDD Technical Meeting, pp. 1-23, **2005**.
15. SODA W., NOBLE A.D., SUZUKI S., SIMMONS R., SINDHUSEN L., BHUTHORNDHARAJ S. Co-composting of acid waste bentonites and their effects on soil properties and crop biomass. J. Environ. Qual. **35**, 2293, **2006**.
16. YSSAD H.R., BELKHODJA M. The effect of bentonite on the physic chemical characteristics of sandy soils in Algeria. J. Appl. Sci. **7**, 2641, **2007**.
17. CZABAN J., SIEBIELEC G., CZYŻ E., NIEDŹWIECKI J. Effects of bentonite addition on a sandy soil chemistry in a long-term plot experiment. I. Effect on organic carbon and total nitrogen. Pol. J. Environ. Stud. **22**, (6), 1661, **2013**.
18. MCGRATH, S.P., CUNLIFFE C.H. A simplified method for the extraction of the metals Fe, Zn, Cu, Ni, Cd, Pb, Cr, Co and Mn from soils and sewage sludges. J. Sci. Food Agric. **36**, 794, **1985**.
19. OSTROWSKA A., GAWLIŃSKI S., SZCZUBIAŁKA Z. Methods for analyzing and assessing the properties of soil and plants. Instytut Ochrony Środowiska, Warsaw, Poland, **1991** [In Polish].
20. BURT R. Soil Survey Field and Laboratory Methods Manual. NSSC, NRCS, USDA, Lincoln, Nebraska, pp. 407, **2009**.
21. FOTYMA M., MERCIK S., FABER A. Chemical Bases of Soil Fertility and Fertilization. PWRL, Warszawa, pp. 320, **1987** [In Polish].
22. DZIENIA S., DOJSS D., WERESZCZAKA J. The influence of crop-rotation and fallow on some chemical properties of a sandy soil. Roczniki Gleboznawcze – Soil Science Annual. **48b**, 15, **1997** [In Polish].
23. SIENKIEWICZ S., WOJNOWSKA T., KOC J., IGNACZAK S., HARASIMOWICZ-HERMANN G., SZYMCZYK S., ŻARCZYŃSKI P. Chemical changes in soils depending on the fallowing system. Part I. Soil reaction and the contents of total nitrogen and organic carbon. Zeszyty Problemowe Postępów Nauk Rolniczych. **493**, 685, **2003** [In Polish].
24. SIEBIELEC G., SMRECZAK B., KLIMKOWICZ-PAWLAS A., MALISZEWSKA-KORDYBACH B., TERELAK H., KOZA P., ŁYSIAK M., GAŁĄZKA R., PECIO M., SUSZEK B., MITURSKI T., HRYŃCZUK B. Monitoring of Soil Quality in Poland in 2010-2012. Biblioteka Monitoringu Środowiska. Warszawa, Poland 196 pp. 2012 [in Polish]. http://www.gios.gov.pl/chemizm_gleb/index.php?mod=monit.
25. CHASTAIN J.P., CAMBERATO J.J., ALBRECHT J.E. Nutrient content of livestock and poultry manure. Clemson University. pp. 32, **2001**.
26. CHASTAIN J.P., CAMBERATO J.J. Dairy manure production and nutrient content. Chapter 3a. In: Confined Animal Manure Managers Certification Program Manual B Dairy Version 1. Clemson University Cooperative Extension Service pp. 3a1-3a16, 5/**2004**.
27. ERIKSSON J. Concentrations of 61 trace elements in sewage sludge, farmyard manure, mineral fertiliser, precipitation and in oil and crops. Swedish Environmental Protection Agency. pp. 69, **2001**.
28. HANSEN D.J. Manure as a nutrient source. In: The Mid-Atlantic Nutrient Management Handbook. (Eds.) Haering K.C., Evanylo G.K. Richmond VA. pp. 207-225, **2006**.
29. TENNAKOON N.A., HEMAMALA BANDARA S.D. nutrient content of some locally available organic materials and their potential as alternative sources of nutrients for coconut Cocos **15**, 23, **2003**.
30. KABATA-PENDIAS A. Trace Elements in Soils and Plants. 4th ed.; CRC Press, Boca Raton USA. pp. 520, **2011**.
31. AYDINALP C., MARINOVA S. Distribution and forms of heavy metals in some agricultural soils. Pol. J. Environ. Stud. **12**, (5), 629, **2003**.
32. ALLOWAY B.J. Zinc in Soils and Crop Nutrition. 2^{nd} ed.; International Zinc Association and International Fertilizer Industry Association, Brussels, Belgium and Paris, France, pp. 136, **2008**.

33. DE VRIES W., RÖMKENS P.F.A.M., VOOGD J.C.H. Prediction of the long term accumulation and leaching of zinc in Dutch agricultural soils: a risk assessment study. Alterr-report 1030, Wageningen, pp. 93, **2004**.
34. GRÄBER I., HANSEN J.F., OLESEN S.E., PETERSEN J., ØSTERGAARD H.S., KROGH L. Accumulation of copper and zinc in Danish agricultural soils in intensive pig production areas. Dan. J. Geogr. **105**, 15, **2005**.
35. DORTZBACH D., LÉIS C.M., COMIN J.J., FILHO P.B., PEREIRA M.G. Accumulation of zinc, copper and manganese in soil fertilized with pig manure and urea in Southern State of Santa Catarina (Brazil). 19th World Congress of Soil Science, Soil Solutions for a Changing World Brisbane, Australia, **2010**, http://intranetdoc.epagri.sc.gov.br/producao_tecnico_cientifica/DOC_2548.pdf.
36. KHOO C., SEN T.K. Adsorption characteristics of zinc (Zn^{2+}) from aqueous solution by natural bentonite and kaolin clay minerals: a comparative study. Chemeca Conference, Hilton Sydney, Australia, 18-21, **2011**.
37. MELICHOVÁ Z., HROMADA L. Adsorption of Pb^{2+} and Cu^{2+} ions from aqueous solutions on natural bentonite. Pol. J. Environ. Stud. **22**, (2), 457, **2013**.
38. PEREIRA DE ARAUJO A.L., BERTAGNOLLI C., DA SILVA M. G. C., GIMENEZ M.L., SIMÖES DORNELLAS DE BARROS M. Zinc adsorption in bentonite clay: influence of pH and initial concentration. Acta Scient. **35**, 325, **2013**.
39. SHETA A.S., FALATAH A.M., AL-SEWAILEM M.S., KHALED E.M., SALLAM A.S.H. Sorption characteristics of zinc and iron by natural zeolite and bentonite. Microporous and Mesoporous Materials **61**, 127, **2003**.
40. JONES C., JACOBSEN J. Plant Nutrition and Soil Fertility. Nutrient Management Module No. 2. Montana State University Extension Service. pp. 11, **2001**.
41. SUGANYA S., SIVASAMY R. Moisture retention and cation exchange capacity of sandy soil as influenced by soil additives. J. Appl. Sci. Res. **2**, 949, **2006**.
42. DEBAENE G., NIEDŹWIECKI J., PECIO A. Visible and near-infrared spectrophotometer for soil analysis: preliminary results. P. J. Agron. **3**, 3, **2010**.
43. FILIPIAK K. Synthetic parameter of soil fertility. Nawozy i Nawożenie (Fertilizers and Fertilization) **41**, 7, **2010** [In Polish].
44. SIENKIEWICZ S., KRZEBIETKE S., WOJNOWSKA T., ŻARCZYŃSKI P., OMILIAN M. Effect of long-term differentiated fertilization with farmyard manure and mineral fertilizers on the content of available forms of P, K and Mg in soil. J. Elementol. **14**, 779, **2009**.
45. ŠTIPEK K., VANĚK V., SZÁKOVÁ, ČERNÝ J., ŠILHA J. Temporal variability of available phosphorus, potassium and magnesium in arable soil. Plant Soil Environ. **50**, 547, **2004**.
46. WYSZKOWSKI M., SIVITSKAYA V. Changes in the content or organic carbon and available forms of macronutrients in soil under the influence of soil contamination with fuel oil and application of different substances. J. Elem. **17**, 139, **2012**.