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CHANGES IN THE CONTENT OF SOIL PHOSPHORUS AFTER ITS APPLICATION INTO CHERNOZEM AND HAPLIC LUVISOL AND THE EFFECT ON YIELDS OF BARLEY BIOMASS

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Abstract

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The pot experiment was established in vegetation hall in the year 2015. Spring barley, variety KWS Irina, was grown. Two different soils – chernozem from Brno (with a low phosphorus content and alkali soil reaction – 7.37) and haplic luvisol from Jaroměřice nad Rokytnou (with a high phosphorus content and slightly acid soil reaction – 6.01) were used for comparison. The rates of phosphorus in the form of triple superphosphate (45 % P_2O_5) were increased from 0.3–0.6–1.2 g per pot (5 kg of soil – Mitscherlich pots). Nitrogen was applied in the form of CAN (27 % N) at a rate of 1 g N per pot in all the treatments incl. the control. Using statistical analysis, significant differences were found between the two soil types both in terms of the postharvest soil P content and yields of aboveground biomass. The content of post-harvest soil phosphorus increased significantly with the applied rate (96–141–210 mg/kg in chernozem and 128–179–277 mg/kg in haplic luvisol). Dry matter yields of the aboveground biomass grown on chernozem were the lowest in the control treatment not fertilised with P (38.97 g per pot) and increased significantly with the P rate applied (46.02–47.28 g per pot), although there were no significant differences among the fertilised treatments. On haplic luvisol phosphorus fertilisation was not seen at all, demonstrating that the weight of the biomass in all the treatments was balanced (48.12–49.63 g per pot).

Keywords: phosphorus, fertilisation, barley, soil, supply, aboveground biomass

INTRODUCTION

A key criterion of optimal plant nutrition is the adequate supply of phosphorus (P) in the soil (McDowell *et al.,* 2008). Its interaction with nitrogen significantly contributes to optimum crop yields and nitrogen use effectiveness (Usherwood and Segars, 2001). Under N enriched conditions phosphorus availability has been shown to limit plant growth (Phoenix *et al.,* 2004). Phosphorus is an essential nutrient for the provision of sufficient crop production, sufficient foods for the increasing human population on Earth (Denison and Kiers 2005; Reid and Scholas, 2005). The significant decrease in the use of mineral phosphate fertilisers in the Czech Republic began after the political-social changes in the year 1989. If in the 1980s about 29–33 kg P/ha/year was applied annually, between 1991–2013 it decreased to 6 kg P/ha/year. Together with the decrease of mineral fertilisers, also phosphorus input into soils from organic fertilisers decreased as a consequence of the reduction of livestock to about a half before the year 1989 (Čermák *et al.*, 2014). In consequence, available phosphorus decreased between 1990 and 2005 from 107 to 92 mg/kg (Vaněk *et al.*, 2007). The acreage of arable soil (%) in terms of P-supply categories are as follows: low – 27.04 %, satisfactory – 28.56 %, good – 21.35 %, high – 16.55 %, very high – 6.47 %. More than 75 % of arable land in the Czech Republic (low category – satisfactory – good) therefore requires phosphorus fertilisation. The situation is similar in orchards, vineyards and hop fields (Smatanová and Sušil, 2015). The uptake of phosphorus converted per 1 ton of barley grain yield from the field is 3.3 kg P/ha (Klír *et al.*, 2008).

The total soil P content (inorganic and organic forms) is usually divided into different pools (e.g. stable, labile, available (Jones *et al.*, 1984). In the upper layer of arable soils the percentage of organically bound phosphorus can range from 20 % to 80 % of total P concentration. Approximately 40 % of organic soil P are found in the inositol P fractions whereas 7 % are bound in lipids and nucleic acids (Dalal, 1977). It is known that organic P is involved to a great extent in the dynamics and cycling of soil P (Helal and Sauerbeck, 1984; Helal and Dressler, 1989).

From the aspect of the long-term strategy of soil fertility conservation for the necessary production of foods and feeds for the increasing human population on Earth phosphorus taken up by the crop yield from the soil must be recompensed (Tilman *et al.*, 2002, Denison and Kiers, 2005). However, only the efficient reserve of labile forms of phosphorus should be maintained in agricultural productive soils. It can be ensured by a systematic testing of the nutrient status of soils including agronomic calibration for the present needs of agriculture (Fixen, 2005). Soil testing is a remarkable and unique activity that synthesises a large amount of research information and scientific knowledge for practical needs of the identification and prevention of the majority of disproportions in plant nutrition in the given fields. Soil testing provides farmers with the greatest amount of practically applicable information (Raij, 1994; 1998). Regardless of their present drawbacks chemical methods of agricultural soil testing are the most frequently used tools of diagnostics of the nutrient status of soil and the need for fertilisation derived from it. The main advantage of soil tests is the possible prevention of potential disorders in the nutrient status of the crop before its cultivation in a given field (Matula, 2009). To evaluate the phosphorus supply in soils, different soil tests have been used for a long time; however they differ markedly in extractants and extraction methods. Nevertheless, the result of the test is generally reported as phosphorus available for plants. When the supply of 'available' phosphorus in soil is given, it is always necessary to specify the used soil test including the end-point analytical technique of phosphorus determination to avoid a misleading interpretation of the results (Matula, 2010). The need for economic use of phosphorus in agriculture is accentuated by the finite supply of economical P resources (phosphates) for the production of concentrated fertilisers. Sufficient reserves of P resources are estimated to last for about 70 years and maximally for 300 years (Roberts and Stewart, 2002; Isherwod, 2003). Phosphorus can also be a harmful polluting agent of surface waters (Schröder *et al.*, 2011). The long-term intensive applications of phosphoric fertilisers to soils and phosphorus recycling in farmyard manure caused the situation when soil, originally a strong sink of phosphorus, became a source of its escape into the environs (Sharpley *et al.*, 1992; 1996; 2001; 2004; Haygarth *et al.*, 1998). Adequate rates of P-fertilizer (including knowledge about soil P-content) are also very important in terms of the environment.

I: *Agrochemical characteristics of the soil prior to trial establishment (Mehlich III) – Regulation of Czech Republic No. 275/1998*

Soil type	**pH/ $CaCl_2$**	**mg/kg**			
		P	**K**	**Ca**	**Mg**
chernozem	7.37	47	226	6,081	322
	alkali	low	good	high	high
haplic luvisol	6.01	149	331	1,994	173
	slightly acid	high	high	satisfactory	good

II: *Treatments of the experiment*

Treatment No.	**Description**	**Rate of P (g/pot)**	**Rate of N (g/pot)**
1	P0	0	1
2	P1	0.3	1
3	P2	0.6	1
4	P3	1.2	1

MATERIALS AND METHODS

The pot experiment was established (including sowing) on 1st April 2015 in the outdoor vegetation hall of the Botanical Garden and Arboretum of Mendel University in Brno. Mitscherlich vegetation pots were filled with 5 kg of medium heavy soil (on an oven dry basis at 105 °C) characterised as chernozem and haplic luvisol; Tab. I gives the agrochemical properties.

The experiment involved 4 treatments given in Tab. II.

Phosphorus was applied in the form of triple superphosphate (45 % P_2O_5) and nitrogen in the form of CAN (27 % N) at a rate of 1 g N per pot in all the treatments incl. the control. The pots were watered with de-mineralized water to a level of 60 % of the maximal capillary capacity and were kept free of weeds. The aboveground biomass of spring barley (variety KWS Irina) was harvested at the stage of milk-wax maturity (10 plants/pot) on 25 June 2015. Soil analyses were carried out before the experiment and after harvest using Mehlich 3 method (0.015 M NH4F + 0.2 M CH3COOH + 0.25 M NH4NO3 + 0.013 M HNO3) (Mehlich, 1984). The concentration of P in soil extracts was determined using ICP-OES SPECTROBLUE, SPECTRO AMETEK (Kleve, Germany).

The results were processed statistically using one-way ANOVA followed by testing according to Scheffe (P = 95 %).

RESULTS AND DISCUSSION

Phosphorus deficiency is the main factor limiting cereal production in many regions of the world (Sharpley *et al.*, 1994; Holford, 1997). P deficiencies also decrease the yield of barley (Rowe and Johnson 1995; Hoppo *et al.*, 1999). Overwhelming evidence indicates that phosphorus fertilisers for annual plants should be applied principally prior to planting. Phosphorus moves to plant roots primarily by diffusion, and young seedlings of most annual crops are very sensitive to phosphorus deficits (Burns, 1987).

The content of post-harvest soil phosphorus

Inorganic phosphorus enters into the soil solution by mineralization or fertiliser additions (Sanchez, 2007). It has been reported several times that systematic phosphorus fertilisation increases the plant-extractable soil phosphorus content (Lásztity and Csathó, 1995; Blake *et al.*, 2000; Izsáki, 2009; Ma *et al.*, 2009). The accumulation rate was found to be dependent on the soil type, cropping system, climatic conditions, as well as on the phosphorus rate. The phosphorus content in the soils after harvest in our experiment is shown in Table III. Significant differences were found in the phosphorus content between the two soil types, i.e. in all individual treatments (in Tab. III indicated with uppercase letters – A, B). The content of the post-harvest soil phosphorus increased significantly with the applied rate (96–141–210 mg/kg in chernozem and 128–179–277 mg/kg in haplic luvisol). The lowest postharvest P content was found in the both studied unfertilised control soils. The control treatment (treatment 1) had also a lower postharvest phosphorus content in both soils (43 and 100 mg/kg in chernozem and haplic luvisol, respectively) than at the beginning of the experiment (47 and 149 mg/kg in chernozem and haplic luvisol, respectively). It is because the phosphorus uptake by the barley plants in this unfertilised control treatment (treatment 1) was not compensated with an application of phosphorus fertiliser and was not released sufficiently from mineralization of organic matter in the pot. In the phosphorus-fertilised treatment 2 (Tab. III) the postharvest P content in haplic luvisol (128 mg P/kg) decreased below the rate monitored at the beginning of the experiment (149 mg P/kg, Tab. I) suggesting that more P was taken up by barley plants in the treatment 2 than was supplied in the fertiliser. It means that the intensive uptake of phosphorus by the plant could be supported by the weakly acid soil reaction (pH – 6.01) preserving more P in the soil solution. The phosphorus fertiliser is essential for optimum production, especially when soil test levels are low (McKenzie *et al.*, 1998). In European field experiments (three sites with different soils in the humid oceanic and humid continental climatic regions), where the annual P fertiliser rate ranged between 23 and 35 kg/ha, the soil phosphorus content did not increase significantly (Blake *et al.*, 2000). On a chernozem soil (Hungary: temperate climate) a 100 kg/ha increase of the P balance raised the Al-P content of the ploughed layer by

III: *The content of post-harvest soil phosphorus*

Treatment No.	Description	Rate of P (g/pot)	Soil P content (mg/kg)	
			chernozem	haplic luvisol
1	P0	0	43 aA	100 aB
2	P1	0.3	96 bA	128 bB
3	P2	0.6	141 cA	179 cB
4	P3	1.2	210 dA	277 dB

Mean values of post-harvest soil phosphorus content (*n* = 4). Different small letters (a, b) indicate significant differences at the level of α = 0.05 among individual treatments and different uppercase letters (A, B) indicate significant differences at the level of α = 0.05 between individual soils.

3.1–4.4 mg/kg/year, when different P fertiliser levels were compared (Izsáki, 2009). At different sites in China having different soil types, with 65.5 kg/ha/year P fertilization rate, accumulation rates of P_{Olsen} content varying between 0.95 and 1.24 mg/kg/year were observed (Ma *et al.*, 2009).

Dry matter yields of the aboveground biomass

The yields of aboveground biomass (g DM/pot) are shown in Table IV. Significant differences were found between the two soil types in two treatments (1 and 3). Values detected in the control (unfertilised) treatments show the radical effect of the soil (soil type and soil texture) and its properties (physical, chemical, biological) on crop yields. In the control treatment the yields on haplic luvisol were 48.12 g per pot, while on chernozem the yields were only 38.97 g per pot. In chernozem the dry matter yields of the aboveground biomass were the lowest in the control treatment (38.97 g per pot) and increased significantly with the P rate applied (46.02–47.28 g per pot), although no significant differences were detected among the fertilised treatments (2–4). The lowest rate of phosphorus (0.3 g P per pot, treatment 2) was sufficient to achieve the adequate yields and the content of 96 mg P/kg is considered to be a "good" supply in the soil.

On haplic luvisol (Tab. IV) no significant differences in yields among the 4 treatments (48.12–49.63 g per pot) were observed. In fact, the soil in the control treatment contained at the beginning of experiment 149 mg P/kg classified as the high P supply; in the fertilised treatments it was further increased to a luxury level. Under such conditions the plant is not able to utilise P for biomass formation. In soils with a high and very high supply of phosphorus (treatments 2–4, Table III) the application of P for barley is useless and uneconomic.

McKenzie *et al.* (1998) described that phosphate fertiliser significantly increased barley silage yield at 25 of 32 site-year locations. Varieties responded differently to applied P. Some varieties responded to P fertilisation regardless of the soil test level. Applied P commonly increased yield by about 25 %, but occasionally the response was much higher.

Nyborg *et al.* (1999) conducted field experiments at 60 sites to determine the yield response of barley to phosphorus fertiliser. On the unfertilised plots, barley yields increased with increasing concentrations of extractable P in the soil. Nitrogen (Gregory *et al.*, 1984; Léon, 1992; Le Gouis *et al.*, 1999) and phosphorus (Gregory *et al.*, 1984, Rodriguez and Goudriaan, 1995) deficiencies diminish biomass accumulation, but they seem to follow a different timing. P deficiencies usually diminish barley biomass accumulation early in the growth period and, then, differences between stressed and non-stressed crops tend to be maintained in absolute terms and reduced in relative terms (Gregory *et al.*, 1984). On the other hand, N deficiency also diminished biomass accumulation early in the growth period, but differences between stressed and non-stressed crops tend to increase in absolute terms during crop growth (Gregory *et al.*, 1984; Léon, 1992; Le Gouis *et al.*, 1999). In container experiments with phosphorus (rate corresponding to 19 kg P/ha – P1 and 57 kg P/ha – P2) Prystupa *et al.* (2004) described the increase in the aboveground dry matter content of barley at heading: 602 (N0P0) – 878 (N0P1) – 978 (N0P2) g DM/m^2. If the nitrogen was applied additionally, the yield of barley aboveground biomass increased only in connection with a lower P-dose: 896 (N0P0) – 1622 (N0P1) – 1390 (N0P2) g DM/m^2.

IV: *Dry matter yields of the aboveground biomass (g DM/pot)*

Treatment No.	Description	Rate of P (g/pot)	Yields (g DM/pot)	
			chernozem	haplic luvisol
1	P0	0	38.97 aA	48.12 aB
2	P1	0.3	47.28 bA	48.98 aA
3	P2	0.6	46.02 bA	49.63 aB
4	P3	1.2	46.89 bA	48.43 aA

Mean values of dry matter yields of the aboveground biomass ($n = 4$). Different small letters (a, b) indicate significant differences at the level of $\alpha = 0.05$ among individual treatments and different uppercase letters (A, B) indicate significant differences at the level of $\alpha = 0.05$ between individual soils.

CONCLUSION

The contents of soil nutrients and the yield levels are primarily dependent on the specific soil type and the soil properties. The results showed that applications of water-soluble phosphorus can significantly increase the P content in soils with lower phosphorus supply which can move to higher (good) categories of supply. Phosphorus fertilisation of soils with the high and very high P content (particularly in a weakly acid soil environment) cannot be recommended and/or under such conditions can be omitted. An adequate amount of available phosphorus in soils increases the efficiency of nutrient utilization which results in higher biomass yields.

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REFERENCES

BLAKE, L., MERCIK, S., KÖRSCHENS, M., MOSKAL, S., POULTON, P. R., GOULDING, K. W. T., WEIGEL, A., POWLSON, D. S. 2000. Phosphorus content in soil, uptake by plants and balance in three European long-term field experiments. *Nutrient Cycling in Agroecosystems*, 56: 263–275.

BURNS, I. G. 1987. Effect of interruptions in N, P or K supply on the growth and development of lettuce. *Journal of Plant Nutrition*, 10: 1571–1578.

ČERMÁK, P., LOŠÁK, T., HLUŠEK, J. 2014. Fertilization level and available nutrients content in arable land of the Czech Republic. In: *Proceedings of 9th International Soil Science Congress on The soul of soil and civilization*. Antalya, Turkey, 697.

DALAL, R. C. 1977. Soil organic phosphorus. *Advances in Agronomy*, 29: 85–117.

DENISON, R. F., KIERS, E. T. 2005. Sustainable crop nutrition: constraints and opportunities. In: BROADLEY, M. J., WHITE, P. J. (eds.), *Plant Nutritional Genomics*. Blackwell, Oxford, 242–286.

FIXEN, P. E. 2005. Decision support systems in integrated crop nutrient management. In: *The International Fertilizer Society Proceedings 569*. The International Fertilizer Society, York, UK.

GREGORY, P. J., SHEPHERD, K. D., COOPER, P. J. 1984. Effects of fertilizer on root growth and water use in northern Syria. *Journal of Agricultural Sciences*, 103: 429–438.

HAYGARTH, P. M., HEPWORTH, L., Jarvis, S. C. 1998. Forms of phosphorus transfer in hydrological pathway from soil under grazed grassland. *European Journal of Soil Science*, 49: 65–72.

HELAL, H. M., DRESSLER, A. 1989. Mobilization and turnover of soil phosphorus in the rhizosphere. *Zeitschrift für Pflanzenernährung und Bodenkunde*, 152: 175–180.

HELAL, H. M., SAUERBECK, D. 1984. Influence of plant roots on C and P metabolism in soil. *Plant and Soil*, 76: 175–182.

HOLFORD, I. C. R. 1997. Soil phosphorus: its measurements, and its uptake by plants. *Australian Journal of Soil Research*, 35: 227–239.

HOPPO, S. D., ELLIOT, D. E., REUTER, D. J. 1999. Plant tests for diagnosing phosphorus deficiency in barley (*Hordeum vulgare* L.). *Australian Journal of Experimental Agriculture*, 39: 857–872.

ISHERWOOD, K. F. 2003. Fertiliser Consumption and Production: Long Term World Prospects. In: *The International Fertiliser Society Proceeding 507*. The International Fertiliser Society, York, UK.

IZSÁKI, Z. 2009. Phosphorus turnover of chernozem meadow soil in a long-term mineral fertilisation field experiment. *Cereal Research Communications*, 37: 49–52.

JONES, C. A., COLE, C. V., SHARPLEY, A. N., WILLIAMS, J. R. 1984. A simplified soil and plant phosphorus model. I. Documentation. *Soil Science Society of America Journal*, 48: 800–805.

KLÍR, J., KUNZOVÁ, E., ČERMÁK, P. 2008. *The frame methodics of plant nutrition and fertilization*. Praha: Crop Research Institute.

LÁSZTITY, B., CSATHÓ, P. 1995. Studies on the effect of NPK fertilization in long-term experiments on pseudomyceliar chernozem soil in the Mezöföld region. *Agrochemistry and Soil Science*, 44: 47–62.

LE GOUIS, J., DELEBARRE, O., BEGHIN, D., HEUMEZ, E., PLUCHARD, P. 1999. Nitrogen uptake and utilisation efficiency of two-row and six-row winter barley cultivars grown at two N levels. *European Journal of Agronomy*, 10: 73–79.

LÉON, J. 1992. Crop growth rate and durativ of spring barley cultivars as affected by varied N supply and seedling rates. *Journal of Agronomy and Crop Science*, 169: 1–8.

MA, Y., LI, Y., LI, X., TANG, X., LIANG, Y., SHAOMIN, H. S., WANG, B., LIU, H., Yang, X. 2009. Phosphorus accumulation and depletion in soils in wheat-maize cropping systems: Modeling and validation. *Field Crops Research*, 110: 207–212.

MATULA, J. 2009. A relationship between multi-nutrient soil tests (Mehlich 3, ammonium acetate, and water extraction) and bioavailability

of nutrients from soils for barely. *Plant, Soil and Environment*, 55: 173–180.
MATULA, J. 2010. Differences in available phosphorus evaluated by soil tests in relation to detection by colorimetric and ICP-AES techniques. *Plant, Soil and Environment*, 56: 297–304.
McDOWELL, R. W., CONDRON, L. M., STEWART, I. 2008. An examination of potential extraction methods to assess plant-available organic phosphorus in soil. *Biology and Fertility of Soils*, 44: 707–715.
McKENZIE, R. H., MIDDLETON, A., SOLBERG, E., DeMULDER, J., NAJDA, H. 1998. Nitrogen and phosphorus optimizme barley silage production. *Better Crops*, 82: 22–23.
MEHLICH, A. 1984. Mehlich 3 soil test extractant: a modification of the Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis,* 15: 1409–1416.
NYBORG, M., MALHI, S. S., MUMEY, G., PENNEY, D. C., LAVERTY, D. H. 1999. Economics of phosphorus fertilization of barley as influenced by concentration of extractable phosphorus in soil. *Communications in Soil Science and Plant Analysis*, 30: 1789–1795.
PHOENIX, G. K., BOOTH, R. E., LEAKE, J. R., READ, D. J., GRIME, J. P., LEE, J. A. 2004. Stimulated pollutant nitrogen deposition increases P demand and enhances root- surface phosphatase activities of three plant functional types in a calcareous grassland. *New Phytologist,* 161: 279–289.
PRYSTUPA, P., SAVIN, R., SLAFER, G. A. 2004. Grain number and its relationship with dry matter, N and P in the spikes at fading in response to N x P fertilization in barely. *Field Crops Research*, 90: 245–254.
RAIJ, van B. 1994. New diagnostic techniques, universal soil extractants. *Communications in Soil Science and Plant Analysis*, 25: 799–816.
RAIJ, van B. 1998. Bioavailable tests: alternatives to standard soil extractions. *Communications in Soil Science and Plant Analysis*, 29: 1553–1570.
REID, W. V., SCHOLAS, R. 2005. *Millennium Ecosystems and Human Well-being: Synthesis*, Washington D. C.: Island Press.
ROBERTS, T. L., STEWART, V. M. 2002. Inorganic phosphorus and potassium productions and reserves. *Better Crops*, 86: 7.
RODRIGUEZ, D., GOUDRIAAN, J. 1995. Effects of phosphorus and drought stress on dry matter and phosphorus allocation in wheat. *Journal of Plant Nutrition*, 19: 2501–2517.
ROWE, B. A., JOHNSON, D. E. 1995. Residual benefits of limestone and superphosphate on barley yields and soil-water deficits on a krasnozem in north-western Tasmania. *Australian Journal of Experimental Agriculture*, 35: 611–617.
SANCHEZ, Ch. A. 2007. Phosphorus. In: BARKER, A. V., PILBEAM, D. J. (eds), *Handbook of Plant Nutrition.*Boca Raton: Taylor and Francis.
SCHRÖDER, J. J., SMIT, A. L., CORDELL, D., ROSEMARIN, A. 2011. Improved phosphorus use efficiency in agriculture: A kdey requirement for its sustainable use. *Chemosphere*, 84: 822–831.
SHARPLEY, A. N., SMITH, S. J., JONES, O. R., BERG, W. A., COLEMAN, G. A. 1992. Transport of bioavailable phosphorus in agricultural runoff. *Journal of Environmental Quality*, 21: 30–35.
SHARPLEY, A. N., SIMS, J. T., PIERZYNSKI, G. M. 1994. Innovative soil phosphorus availability indices: assesing inorgatic phosphorus. In: HAVLIN, J. L., JACOBSEN, J. S. (Eds.), *Soil Testing: Prospects for Improving Nutrient Recommendations*. SSSA Special Publication 40. SSSA/ASA, Madison, USA, 115–142.
SHARPLEY, A. N., DANIEL, T. C., SIMS, J. T., POTE, D. H. 1996. Determining environmentally sound soil phosphorus levels. *Journal of Soil and Water Conservation*, 51: 160–166.
SHARPLEY, A. N., KLEINMAN, P., McDOWELL, R. 2001. Innovative management of agricultural phosphorus to protect soil and water resources. *Communications in Soil Science and Plant Analysis*, 32: 1071–1100.
SHARPLEY, A. N., McDOWELL, R. W., KLEINMAN, P. J. A. 2004. Amounts, forms and solubility of phosphorus in soils receiving manure. *Soil Science Society of America Journal*, 68: 2048–2057.
SMATANOVÁ, M., SUŠIL, A. 2015. *Results of agrochemical testing of agricultural soils in period 2009–2014.* Brno: Central Institute for Supervising and Testing in Agriculture.
TILMAN, D., CASSMAN, K. G., MATSON, A., NAYLOR, R., POLASKY, S. 2002. Agricultural sustainability and intensive production practices. *Nature*, 418: 671–676.
USHERWOOD, N. R., SEGARS, W. I. 2001. Nitrogen interactions with phosphorus and potassium for optimum crop yield, nitrogen use effectiveness, and environmental stewardship. *The Scientific World Journal*, 1: 57–60.
VANĚK, V., ČERMÁK, P., KOLÁŘ, L., ČERNÝ, J. J. 2007. The consuption of phosphorus fertilizers and development of available phosphorus content in soils of the Czech Republic, *Proceeding of international conference Reasonable use of fertilizers.* Prague: ČZU, 52–59.

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