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CONTENT OF CERTAIN MACRO- AND MICROELEMENTS IN ORCHARD SOILS IN RELATION TO AGRONOMIC CATEGORIES AND REACTION OF THESE SOILS*

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Abstract

The level of macro- and microelements in soil and its reaction are among those physico-chemical properties that have a decisive impact on plant production, including orchard plantations. Evaluation of those properties provides extremely important information that can help the fruit farmer in making rational and correct decisions concerning the application of mineral, natural and organic fertilisers, as well as soil liming. Therefore, in the years 2009-2011 environmental studies were conducted, the aim of which was to evaluate the actual reaction and abundance of orchard soils (mainly apple tree orchards) of south-eastern Poland, as one of the largest fruit-growing regions in Poland, in the assimilable forms of macro- and micronutrients (phosphorus, potassium, magnesium, boron, copper, iron, manganese and zinc) and to determine the relations of these elements with the agronomic category and pH_{KCl}. The research was conducted using the results of chemical analyses of 1,611 soil samples (3 replications per each soil sampling point) collected in the late autumn, after the fruit harvest and before all agrotechnical treatments, from the arable horizon 0-20 cm. In the samples, the particle size distribution and reaction were determined and agronomy categories and reaction classes were specified. The content of available forms of phosphorus, potassium and magnesium was determined in 1,611 samples, whereas the content of boron, copper, iron, manganese and zinc was assessed in 1,518 soil samples. It was found that the reaction of the investigated orchard soils was mainly in the slightly acidic range. In most cases, the content of assayed available forms of macro-

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(P, K, Mg) and microelements (B, Cu, Fe, Mn, Zn) displayed significant and positive correlation with the agronomic category and soil reaction class (except for iron) and also with the content of the other analysed elements.

Keywords: soil nutrients, horticultural soils, pH_{KCl}, agronomic categories of soils, correlation coefficients.

INTRODUCTION

For proper growth and large, high quality yielding, fruit trees and shrubs need appropriate amounts of water, nutrients, solar radiation and carbon dioxide. This means that the fruit yield and fruit quality are affected by a number of external factors over which the farmer has no control, such as the precipitation, temperature, insolation or concentration of CO_2 in the atmosphere. Additionally, for the optimal growth and development of the root system, fruit trees require highly structural soils with high humus content and water capacity. The highest yield is obtained on soils from the medium agronomic category with loamy subsoil, whereas substantially lower yield is harvested from plants growing on heavy or very light soils. Among factors that have a decisive impact on orchard production that can be controlled by a fruit farmer are the level of macro- and microelements in soil and soil reaction (Tyler, Olsson 2001, Zia et al. 2006, Tkaczyk et al. 2016). The soil pH not only influences soil structure, but it also affects its retention properties and the development of the soil biota, in addition to which it determines the proper absorption of nutrients during the growing season (Berbecea et al. 2011). All of the above are important for the proper development of the root system, and thus for the high quality of yield. Plants absorb particular nutrients from the substrate only within a certain pH range. Broadly speaking, orchard soils should have pH within 6.0-7.3 (Wang et al. 2015). Soil pH within this range is optimal and favours the intensive development of soil microorganisms that effectively mineralize the organic mass and increase the availability of basic mineral nutrients (Jarociński 2005). Within the soil pH < 6.0, forms of Mg, Ca, P and Mo become less available and when pH falls below 5.5 the uptake of N, K and S becomes hindered. Therefore, growing trees and shrubs in highly acidic soils results in the inhibition of their overall growth and reduction in the growth of long shoots and leaf area, which consequently leads to poor setting of fruits. Contrary, at pH > 7.3, Fe, Mn, B and Cu become hardly available for plants and as a result fruit trees succumb to calcium chlorosis (Zia et al. 2006). Of course, individual species differ in their soil pH requirements, for example apple trees prefer acidic and slightly acidic soils with the optimal pH close to 6.0 (Tkaczyk et al. 2014).

Nutrient deficiencies or excesses have a direct effect on the yielding and quality of plants (Tyler, Olsson 2001, Murawska et al. 2015, Tkaczyk et al.

2017*a*). Although each deficiency or excess manifests itself in a specific way, they all led to fruits being smaller in size, coarse, with poor, non-uniform colour and poor flavour. For example, under P deficiency shoots grow thin and either trees do not bloom or fruits drop prematurely (Nazarkiewicz, Kaniuczak 2012). Therefore, to ensure optimal conditions for the growth and harvest yield of appropriate quality, fertile soil with a regulated value of soil reaction and adequate supply of nutrients is needed (Brunetto et al. 2015).

Currently excessive soil acidification in Poland reduces plant yielding over an area exceeding 50% of agricultural lands, which is mainly a result of inappropriate soil management (Filipek, Skowrońska 2013). This also applies to orchards, which means that periodic liming of orchard soils with fertilizers intended for deacidification of soil, i.e. those containing Ca and Mg, becomes more and more necessary (Pacholak 2008), as it affects directly nutrient transformations in soil. Improvement of soil physical characteristics can also be obtained with proper cultivation treatments and melioration (Lamorski et al. 2013). The necessity of liming or fertilisation should be determined by specifying the soil type and performing chemical analysis of soil samples to estimate the current levels of soil acidification and its abundance in macro- and microelements (Tkaczyk et al. 2017*b*). Only then one can consciously draw up a nutrient balance for a given crop according to the principle "as much as necessary, as little as possible". Evaluation of soil physicochemical properties provides extremely important information for a fruit farmer that can help him make rational and correct decisions about soil liming and the application of mineral, natural and organic fertilisers in appropriate amounts, dates and in the right form, which will result in higher yield.

On the other hand, representative data about the content of macro- and microelements in various regions in different soil types and their relation with cultivation treatments are nowadays extremely important for developing and calibrating models with extended soil models, for example crop growth models. These models can include the soil-crop water relationship and nutrient balance in soil. Currently, crop growth models are often used for evaluating agrotechnical treatments with numerous environments and genotypes included (Pirttioja et al. 2015, Fronzek et al. 2018, Ruiz-Ramos et al. 2018). As such research takes into account the impact of climate change on crop production, spatio-temporal changes in climate dynamics need to be analysed as well (Baranowski et al. 2015, Hoffmann et al. 2017, Krzyszczak et al. 2017). This esnures that some valuable information on the impact of climate change on macro- and micronutrient content in soil can be obtained.

The objective of the study was to evaluate the current pH and abundance of orchard soils in Poland in available forms of P, K, Mg, B, Cu, Fe, Mn and Zn, and to determine their relation with the soil agronomic category and reaction class.

MATERIAL AND METHODS

To assess the actual pH_{KCl} and abundance of orchard soils (mainly apple tree orchards) in nutrients, environmental studies were carried out in the years 2009-2011. The main focus was on soils of south-eastern Poland, which is one of the largest fruit-growing regions in Poland. During three consecutive years, 1,668 soil samples (3 repetitions per each sampling point) were collected with an Egner's stick from the arable horizon (0-20 cm). A map showing the location of orchards from which soil samples were collected is in Figure 1. Samples (in each year) were collected in the late autumn after the

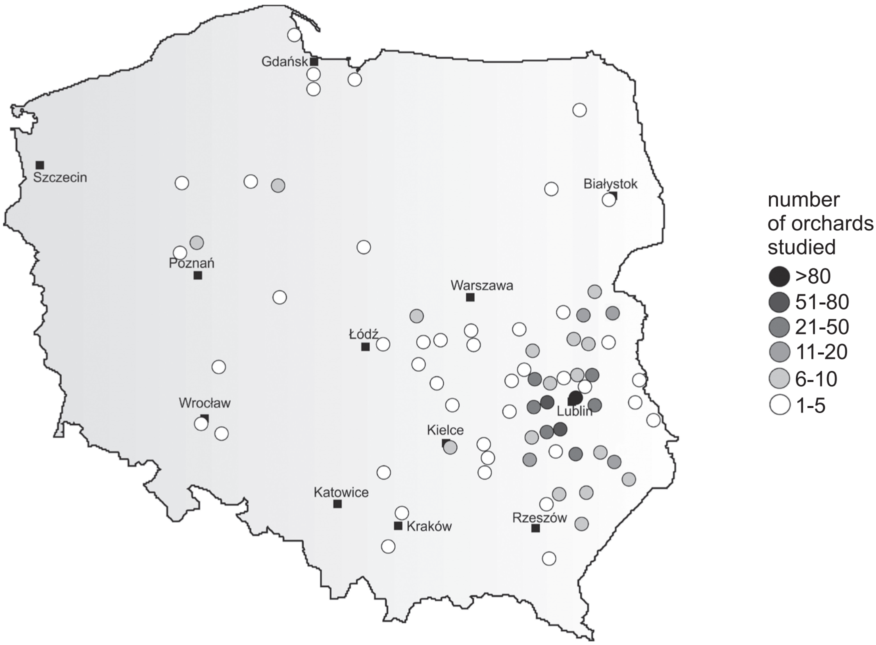

Fig. 1. Location of orchard plantations from which soil samples were collected

fruit harvest and before all agrotechnical treatments, including soil fertilization and soil liming, and subjected to chemical analyses performed at an accredited laboratory of the Regional Agrochemical Station in Lublin. Each sample weighed approximately 500 g. The soil reaction and the content of P, K and Mg were assayed in 1,611 samples, whereas the content of B, Cu, Fe, Mn and Zn was determined in 1,518 samples. After determination of soil reaction in 1 mol dm^{-3} KCl, soil samples were assigned to pH classes, such as highly acidic, acidic, slightly acidic, neutral and alkaline soils (pH < 4.5; between 4.6-5.5; 5.6-6.5; 6.6-7.2 and with pH > 7.2, respectively). The content of P and K was assayed with the Egner-Riehm method, using calcium lactate buffer as the extracting agent, whereas Mg was determined using an ASA method, after being extracted from soil with 0.0125 mol dm^{-3} $CaCl_2$. Cu, Fe, Mn and Zn were extracted from soils using 1 mol dm^{-3} HCl and assayed with an ASA method, while the B content was tested with the colorimetric method using curcumin (Catalogue of Methods 2011). The particle size distribution was determined using the laser diffraction method and agronomic categories were assigned to soil samples following the classification of soils into very light, light, medium and heavy ones (respectively <10%; 11-20%; 21-35% and >35% of fraction with diameter <0.02 mm). The results were evaluated statistically using the one-way non-orthogonal analysis of variance classification with the Tukey semi-intervals of confidence (p = 0.05). Relationships between the content of the assayed macro- and micronutrients, pH and agronomic categories of soils were expressed using correlation coefficients.

RESULTS AND DISCUSSION

The results of chemical analyses of the reaction and content of nutrients in the analysed orchard soils divided into the agronomic categories are presented in Table 1. On average, the orchards soils analysed could be classified as slightly acidic, with the reaction close to 6, which is optimal for apple tree orchards. The number of soils within the medium agronomic category was the highest (about 63% of all soils). A slight increase in the mean pH value of soils classified into the heavier category can be observed, but the differences in very light, light and medium soils were insignificant. The pH in heavy soils was significantly higher than in light and medium ones, but it did not differ statistically from the pH in very light soils. In each agronomic category, there were both highly acidic and neutral (or even alkaline) soils, but they constituted only around 24% of all assayed soil samples. The relatively high variation of pH within categories may be due to the application of various cultivation treatments in different orchards or because of soil liming.

The mean P content in orchard soils was not significantly related to the agronomic category (Table 1), even if its increase within the heavier soil category could be observed. The P supply in very light soils, according to the Egner-Riehm threshold values, was moderate, whereas in light and medium soils it was high and in heavy soils – very high. The P content in light soils was 1.4 times higher, in medium about 1.5 times and in heavy soils 1.9 times higher than in very light soils, which may result from both the natural diversity of fertility of soils falling into different categories and the application of various fertilisers. The differences in the mean K content in very light and light soils were insignificant, same as between medium and heavy soils. The K supply of very light, light and heavy soils was moderate, whereas in medium soils it was high. It was found that an increase in the content of clay particles (heavier agronomic category) in assayed soils was concomitant with a steady increase in the K content, although this may have been the

Table 1

Mean values and ranges of variability (in brackets) of pH_{KCl} and the content of available forms of macro- and microelements in orchard soils in relation to their agronomic categories

Soil agronomic category	pH_{KCl}	P	K	Mg	B	Cu	Fe	Mn	Zn
		(mg kg^{-1})							
Very light	5.52 *a, b* (4.06 ÷ 7.68)	56.6 *a* (4.0 ÷ 148.0)	90.3 *a, b* (27.0 ÷ 180.0)	40.6 *a* (11.0 ÷ 95.0)	0.51 *a* (0.12 ÷ 1.21)	3.37 *a* (0.35 ÷ 13.67)	436.7 *a* (228.0 ÷ 817.0)	72.0 *a* (15.3 ÷ 200.3)	7.08 *a* (0.63 ÷ 27.40)
Light	5.71 *a* (4.02 ÷ 7.88)	78.5 *a* (7.0 ÷ 467.0)	117.7 *a* (22.0 ÷ 454.0)	53.1 *a* (7.0 ÷ 190.0)	0.89 *a* (0.05 ÷ 18.00)	3.47 *a* (0.39 ÷ 36.00)	647.1 *a* (231.6 ÷ 1675.0)	103.6 *a* (0.9 ÷ 279.7)	10.29 *a* (1.27 ÷ 212.00)
Medium	5.72 *a* (4.00 ÷ 7.70)	83.8 *a* (8.0 ÷ 706.0)	185.6 *c* (33.0 ÷ 1287.0)	69.5 *b* (12.0 ÷ 213.0)	1.12 *a* (0.14 ÷ 9.10)	4.12 *a* (0.67 ÷ 29.50)	973.6 *b* (148.9 ÷ 2728.0)	170.6 *b* (28.4 ÷ 540.7)	10.41 *a* (1.59 ÷ 175.50)
Heavy	6.19 *b* (4.17 ÷ 7.57)	107.8 *a* (18.0 ÷ 641.0)	202.0 *b, c* (56.0 ÷ 686.0)	73.5 *b* (10.0 ÷ 140.0)	1.84 *b* (0.35 ÷ 6.87)	4.04 *a* (1.28 ÷ 20.40)	875.6 *b* (245.0 ÷ 1437.0)	154.1 *b* (50.2 ÷ 296.2)	8.78 *a* (2.95 ÷ 49.90)

a, b, c – means denoted with the same letter do not differ significantly at $p \leq 0.05$

result of using various fertilisers or due to partial release of fixed K. The differences in the mean Mg content between very light and light and between medium and heavy soils were statistically insignificant, whereas the Mg content in medium and heavy soils was significantly higher than in very light and light soils. The Mg content increased consistently within the heavier category of soils, which suggests that it depends on the quantity of soil finest particles (clay fraction). PACHOLAK (1991) noted that high doses of NPK fertilisers caused an evident increase of the P and K content and decreased the Mg level in the 0-20 cm soil layer. SZEWCZUK et al. (2011) stated that fertilisation with various K fertilisers increased the K content in the 0-20 cm layer in apple tree orchard soils, but had no effect on the P and N levels. NAZARKIEWICZ, KANIUCZAK (2012) noted that liming and mineral fertilisation are the main reasons for a significant increase in the P and K content and a decrease in the Mg content in grey-brown podzolic soils.

The differences in the mean B content between the very light, light and medium soils were insignificant, while in heavy soils it was significantly higher than in the other categories (Table 1). It was observed that the B content was related to the quantity of clay particles, as its content was higher than in very light soils by 1.75-fold in light, 2.2-fold in medium and 3.6-fold in heavy soils. Even if Cu, Fe, Mn and Zn levels increase noticeably in the heavier category soils until the medium ones, only to decrease in heavy soils, significant dependence on the agronomic category was observed only for the Fe and Mn content. The Fe content did not differ significantly between very light and light and between medium and heavy soils, but in medium and heavy soils it was significantly higher than in very light and light soils. Same relations were observed for the Mn content, whereas Cu and Zn levels did not differ significantly between soil categories. JAROCIŃSKI (2005) stated that a low supply of Cu and B could be observed in apple tree orchard soils, whereas Zn, Mn and Fe were often on an optimal level. ZIA et al. (2006) noted that in soils covering large areas of various plantations, including apple orchards, deficits of Zn, B and Fe were present. LIPIŃSKI, BEDNAREK (1998) observed that the particle size distribution had a crucial effect on the Mg and Mn levels in particular ranges of pH. MURAWSKA et al. (2015) stated that long-term fertilisation with N and K led to soil acidification and to distinct differentiation in the Zn and Cu content in soil, whereas SIENKIEWICZ et al. (2009) observed the same for the Cu, Zn and Mn content in orchard soils.

The content of nutrients in assayed soils divided into soil pH classes is presented in Table 2. The mean P, K and Mg content depended significantly on the soil reaction class. The content of P increased steadily with a higher pH class, whereas an increase in the K and Mg content was observed up to neutral soils; in alkaline soils the levels of these elements decreased. Differences in the P content between highly acidic, acidic and slightly acidic soils were insignificant, same as between neutral and alkaline soils. Contrary, the P content was significantly higher in neutral and alkaline than in highly acidic, acidic and slightly acidic soils. This is most likely because in acidic

Table 2

Mean values and ranges of variability (in brackets) of the content of available forms of macro- and microelements in orchard soils in relation to their reaction classes

Soil reaction class	P	K	Mg	B	Cu	Fe	Mn	Zn
	(mg kg^{-1})							
Highly acidic	60.8 *a* (7.0 ÷ 310.0)	127.5 *b* (22.0 ÷ 469.0)	41.8 *d* (7.0 ÷ 104.0)	0.78 *a* (0.06 ÷ 18.00)	2.22 *a* (0.35 ÷ 9.61)	871.5 *a* (281.0 ÷ 1483.0)	122.0 *a* (18.0 ÷ 316.9)	6.13 *b* (0.78 ÷ 32.80)
Acidic	69.1 *a* (4.0 ÷ 706.0)	135.1 *b*, *c* (27.0 ÷ 415.0)	58.1 *a* (11.0 ÷ 139.0)	0.69 *a* (0.05 ÷ 2.81)	3.18 *a*, *b* (0.37 ÷ 25.60)	849.0 *a* (168.0 ÷ 1673.0)	130.3 *a* (0.9 ÷ 360.8)	8.22 *a*, b (0.63 ÷ 118.90)
Slightly acidic	81.1 *a* (7.0 ÷ 355.0)	177.2 *a* (33.0 ÷ 1287.0)	78.5 *c* (18.0 ÷ 190.0)	0.93 *a* (0.16 ÷ 2.93)	4.69 *a* (0.73 ÷ 29.50)	862.0 *a* (148.9 ÷ 1690.0)	152.1 *b* (19.9 ÷ 369.5)	9.88 *a*, *b* (1.27 ÷ 175.50)
Neutral	106.2 *b* (11.0 ÷ 641.0)	215.1 *a* (44.0 ÷ 1121.0)	79.7 *b*, *c* (22.0 ÷ 196.0)	1.49 *b* (0.30 ÷ 5.40)	5.79 *b* (1.09 ÷ 36.00)	880.2 *a* (274.0 ÷ 2015.0)	182.5 *c* (3.2 ÷ 540.7)	14.18 *a* (2.94 ÷ 102.50)
Alkaline	125.7 *b* (20.0 ÷ 567.0)	194.5 *a* (44.0 ÷ 955.0)	59.4 *a*, *b* (10.0 ÷ 213.0)	2.62 *c* (0.45 ÷ 9.10)	5.63 *a*, *b* (0.86 ÷ 59.30)	802.2 *a* (220.0 ÷ 2728.0)	170.3 *b*, *c* (79.0 ÷ 324.1)	15.36 *a* (2.76 ÷ 212.00)

a, *b*, *c*, *d* – same as in Table 1

soils soluble inorganic P is fixed by Al and Fe oxides, whereas at higher pH P release from Al and Fe phosphates occurs. Levels of K did not differ significantly between highly acidic and acidic, as well as neutral and alkaline soils. The Mg content did not differ significantly between acidic and alkaline; slightly acidic and neutral; and neutral and alkaline soils. The mean B, Cu, Mn and Zn content depended on the soil reaction class. The B content increased steadily with an increase of soil pH (with a slight, insignificant decrease in acidic soils). The Fe content was almost the same regardless the pH class, with a small decrease in alkaline soils. The Mn and Zn content increased steadily from highly acidic to neutral, and from highly acidic to alkaline soils, respectively. Differences in the B content between highly acidic, acidic and slightly acidic soils were insignificant, but the B level was significantly higher in neutral soils than in all acidic soils and in alkaline soils than in the other pH classes. Differences in the Cu content between highly acidic, acidic, slightly acidic and alkaline soils, as well as between acidic, neutral and alkaline soils were insignificant. The same was observed for the Mn content between highly acidic and acidic and also between neutral and alkaline soils or for the Zn content between highly acidic, acidic and slightly acidic soils, and also between acidic, slightly acidic, neutral and alkaline soils. Tkaczyk, Bednarek (2011) stated that 52 % of soils in south-eastern Poland were highly acidic and acidic, 23% slightly acidic and 25% neutral or alkaline. It is worth noting that the percentage of highly acidic and acidic soils decreased during the following years of the studies, while an increase in the area covered by neutral and alkaline soils was observed. In their subsequent study, Tkaczyk et al. (2016) observed that the pH of soils in the same region was mostly acidic or slightly acidic and that the levels of P, K and Mg depended on the agronomic category and pH class, which is in agreement with the results presented for orchard soils.

Dependencies between soil agronomic category, pH and content of nutrients expressed with correlation coefficients are shown in Table 3. In most cases, the content of nutrients displayed significant and positive correlations with the agronomic category, pH class and with the other assayed elements. The highest correlation in orchard soils was found between the Fe and Mn content (0.577) and the agronomic category and the Mn content (0.428). Kumar, Babel (2011) showed that content of Zn, Cu, Fe, Mn and B in soils displayed a positive correlation with the organic carbon and colloidal clay. Kobierski (2004) noted a significant positive correlation between the content of Cu, Zn, Mn and Fe in orchard soils extracted with DTPA and the organic carbon content. The correlation coefficients obtained in this study confirm and expand previous literature reports.

Table 3

Correlation coefficients for dependencies between the content of available forms of macro- and microelements and certain physicochemical properties of soils

Variable	Agr. cat.	pH_{KCl}	P	K	Mg	B	Cu	Fe	Mn	Zn
Agr. cat.	-	0.085^{*}	0.088^{*}	0.234^{***}	0.327^{***}	0.139^{***}	n.s.	0.362^{***}	0.428^{***}	n.s.
pH_{KCl}		-	0.293^{***}	0.179^{***}	0.287^{***}	0.181^{***}	0.122^{**}	n.s.	0.290^{***}	0.151^{***}
P			-	0.397^{***}	0.189^{***}	0.193^{***}	n.s.	0.117^{**}	0.296^{***}	0.230^{***}
K				-	0.270^{***}	0.191^{***}	0.089^{*}	0.213^{***}	0.398^{***}	0.148^{***}
Mg					-	0.197^{***}	0.098^{*}	0.356^{***}	0.319^{***}	0.152^{***}
B						-	n.s.	0.268^{***}	0.295^{***}	0.220^{***}
Cu							-	n.s.	n.s.	0.155^{***}
Fe								-	0.577^{***}	0.173^{***}
Mn									-	0.162^{***}
Zn										-

n.s. – non-significant correlation, * significant at $p \leq 0.05$, ** – significant at $p \leq 0.01$, *** significant at $p \leq 0.001$, $n = 537$ (pH_{KCl} and macronutrients), $n = 506$ (micronutrients)

CONCLUSIONS

1. The reaction of the majority of the analysed orchard soils was close to being slightly acidic, the soils belonged to the medium agronomic category and the content of assayed macroelements (P, K, Mg) and microelements (B, Cu, Fe, Mn, Zn) was connected with the agronomic category.

2. The content of the assayed forms of macro- and microelements was significantly related to the soil reaction class (except for iron).

3. In most cases, the content of the assayed forms of macro- and microelements in soils displayed significant and positive correlations with the agronomic category, pH and level of other analysed macro- and microelements.

REFERENCES

Baranowski P., Krzyszczak J., Sławiński C., Hoffmann H., Kozyra J., Nieróbca A., Siwek K., Gluza A. 2015. *Multifractal analysis of meteorological time series to assess climate impacts*. Clim. Res., 65: 39-52. https://doi.org/10.3354/cr01321

Berbecea A., Radulov I., Sala F., Crista F., Lato A. 2011. *Interrelation between metal availability, soil pH and mineral fertilization*. Res. J. Agric. Sci., 43(3): 19-22.

Brunetto G., Melo G.W.B.D., Toselli M., Quartieri M., Tagliavini M. 2015. *The role of mineral nutrition on yields and fruit quality in grapevine, pear and apple*. Rev. Bras. Frutic., 37(4): 1089-1104. https://doi.org/10.1590/0100-2945-103/15

Catalogue of methods for conducting agrichemical tests in agricultural and chemical stations 2011. OSCH-R Lub., 1-19. (in Polish)

Filipek T., Skowrońska M. 2013. *Current dominant causes and effects of acidification of soils under agricultural use in Poland*. Acta Agroph., 20(2): 283–294. (in Polish)

Fronzek S., Pirttioja N., Carter T.R., Bindi M., Hoffmann H., Palosuo T., Ruiz-Ramos M., Tao F., Trnka M., Acutis M., Asseng S., Baranowski P., Basso B., Bodin P., Buis S., Cammarano D., Deligios P., Destain M.-F., Dumont B., Ewert F., Ferrise R., François L., Gaiser T., Hlavinka P., Jacquemin I., Kersebaum K.C., Kollas C., Krzyszczak J., Lorite I.J., Minet J., Minguez M.I., Montesino M., Moriondo M., Müller C., Nendel C., Öztürk I., Perego A., Rodríguez A., Ruane A.C., Ruget F., Sanna M., Semenov M.A., Sławiński C., Stratonovitch P., Supit I., Waha K., Wang E., Wu L., Zhao Z., Rötter R.P. 2018. *Classifying multi-model wheat yield impact response surfaces showing sensitivity to temperature and precipitation change*. Agric. Syst., 159: 209-224. https://doi.org/10.1016/j.agsy.2017.08.004

Hoffmann H., Baranowski P., Krzyszczak J., Zubik M., Sławiński C., Gaiser T., Ewert F. 2017. *Temporal properties of spatially aggregated meteorological time series*. Agric. For. Meteorol., 234-235: 247-257. https://doi.org/10.1016/j.agrformet.2016.12.012

Jarociński B.Z. 2005. *Assessment of orchard soils with respect to essential mineral content*. Zesz. Nauk. Inst. Sad. Kwiac., 13: 17–28. (in Polish)

Kobierski M. 2004. *Copper, zinc, manganese and iron concentrations in soils of 27 and 30-year -old apple tree orchards*. Acta Sci. Pol. Hort. Cult., 3(2): 161-170. (in Polish)

Krzyszczak J., Baranowski P., Zubik M., Hoffmann H. 2017. *Temporal scale influence on multifractal properties of agro-meteorological time series*. Agric. For. Meteorol., 239: 223-235. https://doi.org/10.1016/j.agrformet.2017.03.015

Kumar M., Babel A.L. 2011. *Available micronutrient status and their relationship with soil properties of Jhunjhunu Tehsil, District Jhunjhunu, Rajasthan, India*. J. Agr. Sci., 3(2): 97-106.

Lamorski K., Pastuszka T., Krzyszczak J., Sławiński C., Witkowska-Walczak B. 2013. *Soil water dynamic modeling using the physical and support vector machine methods*. Vadose Zone J., 12(4). https://doi.org/10.2136/vzj2013.05.0085

Lipiński W., Bednarek W. 1998. *Occurrence of readily soluble forms of metals in the soils of Lublin region depending on soil reaction and grain size composition*. Zesz. Probl. Post. Nauk Rol., 456: 399-404. (in Polish)

Murawska B., Lipińska K.J., Mitura K., Piekut A., Jachymska J. 2015. *Mobility of zinc and copper in light soil depending on long-term nitrogen and potassium fertilization*. Infrastruct. Ecol. Rural Areas, III(1): 677-689. (in Polish)

Nazarkiewicz M., Kaniuczak J. 2012. *The influence of liming and mineral fertilization on the content of available forms of phosphorus, potassium and magnesium in Haplic Luvisols*. Soil Sci. Ann., 63(1): 49-54. (in Polish) https://doi.org/10.2478/v10239-012-0011-6

Pacholak E. 1991. *Fertilizer and irrigation intensity apple orchard for the content of mineral elements in the soil and leaves*. Pozn. Tow. Przyj. Nauk Pr. Kom. Nauk Rol. Kom. Nauk Leśn., 71: 75–83. (in Polish)

Pacholak E. 2008. *Effect of 25 years of differentiated fertilization with NPK and magnesium on growth and fruit yield of apple "Cortland" and on the content of minerals in soil and leaves*. J. Fruit Ornam. Plant Res., 16: 201–214.

Pirttioja N., Carter T.R., Fronzek S., Bindi M., Hoffmann H., Palosuo T., Ruiz-Ramos M., Tao F., Trnka M., Acutis M., Asseng S., Baranowski P., Basso B., Bodin P., Buis S., Cammarano D., Deligios P., Destain M.-F., Dumont B., Ewert F., Ferrise R., François L., Gaiser T., Hlavinka P., Jacquemin I., Kersebaum K.C., Kollas C., Krzyszczak J., Lorite I.J., Minet J., Minguez M.I., Montesino M., Moriondo M., Müller C., Nendel C., Öztürk I., Perego A., Rodríguez A., Ruane A.C., Ruget F., Sanna M., Semenov M.A., Sławiński C., Stratonovitch P., Supit I., Waha K., Wang E., Wu L., Zhao Z., Rötter R.P. 2015. *Temperature and precipitation effects on wheat yield across a European transect: a crop model ensemble analysis using impact response surfaces*. Clim. Res., 65: 87-105. https://doi.org/10.3354/cr01322

Ruiz-Ramos M., Ferrise R., Rodríguez A., Lorite I.J., Bindi M., Carter T.R., Fronzek S., Palosuo T., Pirttioja N., Baranowski P., Buis S., Cammarano D., Chen Y., Dumont B., Ewert F., Gaiser T.,

HLAVINKA P., HOFFMANN H., HÖHN J.G., JURECKA F., KERSEBAUM K.C., KRZYSZCZAK J., LANA M., MECHICHE-ALAMI A., MINET J., MONTESINO M., NENDEL C., PORTER J.R., RUGET F., SEMENOV M.A., STEINMETZ Z., STRATONOVITCH P., SUPIT I., TAO F., TRNKA M., DE WIT A., RÖTTER R.P. 2018. *Adaptation response surfaces for managing wheat under perturbed climate and CO_2 in a Mediterranean environment*. Agric. Syst., 159: 260-274. https://doi.org/10.1016/j.agsy.2017.01.009

SIENKIEWICZ S., WOJNOWSKA T., KRZEBIETKE S., WIERZBOWSKA J., ŻARCZYŃSKI P. 2009. *Content of available forms of some micronutrients in soil after long-term differentiated fertilization*. J. Elem., 14(4): 787-794. https://doi.org/10.5601/jelem.2009.14.4.787-794

SZEWCZUK A., KOMOSA A., GUDAROWSKA E. 2011. *Effect of soil potassium levels and different potassium fertilizers on yield, macroelement and chloride nutrion status of apple trees in full fruition period*. Acta Sci. Pol. Hort. Cult., 10(1): 83-94.

TKACZYK P., BEDNAREK W. 2011. *Evaluation of soil reaction (pH) in the Lublin region*. Acta Agroph., 18(1): 173-186. (in Polish)

TKACZYK P., BEDNAREK W., DRESLER S., KRZYSZCZAK J. 2014. *Evaluation of nutrients supply in apple trees cultivated in Lubelskie Region*. Acta Agroph., 21(4): 507-515.

TKACZYK P., BEDNAREK W., DRESLER S., KRZYSZCZAK J. 2016. *Evaluation of soil reaction and content of assimilable nutrients in soils of South-Eastern Poland*. Acta Agroph., 23(2): 249-260.

TKACZYK P., BEDNAREK W., DRESLER S., KRZYSZCZAK J., BARANOWSKI P. 2017*a*. *Relation of mineral nitrogen and sulphate sulphur content in soil to certain soil properties and applied cultivation treatments*. Acta Agroph., 24(3): 523-534.

TKACZYK P., BEDNAREK W., DRESLER S., KRZYSZCZAK J., BARANOWSKI P., SŁAWIŃSKI C. 2017*b*. *Relationship between assimilable-nutrient content and physicochemical properties of topsoil*. Int. Agrophys., 31(4): 551-562. https://doi.org/10.1515/intag-2016-0074

TYLER G., OLSSON T. 2001. *Concentrations of 60 elements in the soil solution as related to the soil acidity*. Eur. J. Soil Sci., 52: 151-165. https://doi.org/10.1046/j.1365-2389.2001.t01-1-00360.x

WANG G., ZHANG X., WANG Y., XU X., HAN Z. 2015. *Key minerals influencing apple quality in Chinese orchard identified by nutritional diagnosis of leaf and soil analysis*. J. Integr. Agric., 14(5): 864-874. https://doi.org/10.1016/S2095-3119(14)60877-7

ZIA M.H., AHMAD R., KHALIQ I., AHMAD A., IRSHAD M. 2006. *Micronutrients status and management in orchards soils: applied aspects*. Soil Environ., 25(1): 6-16.