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Original article

Case Study on High and Medium Yielding Perennial Energy Crops, *Miscanthus* × *Giganteus* Anders. and *Elymus Elongatus* (Host) Runemark, 10-years Cultivation Impact on Main Soil Chemical Properties

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The aim of the research was to determine the effect of 10 years of growing the perennial energy grasses giant silvergrass (GS) and tall wheatgrass (TW) on the content of main soil nutrients, under differentiated nutrition intensity. The following nutrition treatments were monitored: intensive 120 kg/ha N per year (T1), semi-intensive 60 kg/ha N per year (T2), and untreated control (T3), whereby on both treatments T1 and T2 a dose of 30 kg/ha P and 30 kg/ha K was applied before the establishment of crop stands. The small-plot experiment was conducted in soil-climatic conditions of the East Slovak Lowland on heavy Fluvic gleysol in 2013. Over the monitored 10-year period, the cumulative dry matter yield was 266.6; 212.9; 163.2 t/ha at GS, in the order of T1-T2-T3, and 120.5; 96.6; 70.2 t/ha at TW, respectively. The change status (final state of autumn 2022 vs. initial of autumn 2012) of soil main chemical parameters (total nitrogen, and available phosphorus, potassium, magnesium, and calcium content; exchange soil reaction; organic carbon and humus content; and carbon/nitrogen ratio were followed) was crop specific in general, as strongly influenced by the nutrition intensity and by crop cumulative yield as well. Total nitrogen content in soil was changed as follows: +216; +167; +207 kg/ha at GS, and +306; +230; +90 kg/ha at TW, in the order of T1-T2-T3, while soil organic carbon content: +2.036; +1.883; +1.631 t/ha at GS, and +2.743; +2.104; +1.105 t/ha at TW, respectively. The change status of further parameters was positive/negative in ratio of 17/19, thus 29/19 in total.

Key words: giant silvergrass, tall wheatgrass, dry matter yield, nutrition intensity, soil nutrition content

Prospective energy crops include perennial grasses: giant silvergrass (GS) *Miscanthus* ×*giganteus* Anders. and tall wheatgrass (TW) *Elymus elongatus* (Host) Runemark (GS) is originating from south-eastern Asia and TW is native to southern Europe and Asia Minor, whereby GS*,* as a C4 energy crop, has a high potential yield (Lewandowski *et al.* 2000, 2003) and low nitrogen demands (*Cadoux et al*. 2014), while TW is a C3 plant, which is convenient for energy production and can increase carbon sequestration (Martyniak *et al*. 2017). As both grasses are applied worldwide under temperate climate, with the concept of marginal soils being preferred, it is important to have information about the condition and development of soil properties.

The manner of excessive land use and climate problems impact the degradation of soil organic matter. In Slovakia, this degradation threatens up to 70% of soil (Kobza 2014). Since the degradation has a gradual nature, i.e. the decrease of soil

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available nutrient content related to their negative balance, and consequently the deterioration of the chemical and physical parameters of the soil.

The ecological reasons for growing energy crops include their beneficial effect on limiting the leaching of mobile forms of nitrogen during long-term exposure of crops in one location, increasing the content of organic matter in the soil, *etc*. (Hůla & Procházková 2002). In the global carbon cycle, carbon in the soil is of the greatest importance and, depending on the conditions, can eliminate or sequester greenhouse gases in the environment (Barančíková *et al*. 2019). Carbon sequestration or carbon loss from soil depends on plant species (Schneckenberger & Kuzyakov 2007; Hillier *et al*. 2009; Cattaneo *et al*. 2014; Impagliazzo *et al*. 2017; Martani *et al*. 2021).

Atmospheric carbon in the form of carbon dioxide is disseminated from the soil (Chesworth 2008) (increasing from 100 vpm since preindustrial times to 385 vpm at present (Lüthi *et al*. 2008)) and causes increasing gas concentration in the atmosphere. The ratification of the Kyoto Protocol and the compliance with legislation in terms of its reduction targets and the utilization of a wide range of measures have led to a steady reduction in carbon dioxide emissions in Slovakia, where the amount of CO_2 emissions fell by 14.1% in 2012 compared to 2000 (Guštafíková *et al*. 2014). *Miscanthus* could reduce greenhouse gas emissions precisely by sequestering carbon in the soil (Anderson-Teixeira *et al*. 2009; Hillier *et al*. 2009; Nakajima *et al*. 2018).

In general, perennial energy crops are in the focus of interest due to the high yield potential and quality of produced lignocellulose biomass (Manzone *et al*. 2014; Larsen *et al*. 2018; Ouattara *et al.* 2022), and therefore they provide valuable option for mitigating the impact of greenhouse gases (Schweier *et al*. 2017). There are certainly several strategies to increase soil carbon stocks, including planting the energy crops (Lal 2004). Thus, one of the measures to preserve and gradually increase the amount of soil organic carbon, according to the directive of the Ministry of the Environment of the Slovak Republic from 2014, is the planting of perennial crops.

The cultivation of energy crops has the potential to reduce CO_2 emissions and by storing carbon in the soil because of land-use change. In the matter of carbon balance, energy crops raise the carbon stock in arable land (Davis *et al.* 2010; Don *et al*. 2012; Zimmermann *et al*. 2012). The gathering of carbon by energy crops is carried out by perennial grasses (Anderson-Teixeira *et al*. 2009) or on native grasslands (Dondini *et al.* 2009a). To illustrate, GS can incorporate up to 0.59 ± 0.16 t/ha C into the soil per year (Clifton-Brown *et al*. 2007). Removing natural vegetation, mostly through deforestation for the cultivation of energy crops, may release large amounts of CO_2 into the atmosphere (Danielsen *et al*. 2009). Conversion of uncultivated natural land onto biofuel plantations has been found to result in significant losses of soil organic carbon (Anderson-Teixeira *et al.* 2009). On the other hand, also converting agricultural land to energy crop plantations seems to be a better way to go from a carbon balance point of view. Especially with the growth of the biofuel complex, the concept of marginal land (Barro *et al*. 2022) has reemerged as a concept commonly associated with the promotion of agrofuels (Nalepa & Bauer 2012).

Converting agricultural land to plantations of energy plants seems to be a better way of storing carbon in the soil than destroying natural vegetation. Growing energy crops has the potential to reduce CO_2 emissions (Don *et al.* 2012; Zimmermann *et al.* 2012). Volk *et al.* (2004) mention that carbon sequestration under energy crops should be at least 0.25 t/ha C per year.

Different land use affects not only changes in soil parameters and production quality (Duffková *et al*. 2005; Symanowicz *et al*. 2014; Kron *et al*. 2017). Energy crops should not compete with food or feed crops, so it is recommended to grow them on less fertile soils that are not suitable for food and feed crops (Nalepa & Bauer 2012; Agostini *et al*. 2015; Mandalova *et al.* 2017). GS is a good candidate for the development of C4 energy crops for marginal landscapes (Sun *et al.* 2021a). Estimates of carbon sequestered under energy crops by Sartori *et al*. (2007) range between 0.6 − 3.0 t/ha C per year. The increase of organic carbon in the soil is possible due to the high amount of plant residues entering the soil when energy crops grow (Toenshoff *et al*. 2013; Wachendorf *et al*. 2017; Ouattara *et al*. 2021).

Knowledges concerning energy crops is still incomplete (Sun *et al.* 2021b), as these crops belong to several botanical species and have different production potentials basically from medium to high (Tóth 2022). Grasses of the genus *Miscanthus* can accumulate significant amounts of macronutrients in their organs. It is an important source of soil enrichment after plantation termination (Stypczyńska *et al.* 2017). Some other species such as TW *Elymus elongatus* (*Csete et al*. 2011) and perennial rye *Secale cereanum* (Sipos & Halász 2007), both have great industrial potential and are suitable for marginal agro-ecological conditions. These crops are currently being studied by several research institutions (Zapater *et al*. 2017; Miriti *et al*. 2017; Weijde *et al.* 2017; Ashman *et al*. 2018; Gautam 2020; Chupakhin *et al*. 2021; Kamei *et al*. 2021; Mamirova *et al*. 2021; Leroy *et al*. 2022, Huang *et al*. 2023).

Currently, there is not enough agronomically usable knowledge about *Miscanthus ×giganteus* Anders. and *Elymus elongatus* L. in Slovakia. Therefore, there is a need to understand the response of these crops to different soil and climatic conditions as well as nutritional intensity to develop appropriate cultivation technologies (Tóth 2022). In agreement with the status, the objective of this study was to evaluate the changes in selected soil chemical parameters in stands of energy crops grown on Gleyic fluvisol.

MATERIAL AND METHODS

In 2013, it was established an experiment with energy crops GS and TW at the experimental workplace of the National Agricultural and Food Center-Research Institute of Plant Production, Institute of Agroecology situated in Milhostov near town of Trebišov, in the East Slovak Lowland. This region is a fluvial plain with typical Gleyic fluvisol and moderate climate of Central Europe. In the trial, no irrigation was applied.

The monitored soil chemical properties are listed in Table 1, the weather conditions are presented in Table 2. Monitored characteristics of weather came from the SHMÚ (Slovak Hydrometeorological Institute), from the observation station which is closest to the experiment site, which is a part of official network stations. The station is located exactly up to 1 km from the trail site as the crow flies. A more detailed description of the site can be found in related work (Tóth *et al.* 2023). World Meteorological Organization (WMO) recommends using worldwide standard climate norms from the period 1961 − 1990, by which in Slovakia average temperature is 0.26°C warmer than the average of 1901 − 1980, and the last 30-year period 1983 − 2012 is 0.93°C warmer.

The stand of GS was established by the planting of rhizomes, which were obtained from a mother stand, in the spacing of 1×1 m, into finely prepared soil on 2013 April 10. The root shoots were taken from the mother stand 2 weeks before the planting, by ploughed out. The shoots were covered by finely prepared topsoil, whereby the planting depth was 25 cm. The planted root shoots had a minimum length of 15 cm. This way, it reached a high viable of planted rhizomes (96%). During the experiment, no relevant occurrence of fungal diseases and pests was detected, which is in agreement with our former findings (Tóth *et al*. 2023a). In the first and second year of growing, GS stand was protected against weeds only, by applying herbicides in the early stages, and later with mechanical treatment. Beginning from the third utility year, weed pressure was regulated by the crop itself by expanding the branching circle.

Main nutrients N, P and K were supplied to the soil according to the treatment at level of 60 N, 30 P and 30 kg/ha K in the/or a year of establishment (2013) at T1 and T2. In every next production year (2014 − 2022), nitrogen was applied yearly in differentiated doses of 120 kg/ha at T1 and 60 kg/ha at T2. The untreated control T3 was not fertilised. The trial was conducted in a randomized block design with three replications, therefore 9 trial members (3 treatments × 3 replications) were included in the total.

The stand of TW was established by sowing using a small plot grain seeder, with a row space of 12.5 cm, and a sowing rate of 35 kg/ha was applied. The sowing was realized into finely prepared soil on 2013 September 25. And again, during the monitored period of 10 years, we did not record any economically harmful occurrence of disease and insect pests. During the experiment period, TW stand was protected yearly against weeds, by herbicides at the beginning of the vegetation period in early spring. At TW, the nutrition treatment (T1-T2-T3) was the same as in the case of GS.

The collection of soil samples and their ma-

T a b l e 1

Average soil nutrient content (depth of 0 − 30 cm), the initial status of original state from the year 2012 (autumn)

Nt [%]	P [mg/kg]	K [mg/kg]	Mg [mg/kg]	Ca [mg/kg]	pH/KCl	C- Soil organic carbon. [%]	Humus, [%]	C/N
0.156	92.95	229.45	307.6	4705	6.69	1.461	2.515	9.65
	middle	suitable	middle	high	neutral		middle	*Middle

* Low – low total nitrogen content concerning carbon content (calculated by Sotakova method); values/categories determined according to Mehlich 3 method (P, K, Ca), Kjeldahl method (Nt), Tjurin´s method (C-ox, Humus), potentiometric method (pH/KCl).

T a b l e 2

Weather conditions on the trial site of Milhostov, average air temperature and sum of precipitations per year and during the main growing season (IV-IX, April till September) 2013 − 2022, and adequate values of 30-year normal (1961 − 1990)

Parameter	Period	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	average	normal
Temperature [°C]	year	10.3	11.1	11.0	10.5	10.0	11.3	11.3	10.6	10.0	11.2	10.7	8.9
	IV-IX	17.4	17.2	18.0	17.7	17.2	19.2	18.0	16.8	17.1	18.2	17.7	16.0
Precipitations [mm]	year	530	613	447	697	583	512	620	685	539	464	569	550
	IV-IX	298	425	227	350	368	318	395	473	307	295	346	348

nipulation was carried out in agreement with Decree No. 151/2016, (MADR SR, 2016). Each trial member was sampled in depth of 0 − 30 cm, both at the trial beginning (2013) and trial end (2022). The average soil samples were analysed, while the samples were averaged by the crops and treatments. Soil samples were analysed using standard methods for determining soil chemical parameters, whereby classic twin analyses were performed on each of the average samples. Determination of soil organic carbon was done by the Tjurin method (ISO 14235 1998), total nitrogen content by the Kjeldahl method (Hrivňáková & Makovníková *et al*. 2011), available phosphorus and potassium by the Mehlich III method (Mehlich 1984) and the exchange soil reaction was determined by the potentiometric method (ISO 10390 2005).

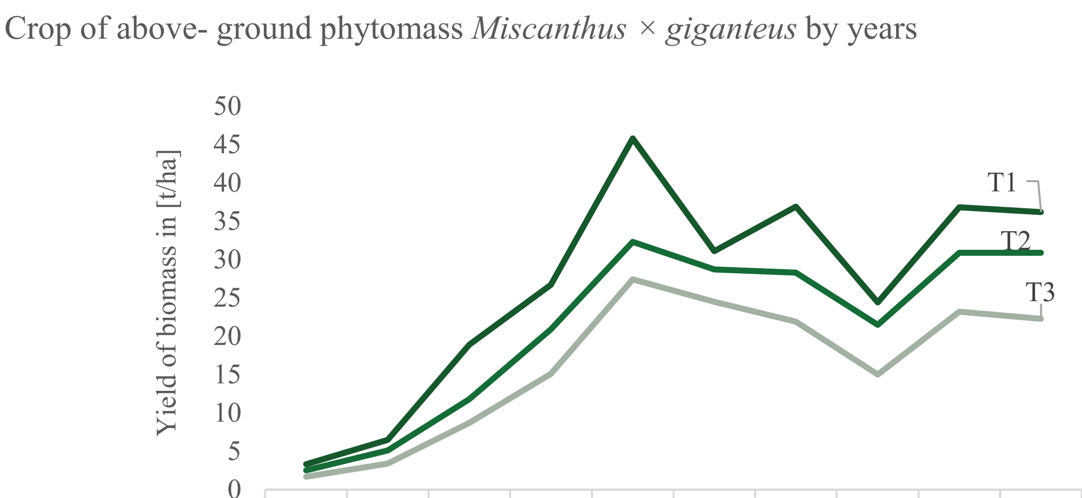
The plant material was harvested yearly, regularly in February or March, when a low content of moisture in above-ground dry matter (DM) was reached at the end of winter or the beginning of spring. Moisture content was measured gravimetrically, then DM yield was calculated subsequently and absolute dry matter content was applied.

RESULTS AND DISCUSSION

Crops yield

In the year of establishment (2013) the yield of above-ground phytomass reached 1.7 − 3.3 t/ha DM, depending on the intensity of nutrition (Figure 1). In 2017, it reached the highest DM yield of 45.8 t/ha at intensive treatment (T1). In the next years, it was recorded a decrease in DM yield to the level of 24.4 − 36.9 t/ha. The highest DM yield on the semi-intensive treatment (T2) in 2017 was 32.3 t/ha. Similarly, DM yield at untreated control (T3) was 27.4 t/ha in 2017, and in the next years, it was in the range of 15.1 − 23.2 t/ha. The cumulative DM yield (total yield during the period of 2013 − 2022) was 266.6 − 212.9 − 163.2 t/ha, in the order of T1-T2-T3. Under conditions of heavy Gleyic fluvisol, the total production of GS phytomass corresponds with the level of nutrition intensity, which conforms suitability of GS growing on East Slovakia Lowland.

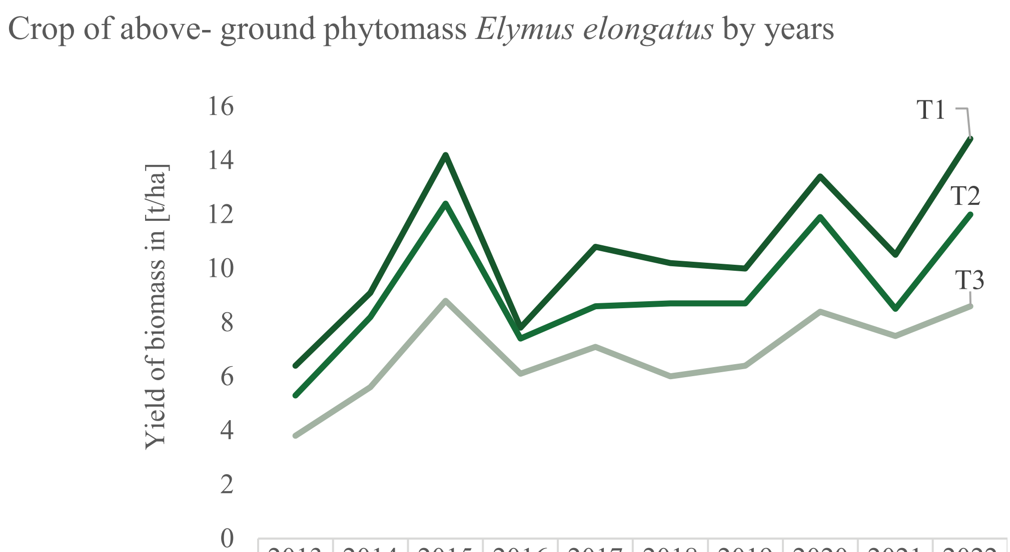
Cultivation of GS has many advantages for the production of biomass, especially due to its high yield per hectare of phytomass in the range of 20 − 40



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
T1 - intensive level nutrition (120 kg/ha)	3.3	6.5	18.9	26.7	45.8	31.1	36.9	24.4	36.8	36.2
T2 - intensive level nutrition (60 kg/ha)	2.5	5.1	11.8	20.9	32.3	28.7	28.3	21.5	30.9	30.9
T3 - control (0 kg/ha)	1.7	3.4	8.7	15.1	27.4	24.5	21.9	15	23.2	22.3

Fertilization levels according to nutritional variants and years

Figure 1. Time development of dry matter yield of *Miscanthus* ×*giganteus*, by the treatments and years.



	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
T1 - intensive level nutrition (120 kg/ha)	6.4	9.1	14.2	7.8	10.8	10.2	10	13.4	10.5	14.8
T2 - intensive level nutrition (60 kg/ha)	5.3	8.2	12.4	7.4	8.6	8.7	8.7	11.9	8.5	12
T3 - control (0 kg/ha)	3.8	5.6	8.8	6.1	7.1	6	6.4	8.4	7.5	8.6

Fertilization levels according to nutritional variants and years

Figure 2. Time development of dry matter yield of *Elymus elongatus*, by the treatments and year.

t/ha DM worldwide. The production potential of this plant under favorable conditions is over 30 t/ha DM. As a C4 plant, GS efficiently uses solar energy, water and nutrients, while the crop is highly resistant to diseases and pests. According to the author (Ouattara *et al.* 2020), GS DM yields are strongly influenced by sprout weight and density and number of sprouts per plant, and light interception (through leaf area index) compared to other *Miscanthus* species.

The production of above-ground phytomass of TW was the highest at the most intensive nutrition treatment (T1), ranging from 7.8 − 14.8 t/ha, which depends on agro-climatic conditions (Figure 2). That confirms the expectation, that under favorable conditions, the production potential of TW can exceed 15 t/ha DM. Under the occurred agro-climatic conditions, TW was highly resistant to diseases and pests. The amplitude of the expansion of the cultivation areas is considerably wide, ranging from 100 − 300 m above sea level (Porvaz *et al.* 2012). The cumulative DM production was 107.2 − 91.7 − 68.3 t/ha, in the order of T1-T2-T3. According to Tóth (2023), TW is convenient for all types of marginal soils included in his pilot large-scale experiments. Moreover, in the pilot trials, TW better tolerated occasional waterlogging on heavy clay soil compared to other energy crops. The crop is suitable for cultivation in the soil conditions of heavy Gleyic fluvisol under the climatic conditions of East Slovakia Lowland.

Soil nutrients content

A critical component of soil health and ecosystem function is soil organic matter, which is solidly influenced by selection of a plant. For C4 type of grasses compared to C3 ones, the more effective use and balance of water, nitrogen and other biogenic substances involved in higher biomass production, which could be typical under appropriate conditions, therefore e.g. the health of organic soil matter is the result of long soil-forming processes. (Majtkowski *et al*. 2004; Porvaz *et al*. 2012). This small-plot trial was performed in the soil-climatic conditions of the East Slovak Lowland on heavy fluvic gleysoil for 10 years (2012 − 2022), with differentiated nutrition intensity. Under these climate conditions, the mineralisation processes depend on the chemical compounds of the crop residuals and their root exudates. A set of basic functional relations could be evaluated between some of the soil's main nutrients and phytomass production (Table 3, Figures 1 and 2).

Total nitrogen, Nt

The soil content of total nitrogen (Nt) is a relatively stable indicator, as its highest quantity is the organic nitrogen and only a low proportion of it is liable to a transformation. It can be noted, that nitrogen content in plant tissue relates to physiological health (Porvaz *et al.* 2012). *Miscanthus* species have a relatively low requirement for nitrogen and other

T a b l e 3

The average content of nutrients in the soil (depth of 0 − 30 cm), the final status at autumn of 2022

Crop	Treatment	Nt [%]	P [mg/kg]	K [mg/kg]	Mg [mg/kg]	Ca [mg/kg]	pH/KCl	C- Soil organic carbon. ox [%]	Humus [%]	C/N
Miscanthus	T1	0.204	123.3	231.0	395.5	5519.7	6.40	1.913	3.297	9.4
	T2	0.193	106.2	227.2	455.9	3142.8	6.38	1.879	3.238	9.7
	T3	0.202	142.2	229.4	387.0	5213.6	6.39	1.823	3.142	9.0
Elymus	T1	0.224	89.5	270.6	331.3	3851.7	6.35	2.070	3.567	9.2
	T2	0.207	82.8	256.5	312.6	3913.0	6.38	1.928	3.323	9.3
	T3	0.176	85.5	232.1	306.5	4068.3	6.40	1.706	2.940	9.7

* Low – total low nitrogen content relating to carbon content (calculated by Sotakova method); values/categories determined according to Mehlich 3 method (P, K, Ca), Kjeldahl method (Nt), Tjurin´s method (C-ox, Humus), potentiometric method (pH/KCl).

fertilisers compared to annual crops (Porvaz *et al.* 2012).

In the current study, the average change in the soil content of Nt was higher in TW than in GS (Figure 3), while the difference was only +0.003% (+0.044 vs.+ 0.047%). It is probably the result of higher nitrogen absorption by GS, due to the higher cumulative yield. From the point of view of crops and treatments, decrease in Nt change status of +0.068; +0.051; +0.020% (T1-T2-T3, respectively) is strongly correlated with the decrease of nutrition intensity (r +0.986) and the total yield of phytomass (r +0.990) at TW, while the change status of +0.048; +0.037; +0.046% is weakly correlated with intensity nutrition (r +0.171) and phytomass harvest (r +0.193) at GS. The high value of +0.046% in the untreated control (T3) at GS can be related to the higher difference in DM yield compared to treatment T2, as well as the adequate difference for TW with lower nitrogen consumption at a lower yield. Another reason can be connected with the rhizobial sphere's different activity, which could be formed differently under the absence of nitrogen treatment.

Fagnano *et al*. (2015) noticed that organic nitrogen in the soil's upper layer is higher, mostly because environmental limitations may have reduced the mineralization and thus enhanced storage in soil organic matter. Observations of soil Nt content after repeated biomass harvesting indicate efficient nutrient cycling and the potential contribution of biological N fixation that was observed in prior studies (Eckert *et al.* 2001; Davis *et al.* 2010). This characteristic of the rise of Nt in the soil is related to carbon sequestration in soil.

In relation to Nt, it was documented a positive change of +37.6 mg/kg in a previous paper (Tóth 2023), which was recorded after 4 years of TW cv. *Szarvasi*-1 production with an average DM yield of 6.01 t/ha. The positive change of +0.047%, which is documented in the presented work for a 10-year period, corresponds to +47.00 mg/kg Nt per year. The difference between values presented in the papers is probably related to a longer period, or more intensive formation of root mass and binding of precipitation nitrogen during the period, with a total benefit of +210.00 kg/ha Nt in 10 years, or +21.00 kg/ha per year.

In regard to the high content of Nt in soil, also Saljnikov *et al*. 2013 already observed that the divergences in Nt amount in soil may be due to soil management practices such as intensive cultivation when no crop residues remain on the soil surface, or nutrition management with more intensive mineralization and higher biomass production under inten-

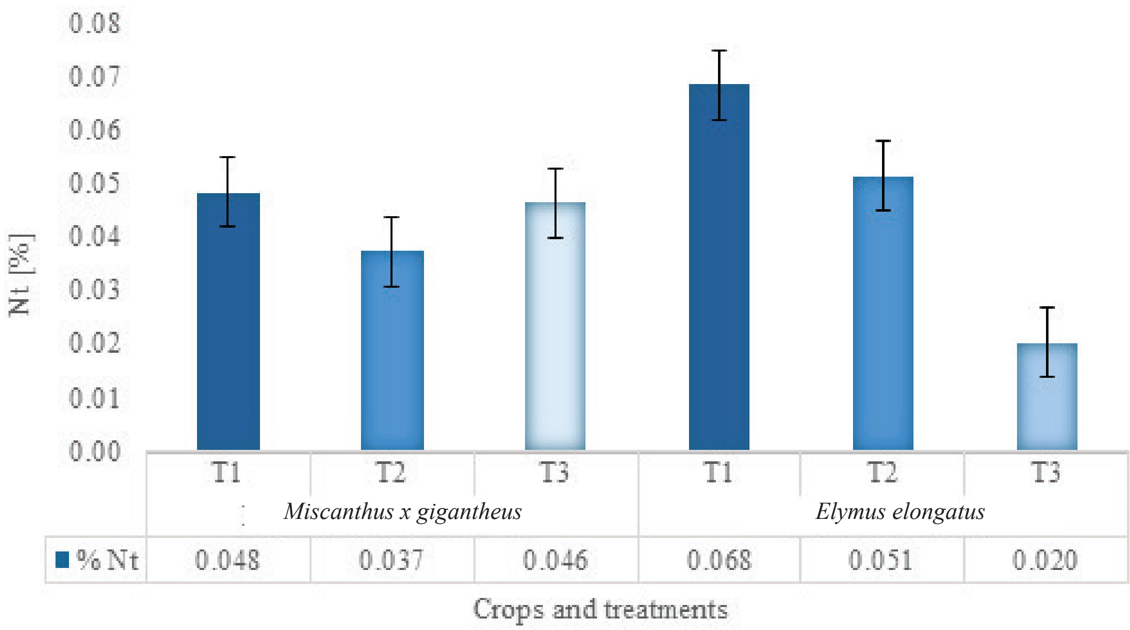


Figure 3. Change status in soil content of total nitrogen (Nt), by the crops (*Miscanthus ×giganteus*, and *Elymus elongatus*) and treatments (T1 – intensive nutrition, T2 – semi-intensive nutrition, T3 – untreated control), standard deviation added.

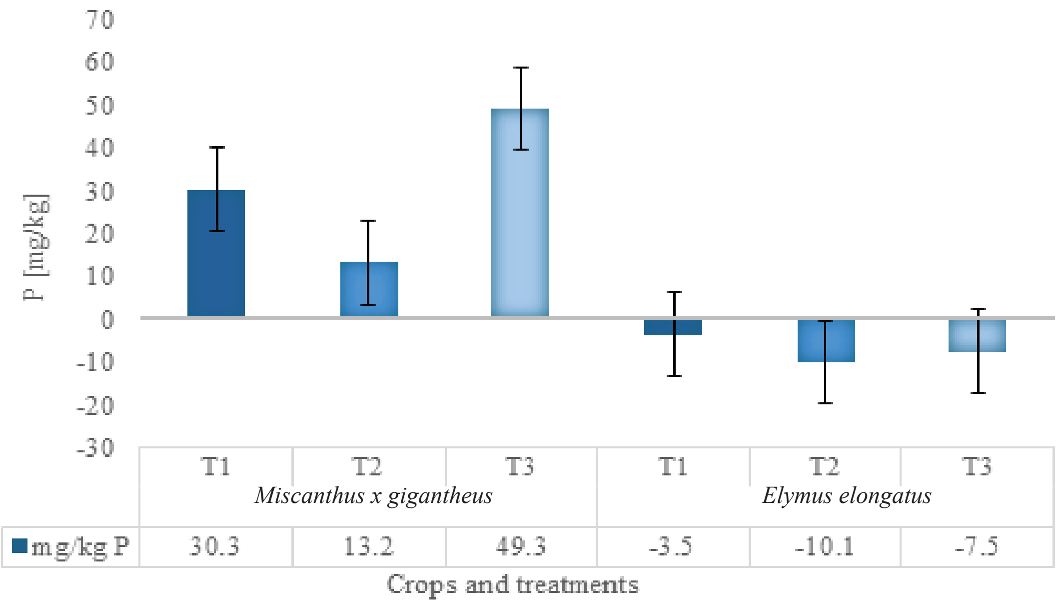


Figure 4. The change status in soil content of available phosphorus (P), by the crops (*Miscanthus ×giganteus,* and *Elymus elongatus*) and treatments (T1 – intensive nutrition, T2 – semi-intensive nutrition, T3 – untreated control), standard deviation added.

sive fertilisation as well. Regardless that the potentially mineralizable nitrogen (Npot) represents only a low proportion of total nitrogen in soil 6.5 – 11.7% in his study, it has an enormous effect on plant nutrition, as microbial processes and soil organic matter turnover. If GS is harvested after nutrient re-translocation from above to below-ground tissues, it can potentially supply considerable amounts of N and P to the soil (Porvaz *et al.* 2012; Pisani *et al.* 2024).

Available phosphorus, P.

In the study it was noticed negative correlation of P with the DM yield and the intensity of fertilisation at GS (r −0.506; r −0.525), and medium correlation at TW (r +0.573; r +0.597) in the same order. In comparison with previous work (Tóth 2023), the value of P change status was positive +21.1 mg/kg, which was noticed after 4 years of TW cultivation at the average DM yield of cv. *Szarvasi*-1 6.01 t/ha. The low value of −7.0 mg/kg P per year is documented in the presented work for the monitored 10-year period (Figure 4), which corresponds with the fact, that P received from the soil as phosphate anion is the least available soil microelement to which plants have developed numerous adaptations to receive it (Porvaz *et al*. 2012).

P content depends on fertilisation and management of absorption by energy crops. Soil acidity influences the mobility and accessibility of the most important plant nutrients, especially P and K. The relationship between soil reaction values and phosphorus in the soil was also noted by *Dong et al.* (2009). The optimal soil reaction for growing GS is in the range of 5.5 – 6.7 pH/KCl, and a reduction in yield was observed at values above 7.0 (Strašil 2009). There is a significant connection and inverse proportionality between fertilisation and nutrient uptake by the energy crop, McLaren *et al.* (2020) confirmed that P can be accumulated in unavailable form in fertilised soil, which contributes to an agricultural inefficiency of P.

Available potassium, K

The leaching of K, of which 0.2 – 10 kg/ha is leached annually in conditions of moderately heavy soils in general, is also one of the limiting factors for K in soil. However, in terms of criteria for the evaluation of chemical analyses of arable soils (Slovak Republic, Regulation No. 151/2016 2016), the content of available K in the the trial was classified as middle (Figure 5). The correlation coefficient was medium, both regarding K change status with the DM yield and the nutrition intensity at GS (r +0.439; r +0.420), but strong at TW (r +0.992; r +0.988, respectively).

The capacity of available K in soil depends on the perception of K by cultivated plants. If there is a trend of lower values of K change status at GS, it can be connected with insufficient K fertilisation (Figure 5).

Available magnesium, Mg

The results show the correlation of Mg with the DM yield and the intensity of fertilisation at GS is low (r +0.091; r +0.113), but at TW is more strong (r +0.951; r +0.960, respectively), Figure 6. Macronutrients P, K, and even Mg, did not effect DM yield decreasing, due to the high soil content.

In conditions of lack of Mg, there is the lower transfer of carbohydrates from above ground part

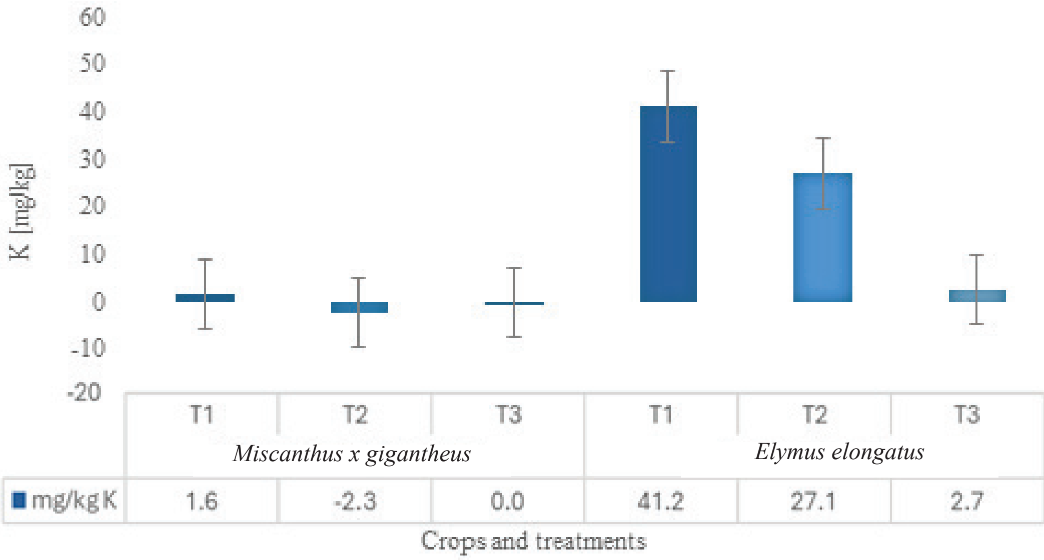


Figure 5. The change status in soil content of available potassium (K), by the crops (*Miscanthus* ×*giganteus*, and *Elymus elongatus*) and treatments (T1 – intensive nutrition, T2 – semi-intensive nutrition, T3 – untreated control), standard deviation added.

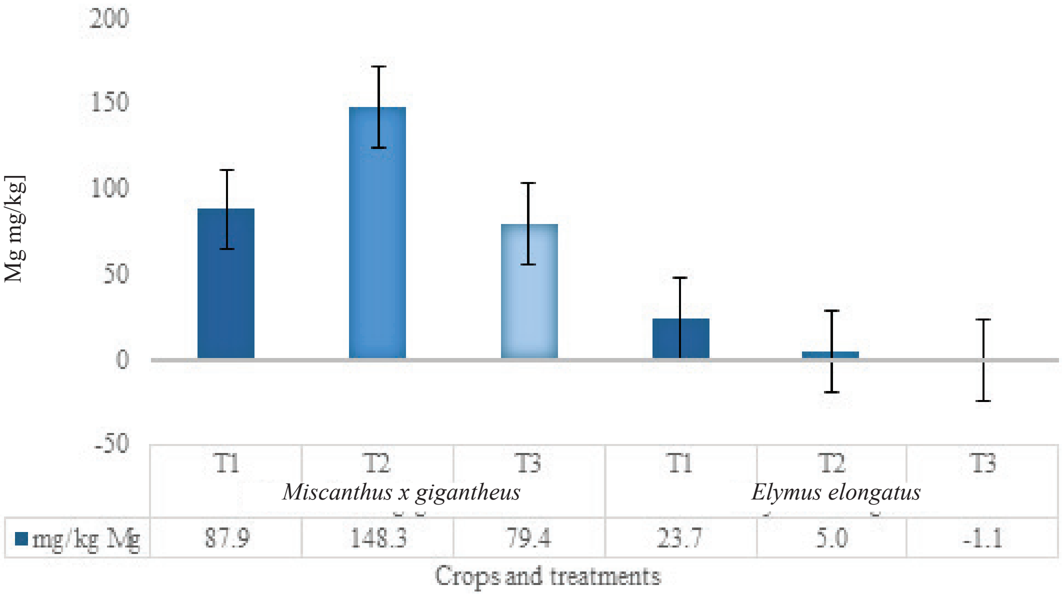


Figure 6. The change status in soil content of available magnesium (Mg), by the crops (*Miscanthus* ×*giganteus*, and *Elymus elongatus*) and treatments (T1 – intensive nutrition, T2 – semi-intensive nutrition, T3 – untreated control), standard deviation added.

to roots, which injures the development of the root system, which gradually decreases the uptake of other nutrients. Soil Mg absence can happen under the following conditions: acidic soil (pH/KCl <5.4), and high K content (Tóth *et al*. 2023b).

Available calcium, Ca

In the experiment, the correlation of Ca change status with the DM yield and nutrition intensity was weak only at GS (r +0.141; r +0.119), while strong at TW (r −0.977; r −0.970), Figure 7. As cited, Tóth

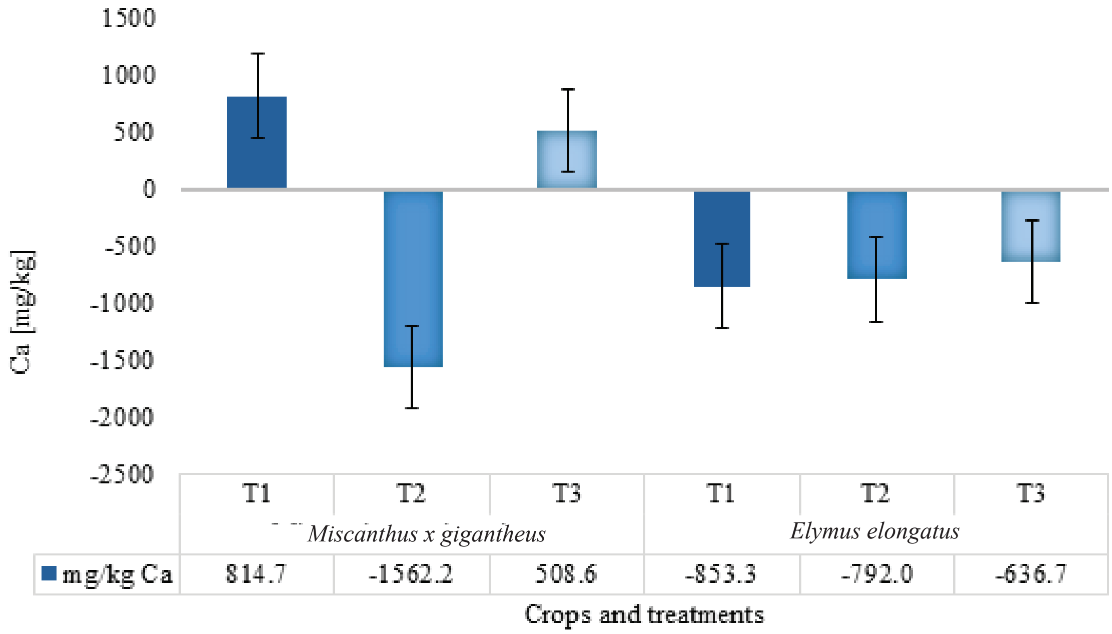


Figure 7. The change status in soil content of available calcium Ca, by the crops (*Miscanthus ×giganteus* and *Elymus elongatus*) and treatments (T1 – intensive nutrition, T2 – semi-intensive nutrition, T3 – untreated control), standard deviation added.

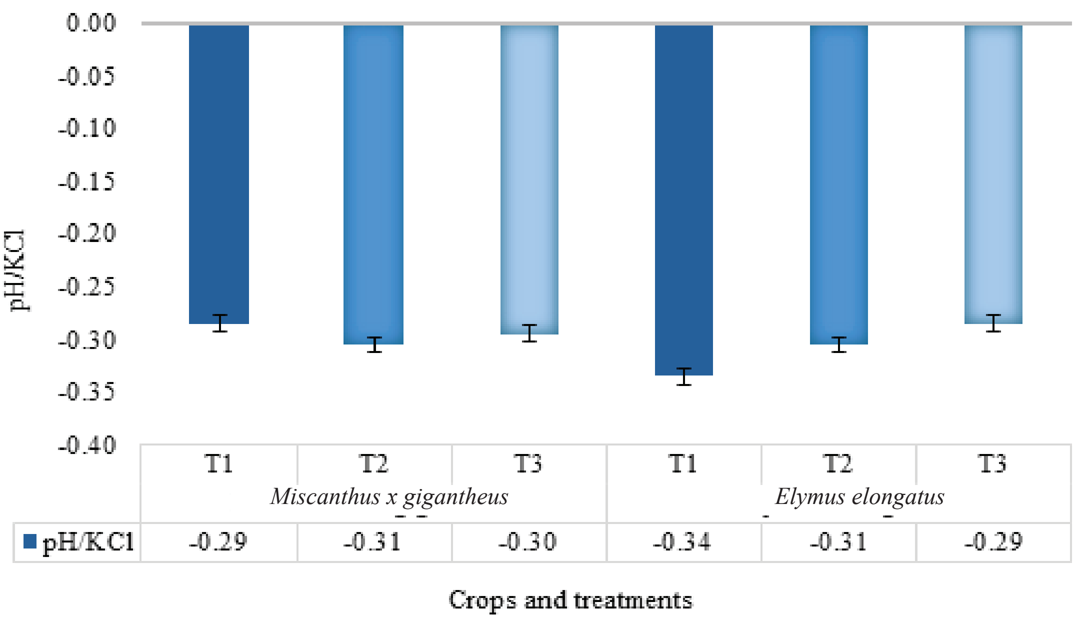


Figure 8. The change status of soil reaction (pH/KCl), by the crops (*Miscanthus ×giganteus* and *Elymus elongatus*) and treatments (T1 – intensive nutrition, T2 – semi-intensive nutrition, T3 – untreated control), standard deviation added.

et al. (2023) worked on the experiment with TW cv. of *Szarvasi-1* and *Alkar* and found out that change in soil nutrients content (K, Ca, Mg) was as follows: the value of K was in positive change of +68.3 mg/kg, value of available Ca was in negative change of −390.2 mg/kg, and value of available Mg was in negative change of −9.0 mg/kg again. At K, we found a positive change of +23.6 mg/kg K per year in the total average. The notable negative change status of Ca (−760.7 mg/kg), and lower value of Mg

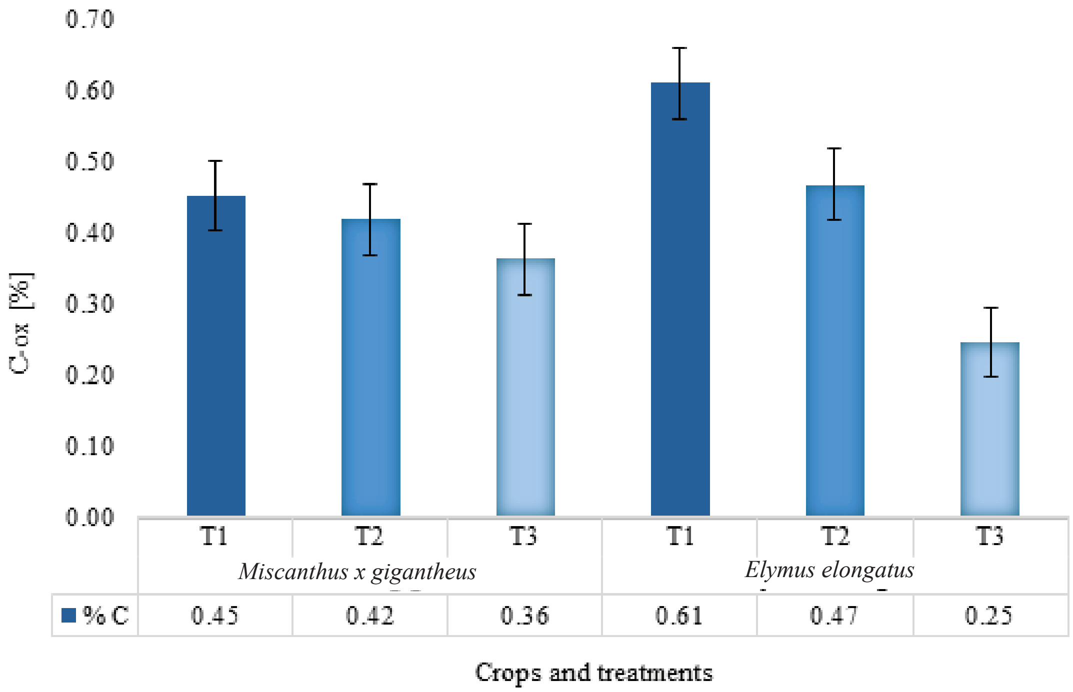


Figure 9. The change status in soil content of organic carbon (C-ox), by the crops (*Miscanthus ×giganteus* and *Elymus elongatus*) and treatments (T1 – intensive nutrition, T2 – semi-intensive nutrition, T3 – untreated control), standard deviation added.

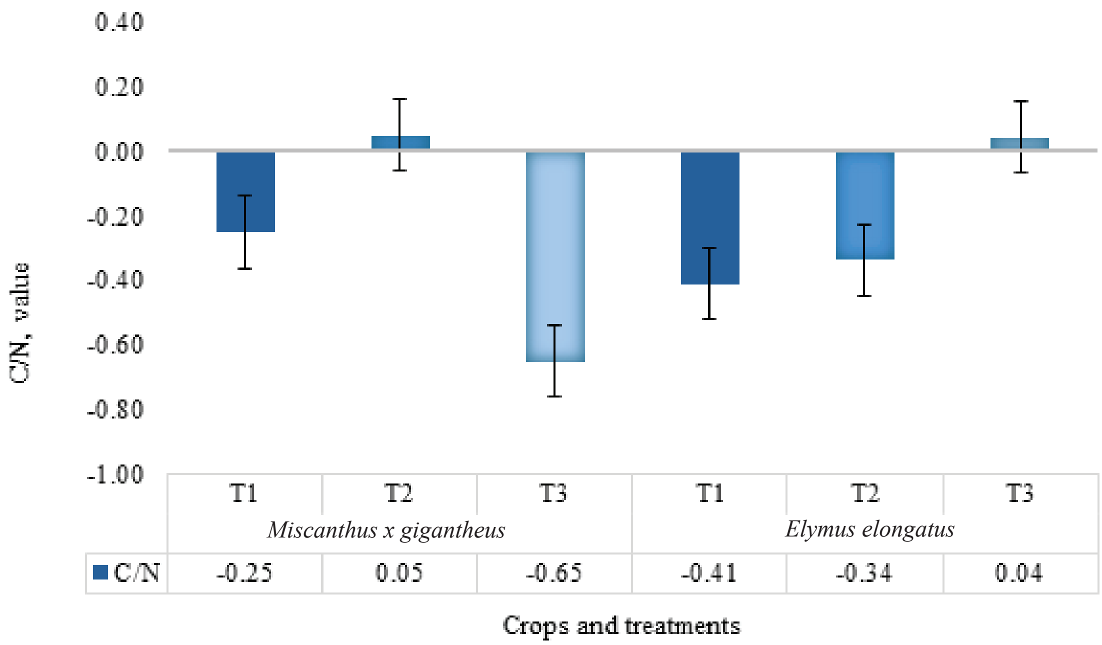


Figure 10. The change status of carbon/nitrogen ratio (C/N ratio), by the crops (*Miscanthus ×giganteus* and *Elymus elongatus*) and treatments (T1 – intensive nutrition, T2 – semi-intensive nutrition, T3 – untreated control), standard deviation added.

(+9.2 mg/kg) per year, as we document in the presented work based on a 10-year period, corresponds with the fact, that both macronutrients compete for absorption sites on soil particles. Excessive Ca in soil can inhibit Mg uptake by plants, and vice versa. This competitive interaction can lead to nutrient imbalances if one nutrient is overly abundant. Therefore, when the Ca/Mg ratio falls too low, the plant absorbs more Mg.

Ca represent important macronutrient in terms of maintenance the soil complexity, mainly by promoting the aggregation of soil particles. In soils with adequate phosphate levels, Ca can react with phosphate and form less soluble calcium phosphate. This reaction reduces the availability of both Ca and P for plant uptake. A straight consequence of the usage of calcareous substances in the soil is the adjustment of the soil reaction and the indirect effect is gradual changes in other soil conditions properties that correspond with the soil reaction worth (Tóth *et al*. 2023b). Yearly deficit of Ca from soil, by leaching and by using fertilisers are described closely by Bizík *et al*. (1998), while it can reach the level of 350 kg/ha CaO. Ca neutralizes soil acidity, therefore to prevent soil acidification, setting up regular soil liming is necessary, which helps to manage changes in acidification.

Soil reaction, pH/KCl

Soil acidification is a naturally occurring process, whereby it can be increased by some agricultural practices, such as excessive use of ammonium-based fertilisers. Therefore predictably, a higher decrease in soil reaction (−0.30; −0.31) was observed in both tested crops, GS and TW (Figure 8). Also the result shows the medium correlation of pH/KCl change status with the DM yield and nutrition intensity at GS (r +0.519; r +0.500), while correlation was strong at TW (r −0.990; r −0.993, respectively).

Soil reaction is a crucial agrochemical property with a straight impact on other soil physical and chemical properties, which effect the growth and development of cultivated plants and microorganisms life in the soil, so it has great importance on soil processes in general (Tóth *et al*. 2023). In this experiment, the exchange soil reaction (pH/KCl) status before starting the trial was 6.69 (in 2012) and in the range of 6.51 to 6.82, which is classified as neutral concerning assessment criteria (Slovak Republic, Regulation No. 151/2016 2016).

Soil organic carbon, C-ox

In the case of energy crops GS and TW, C-ox content in the soil may vary and depends on differentiated nutrition intensity also. At GS, the change status of C-ox was +0.45% at T1, +0.42% C-ox at T2, and +0.36% at T3, whereby adequate values at TW were +0.61; +0.47; +0.25%, respectively (Figure 9).

The modifications in soil organic content (SOC), due to different soil management practices, are long-fraction-term due to the stability of soil organic matter (SOM) (Kogel-Knabner *et al.* 2008). Saljnikov *et al.* (2013) confirmed that up to 60 − 85% of SOM is fixed and just 10 − 30% is an active fraction, which after an intensive encroachment is subject to changes which may be reflected in the change in the content of SOC.

Due to the intensive tillage of the soil for the last decades, the amount of carbon in the soil decreased because of decomposition and mineralization of SOM (Novara *et al*. 2020). Like other perennial grasses, TW can sequester carbon in its root system, contributing to carbon storage in soils. The content of C-ox correlated significantly with microbial biomass C, Nt and soil hydrophobicity.

At GS, it was recorded positive correlation of C-ox with DM yield (r +0.987) and nutrition intensity as well (r +0.990), whereby positive correlations were recorded at TW as well (r +0.995; r +0.992, respectively), Figure 9. The sequestration of C in soil was evident after the 10 years of cultivation of GS. However, a decrease of C after the first year of cultivation could occur due to soil disturbance, soil C increase after the 10 years was confirmed (in 2022). A further hypothesis that there would be more C in both fertilised treatments (T1, T2) in comparison with untreated control (T3), was confirmed too. The accumulation of C in the soil during 10 years of the annual biomass removal has important relevance for farmers because there are GHG (greenhouse gas) benefits of both offsetting C-intensive fuels with *Miscanthus* feedstocks (Dwivedi *et al.* 2015) and sequestering soil C.

Returning to the previous paper (Tóth 2023), it is documented a positive change of +0.265% C-ox recorded after 4 years of TW cultivation at the average DM yield of cv. *Szarvasi*-1 6.01 t/ha. The positive change of +0.045%, which was found out in the presented work based on a 10-year period, corresponds to +45.00 mg/kg C-ox per year. Most probably, the higher change status is related to a longer period of cultivation. Perennial grasses like TW require less soil disturbance and thus contribute to the gradual buildup of C-ox over time. Based on the mentioned research it was found an obvious disparity between C-ox in soil and the amount of C contained in DM cumulative yield. Therefore, the main problem of measuring C sequestration is much wider as involved in this study, when it was used only non-invasive and non-terminative methods regarding the crop stand. Thus the massive root system of both crops was not violated, nor measured as it is standard in general. Overall, TW is a deep-rooting perennial crop, which makes it an effective plant for sequestering C in soil, contributing to soil health, and aiding in climate change mitigation efforts.

If the land changes in the mode of use, the changeover to the cultivation of perennial energy crops will enable the retention and even accumulation of C in soil. It has been already described as a significant positive storage of SOC (Dondini *et al.* 2009b; Dufossé *et al.* 2014), whereas some other papers deviate from this thesis (Richter *et al.* 2015; Ferchaud *et al.* 2016;).

Carbon / nitrogen ratio, C/N

Finally, concerning the C/N ratio was obtained a medium correlation of C/N change status with the DM yield and nutrition intensity (r +0.551; r +0.569) at GS, and a strong negative correlation at TW (r –0.941; r −0.931, respectively). The change status of the C/N ratio is displayed in Figure 10.

Harvesting of GS after the transfer of the nutrients from above-ground to below-ground tissues helps to supply important amounts of N to the soil and contributes an influential role in increasing feedstock quality for biofuels. The results of research on crop residue entry to agricultural soils demonstrate better nutrient management of rhizosphere nutrient exchange which relates to the C sequesteration, which can raise the biofuel quality (Pisani *et al.* 2024).

The amount of total C-ox relates to the total Nt content. The combination of perennial plants, and soil C and N sequestration over 10 years adds value for biomass cropping and reduces the risk for farmers who may seek to cultivate biomass crops with low fertiliser input requirements (Fosu & Davis 2024).

CONCLUSIONS

The objective of this work was to evaluate the effect of 10 years of growing the perennial energy grasses *Miscanthus ×giganteus* (GS) and *Elymus elongatus* (TW) on the content of soil main nutrients, whereby differentiated nutrition intensity was monitored. The following nutrition treatments were monitored: intensive 120 kg/ha N per year (T1), semi-intensive 60 kg/ha N per year (T2), and untreated control (T3).

At GS, the change status (final state of autumn 2022 vs. initial of autumn 2012) of Nt content was as follows: +0.048; +0.037; +0.046%, in the order of T1-T2-T3, P: +30.3; +13.2; +49.3 mg/kg, K: +1.6; −2.3; −0.0 mg/kg, Mg: +87.9; +148.3; +79.4 mg/kg, Ca: +814.7; −1,562.2; +508.6 mg/kg, pH/KCl: −0.29; −0.31; −0.30, C: +0.45; +0.42; +0.36%, C/N: −0.25; +0.05; −0.65, respectively. At TW, the change status of Nt was: +0.068; +0.051; +0.020%, P: −3.5; −10.12; −7.5 mg/kg, K: +41.2; +27.1; +2.7 mg/kg, Mg: +23.7; +5.0; −1.1 mg/kg, Ca: −853.3; −792.0; −636.7 mg/kg, pH/KCl: −0.34; –0.31; −0.29, C: +0.61; +0.47; +0.25, C/N: −0.41; −0.34; +0.04, respectively. The change status of followed parameters was positive/negative in the ratio of 29/19.

Since the open field conditions the experiment with case study character, the achieved results is desirable to be integrated with other similar studies to conclude more exactly the causality of the solved context. However, the achieved results of dry matter (DM) yield demonstrated a strong influence of the intensity of nutrition on DM yield of both the crops and weak to strong impact of DM yield on followed soil parameters change status. If *Miscanthus* is harvested after nutrient retranslocation from above to belowground tissues, it can contribute significant amounts of N and P to the soil, which could be applied for TW also, but in a lower manner. Therefore, unstable status in the availability of individual elements as phosphorus, and potassium, and their reserves in the soil depends on the crop identity and nutrition intensity as well. Humus content in the soil, or C/N ratio influences the ion exchange capacity in the soil, which expresses the number of cations that can be bound and exchanged by the sorption complex of the soil. The content of nutrients in the soil (P and K) directly affects the physico-chemical (exchange) sorption of the soil, which consists in the exchange of ions between the soil colloidal complex and the soil solution. This sorption mechanism is considered the most important. Due to the one-sided use of crop rotations and the cultivation of mainly monocultures, the content of organic substances in the soil decreases, and the biological and physical properties of the soil deteriorate as well, resulting in a decrease in the economic yields of field crops. For this reason, by growing perennial energy plants (as *Miscanthus* or *Elymus*), the sorption complex of the ion exchange capacity in the soil is optimized, and at the same time carbon sequestration from root residues optimized as well, and finally has a positive effect on the physico-chemical properties of the soil.

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