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Original Paper

Yield of *Elymus elongatus* and *Secale cereanum* on marginal soils in Central Europe

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This research was focused on a production potential of tall wheatgrass (TW) and perennial rye (PR) grown in marginal and contrasting soil climatic conditions under the following mineral nutrition: (a) intensive nutrition of 245.0 $kg.ha^{-1}$ NPK, (b) semi-intensive nutrition of 122.5 $kg.ha^{-1}$ NPK and (c) untreated control of 0.0 $kg.ha^{-1}$ NPK. The large-scale pilot field experiments with two varieties of TW: Szarvasi-1 and Alkar as PR: Kriszta and Gergő were carried out on 4 research sites during 4 years (2016/2017 to 2019/2020). Despite the contrasting soil conditions, yields were variously affected by (i) nutrition, (ii) site, (iii) variety and (iv) year (the order based on their F-ratios). A dry matter (DM) yield of 5.29 $t.ha^{-1}$ on average was found, it ranged from 0.01 to 13.46 $t.ha^{-1}$. Average – minimal – maximal variety yields were as follows: Szarvasi-1 6.01–1.05 – 13.46 $t.ha^{-1}$, Alkar 5.86 – 0.62 – 12.90 $t.ha^{-1}$, Kriszta 5.06 – 0.01 – 13.21 $t.ha^{-1}$ and Gergő 4.25 – 0.05 – 10.60 $t.ha^{-1}$. Under intensive or semi-intensive nutrition both crops are suitable for all types of tested marginal soils. TW better tolerated unexpected water-logging that occurred on Site-2 with heavy clay soil than PR, while PR is more suitable for light sandy soil. The following average DM yields were obtained under intensive nutrition on the most productive Site-3 with heavy soil: 11.77 $t.ha^{-1}$ Szarvasi-1, 10.14 $t.ha^{-1}$ Alkar, 8.01 $t.ha^{-1}$ Kriszta and 7.75 $t.ha^{-1}$ Gergő, whereas on Site-1 with light sandy soil under intensive nutrition the following average yields were achieved: 7.74 $t.ha^{-1}$ Gergő, 7.72 $t.ha^{-1}$ Kriszta, 6.29 $t.ha^{-1}$ Szarvasi-1 and 5.17 $t.ha^{-1}$ Alkar. PR had about 148 mm less precipitation on average when compared to TW (187 vs. 334 mm) because of earlier harvest time while the average daily temperature was lower by about 1.9 °C on average (16.3 vs. 18.2 °C). As to varieties Kriszta and Gergő, it is probably one of the first original research papers published and probably the first research based on large-scale experiments of PR from the time when it was recognized as an energy crop.

Keywords: *Elymus elongatus*, *Secale cereanum*, dry matter yield, marginal soils, mineral nutrition

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1 Introduction

When cultivation of energy crops became a part of modern agriculture (Kopecký et al., 2021), many studies were focused on their phytomass energy potential while taking different approaches and goals into account (Hauptvogel et al., 2022; Makovníková et al., 2020; Marišová et al., 2016). Energy crops should not compete with food or fodder crops therefore it is recommended to cultivate energy crops on less fertile soils which are not suitable for food and fodder crops (Agostini et al., 2015; Nalepa and Bauer, 2012). Particularly, with the growth of the biofuel complex, the concept of marginal soil has reemerged (Peterson and Gailbraith, 1932) as a term commonly associated with the promotion of agrofuels (Nalepa and Bauer, 2012).

The knowledge about energy crops is still incomplete, these crops belong to several botanical species and have different production potentials (basically from medium to high). Suitability for cultivation in marginal soil conditions is their special value (Hauptvogel et al., 2022; Kron et al., 2017; Marišová et al., 2016; Porvaz et al., 2012). There are some species which are not been studied enough so far such as tall wheatgrass *Elymus elongatus* (Csete et al., 2011) and perennial rye *Secale cereanum* (Sipos and Halász, 2007). Both these crops have a great industrial potential and undoubtedly are highly suitable for marginal agro-ecological conditions. The crops are currently studied by several research institutions (Kopecký et al., 2021; Ciria et al., 2020; Bernas

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et al., 2019; Vergiev, 2019; Borrajo and Sanches-Moreiras, 2018; Martyniak et al., 2017; Jafari et al., 2014, and others).

There are increased demands on crops in terms of their tolerance to various stressors because marginal conditions for cultivation are of diverse environmental quality. At present, there is not enough agronomically usable knowledge concerning perennial rye and tall wheatgrass in Slovakia. Thus, it is necessary to understand the response of these crops to different soil and climatic conditions as well as nutrition intensity to develop appropriate cultivation technologies. Based on the lack of cultivation experience, agronomically designed polyfactorial field trials are required in different types of marginal conditions.

The main aim of this work was to determine the production potential of tall wheatgrass and perennial rye grown in marginal soil and climatic conditions of Slovakia, a country with continental moderate climate of Central Europe.

2 Material and methods

2.1 Plant and soil material, trial sites and agronomy

Large-scale pilot field trial with newly-introduced energy crops (i) tall wheatgrass *Elymus elongatus* (Host) Runemark and (ii) perennial rye *Secale cereanum* was established on 4 sites located under continental Central European climate on marginal soil conditions. The trial was done in cooperation with local farmers 70 km distant from Michalovce (Slovakia):

- Site-1: Malý Horeš, altitude 120 m, mild slope, light soil and semi-arid climate;
- Site-2: Strážne, altitude 100 m, total flat, heavy soil and semi-arid climate;
- Site-3: Pozdišovce, altitude 115 m, total flat, heavy soil and semi-humid climate;
- Site-4: Košický Klečenov, altitude 340 m, slope, heavy soil and humid climate.

Table 1 Soil type of the experiment with tall wheatgrass and perennial rye, based on clay content in a topsoil layer (0-30 cm)

Site – parameter	1st fraction (%)	2nd fraction (%)	3rd fraction (%)	4th fraction (%)	5th fraction (%)	Content of first category particles (%) (soil type)
Site-1	7.28	6.62	10.29	62.11	13.71	13.90 (loamy-sandy soil/light soil)
Site-2	36.63	26.02	19.38	15.18	2.81	62.65 (clay soil/heavy soil)
Site-3	22.50	26.76	35.38	13.22	2.16	49.25 (clay-loamy soil/heavy soil)
Site-4	31.81	24.43	24.38	15.57	3.83	56.23 (clay-loamy soil/heavy soil)

1st fraction (<0.001 mm), 2nd fraction (0.001–0.01 mm), 3rd fraction (0.01–0.05 mm), 4th fraction (0.05–0.25 mm), 5th fraction (0.25-2.0 mm), content of the first category particles (sum of 1st and 2nd fraction)

Table 2 The dosage of mineral nutrients NPK (kg.ha^{-1}, oxide form) within the experiment with tall wheatgrass and perennial rye

Treatment/NPK dosage	N	P	K	Σ NPK
Intensive nutrition	125.0	60.0	60.0	245.0
Semi-intensive nutrition	62.5	30.0	30.0	122.5
Untreated control	0.0	0.0	0.0	0.0

Table 3 Sowing data of the experiment with tall wheatgrass and perennial rye

Site/parameter	Site-1	Site-2	Site-3	Site-4
Sowing day	31 August 2016	31 August 2016	12 September 2016	12 September 2016
Sowing depth (cm)	5.0	5.0	5.0	5.0
Sowing rate of Szarvasi-1 and Alkar (millions of germinating seeds per hectare)	5.75	5.75	5.75	5.75
Sowing rate of Kriszta and Gergő (millions of germinating seeds per hectare)	4.15	4.15	4.15	4.15

Soil analyses were done prior to the trial. Topsoil samples from a depth of 0-30 cm were taken, results are presented in Table 1 and suplementary Table S1. The trial was established in autumn 2016 and was carried out to 2020. Each trial crop has two varieties tested:

a) tall wheatgrass – Szarvasi-1 and Alkar,
b) perennial rye – Kriszta and Gergő.

Soil tillage was done into a depth of 24 cm on each site in the autumn followed by high-quality pre-sowing preparation aimed to achieve optimal soil-bed for successful germination and emerging. Mineral nutrition was different, there were three NPK treatments including untreated control in the trial so the intensive and semi-intensive nutrition was managed. The tested doses of NPK are presented in Table 2, while the fertilizers (combined NPK 15 : 15 : 15 and ammonium nitrate 27) was applied at the beginning of the growing season, i.e. every year in the last decade of March. The sowing data can be seen in Table 3. The experimental lay-out was randomized block design.

Notice: Due to the extreme weather difficulties on Site-2, water-logging occurred in the research field; it started in late autumn 2016 and lasted to early spring 2017. Based on these circumstances the trial stand on Site-2 was damaged, meanwhile:

- the Kriszta and Gergő plots were oversowed on 29th March 2017
- the Szarvasi-1 and Alkar plots were not oversowed; both tall wheatgrass varieties were in similar conditions and less damaged in comparison with both perennial rye varieties which were able to regenerate themselves.

2.2 Weather and soil-climate data

Part of the weather situation data presented in suplementary Table S2, the data refers to the period after sowing. The main weather situation and soil climate/condition data are presented in Table S3. Meteorological observation data were obtained from meteorological stations closest to each experimental site. The stations belong to the Slovak Hydro-meteorological Institute (SHMÚ) network with guaranteed quality data.

Soil-climate and conductivity data were taken twice a day at 12.00 AM and 12.00 PM and were measured by Em50 DECALOG Data Logger installed on each site to record the parameters from two soil layers (topsoil in the depth of 15 cm and subsoil in the depth of 45 cm) during the main vegetation period from April till September of 2016/2017–2019/2020.

2.3 Harvest and laboratory analyses

The crops were harvested in regard to their optimal stage, the harvest dates can be found in Table S4. The samples of green phytomass for DM content analyses were taken at harvest and DM content was determined gravimetrically by laboratory analyses, whereas the samples were dried at 70 °C untill the constant weight is reached.

In 2020 at harvest, soil samples were taken to determine the most important soil chemical properties. Both soil samples, taken at the beginning of the trial (i) initial (2016) and at the end (ii) final (2020) were taken from a topsoil (the depth of 0-30 cm) and each of 48 plots in total were sampled (4 sites × 4 varieties × 3 nutrient treatments). Soil sampling, sample storage as well as processing was done according to Slovak Law No. 151/2016, Law Digest (2016). Laboratory analyses of the soil samples were done according to the Mehlich 3 method (Mehlich, 1984), for soil texture parameters the Novak method (cit. Kolektív, 2000) was employed.

2.4 Statistical methods

Totally 3,072 crop data (yield, DM content, stand height and coverage) and 1,728 soil chemical properties data as well as 11,520 weather data plus 34,560 soil-climate data were statistically evaluated.

A two-step multi-factorial ANOVA was performed to identify significant factors having influence on the yield variability using Statgraphics 15.2.14. At first, an effect of 4 replications was evaluated based on 768 complete yield data. This first ANOVA resulted in a huge output, whereas the replications were quantified to be out of statistical importance as a source of variability of yields (*F*-ratio 0.00, *P*-value 0.9999). Two-, three-, and four-way interactions of the replications were found to be out of statistical importance too, hence a (i) high quality of the experiment was confirmed and (ii) any replication effects were excluded to be significant. Subsequently, this non-significant effect of the replications allowed to process the yields data within a simplified set of 192 complete yield data, based on the averages of the 4 replications respectively. The set of averages of yield data was re-analyzed by second multi-factorial ANOVA to achieve a valuation presented for main effects (Table 4).

Moreover, (i) correlation analysis or mainly (ii) second order polynomial lines in the case of trend analyses were also used for statistical evaluation.

Table 4 ANOVA of the yield data of the experiment with tall wheatgrass and perennial rye

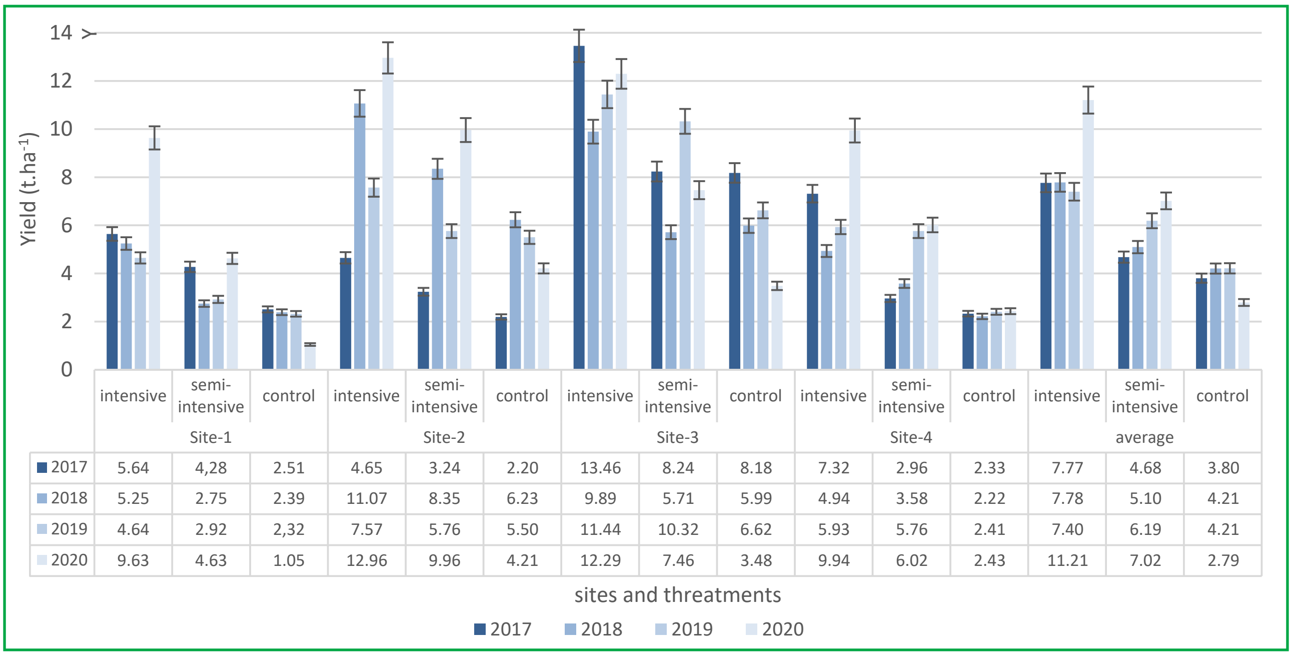
IO	Source of variability	Sum of squares	*df*	*F*-ratio	*P*-value	Homogenous groups				LS mean	LS sigma
3.	varieties	131.944	3	10.04	0.0000		A		Gergő	3.896	0.3021
							A		Kriszta	4.695	0.3021
								B	Alkar	5.791	0.3021
								B	Szarvasi-1	5.913	0.3021
2.	sites	212.995	3	16.20	0.0000	A			Site-4	3.945	0.3021
						A			Site-1	4.213	0.3021
							B		Site-2	5.598	0.3021
								C	Site-3	6.539	0.3021
4.	years	103.116	3	7.85	0.0001		A		2018	3.879	0.3021
								B	2017	5.108	0.3021
								B	2019	5.500	0.3021
								B	2020	5.807	0.3021
1.	nutrition	725.946	2	82.84	0.0000	A			control	2.697	0.2616
							B		semi-intensive	6.060	0.2616
								C	intensive	7.460	0.2616
Residual		788.649	180	*4.38							
Total		1962.650	191								

IO – impact order (according to *F*-ratio), df – degree of freedom, * – mean square (for residual)

3 Results and discussion

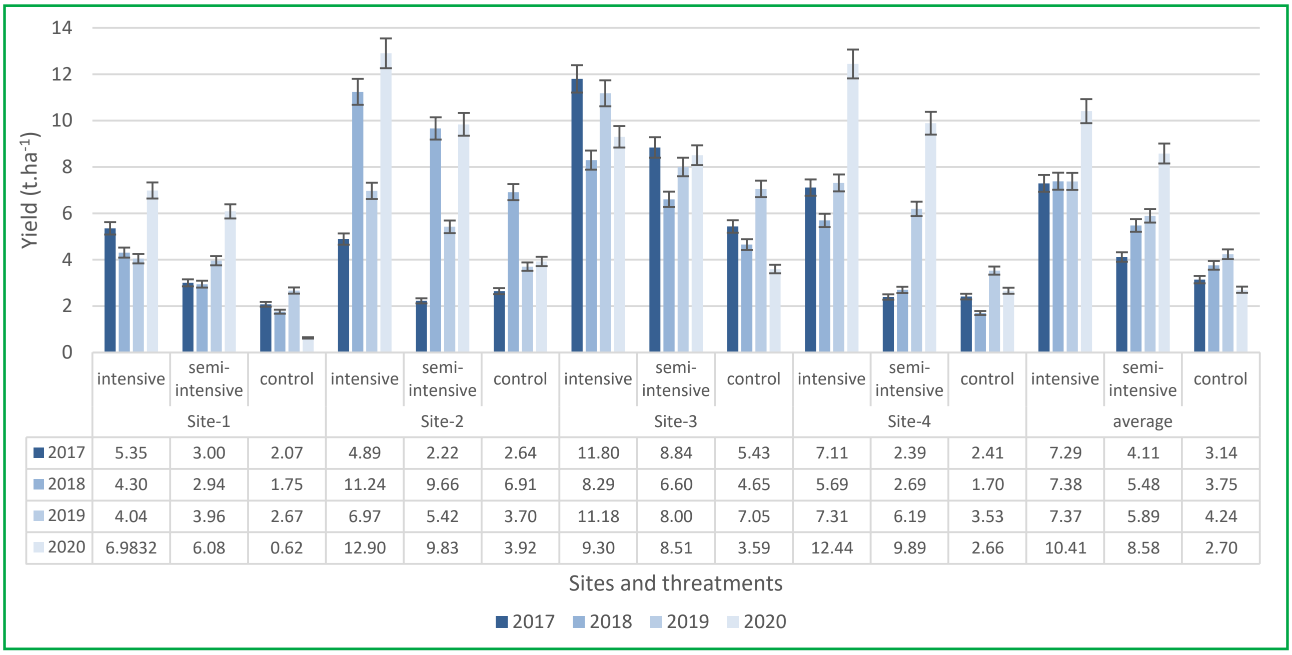
3.1 Crops and green phytomass yield

The yield of green phytomass data is presented in Figures 1–4, as calculated to dry matter (DM) yield. Referring to the yield data collected from all 4 experimental sites, it can be noticed that due to water-logging on Site-2 at early crop stages shortly after emerging, the crop stands were strongly affected (i) immediately by water stress, (ii) later by secondary changes because soil compaction



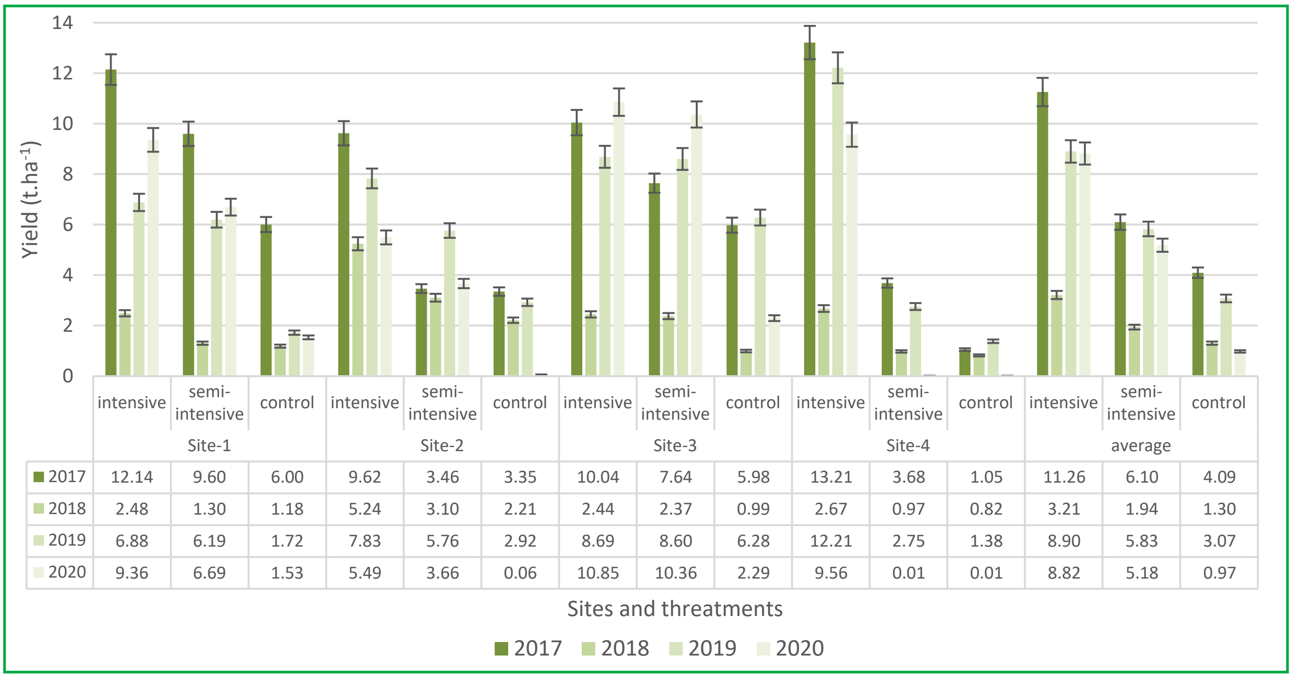
	Site-1 intensive	Site-1 semi-intensive	Site-1 control	Site-2 intensive	Site-2 semi-intensive	Site-2 control	Site-3 intensive	Site-3 semi-intensive	Site-3 control	Site-4 intensive	Site-4 semi-intensive	Site-4 control	average intensive	average semi-intensive	average control
2017	5.64	4,28	2.51	4.65	3.24	2.20	13.46	8.24	8.18	7.32	2.96	2.33	7.77	4.68	3.80
2018	5.25	2.75	2.39	11.07	8.35	6.23	9.89	5.71	5.99	4.94	3.58	2.22	7.78	5.10	4.21
2019	4.64	2.92	2,32	7.57	5.76	5.50	11.44	10.32	6.62	5.93	5.76	2.41	7.40	6.19	4.21
2020	9.63	4.63	1.05	12.96	9.96	4.21	12.29	7.46	3.48	9.94	6.02	2.43	11.21	7.02	2.79

Figure 1 The yields of tall wheatgrass cv. Szarvasi-1 according to sites and treatments



	intensive	semi-intensive	control	intensive	semi-intensive	control	intensive	semi-intensive	control	intensive	semi-intensive	control	intensive	semi-intensive	control
		Site-1			Site-2			Site-3			Site-4			average	
■ 2017	5.35	3.00	2.07	4.89	2.22	2.64	11.80	8.84	5.43	7.11	2.39	2.41	7.29	4.11	3.14
■ 2018	4.30	2.94	1.75	11.24	9.66	6.91	8.29	6.60	4.65	5.69	2.69	1.70	7.38	5.48	3.75
■ 2019	4.04	3.96	2.67	6.97	5.42	3.70	11.18	8.00	7.05	7.31	6.19	3.53	7.37	5.89	4.24
■ 2020	6.9832	6.08	0.62	12.90	9.83	3.92	9.30	8.51	3.59	12.44	9.89	2.66	10.41	8.58	2.70

Figure 2 The yields of tall wheatgrass cv. Alkar according to sites and treatments



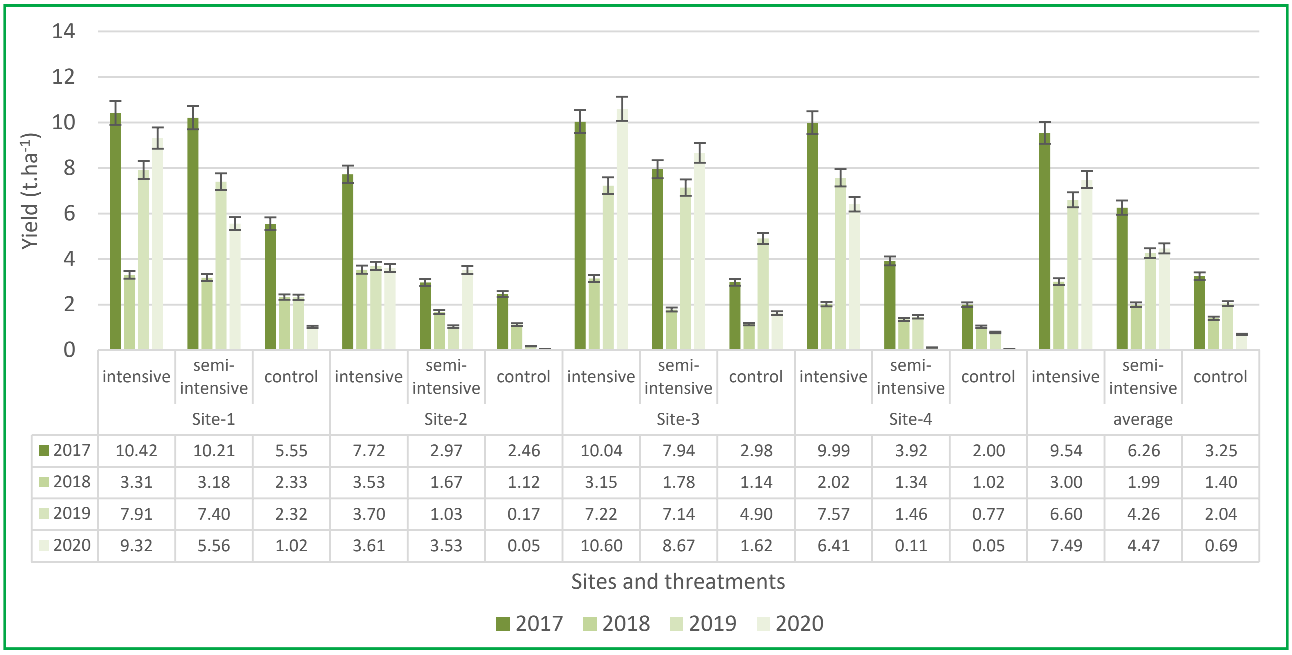
	intensive	semi-intensive	control	intensive	semi-intensive	control	intensive	semi-intensive	control	intensive	semi-intensive	control	intensive	semi-intensive	control
		Site-1			Site-2			Site-3			Site-4			average	
■ 2017	12.14	9.60	6.00	9.62	3.46	3.35	10.04	7.64	5.98	13.21	3.68	1.05	11.26	6.10	4.09
■ 2018	2.48	1.30	1.18	5.24	3.10	2.21	2.44	2.37	0.99	2.67	0.97	0.82	3.21	1.94	1.30
■ 2019	6.88	6.19	1.72	7.83	5.76	2.92	8.69	8.60	6.28	12.21	2.75	1.38	8.90	5.83	3.07
■ 2020	9.36	6.69	1.53	5.49	3.66	0.06	10.85	10.36	2.29	9.56	0.01	0.01	8.82	5.18	0.97

Figure 3 The yields of perennial rye cv. Kriszta according to sites and treatments

occurred. To obtain the overall correct closure, yield data from the Site-2 were included to statistic evaluation (Table 4), although results achieved on the site could be valuable within a unique view of impact of the accident as well.

The impact of marginal and contrasting soil condition of the sites caused higher yield variability in general than under normal conditions. Nevertheless, soil conditions were not found as a main source of yield variability. Overall, it was achieved 5.29 t.ha^{-1} of DM on average, while yields varied from 0.01 t.ha^{-1} to 13.46 t.ha^{-1}. Yields in regard to the tested varieties were as follows: average – minimum – maximum:

a) Szarvasi-1: 6.01 – 1.05 – 13.46 t.ha^{-1},
b) Alkar: 5.86 – 0.62 – 12.90 t.ha^{-1},
c) Kriszta: 5.06 – 0.01 – 13.21 t.ha^{-1},
d) Gergő: 4.25 – 0.05 – 10.60 t.ha^{-1}.



	intensive	semi-intensive	control	intensive	semi-intensive	control	intensive	semi-intensive	control	intensive	semi-intensive	control	intensive	semi-intensive	control
	Site-1			Site-2			Site-3			Site-4			average		
2017	10.42	10.21	5.55	7.72	2.97	2.46	10.04	7.94	2.98	9.99	3.92	2.00	9.54	6.26	3.25
2018	3.31	3.18	2.33	3.53	1.67	1.12	3.15	1.78	1.14	2.02	1.34	1.02	3.00	1.99	1.40
2019	7.91	7.40	2.32	3.70	1.03	0.17	7.22	7.14	4.90	7.57	1.46	0.77	6.60	4.26	2.04
2020	9.32	5.56	1.02	3.61	3.53	0.05	10.60	8.67	1.62	6.41	0.11	0.05	7.49	4.47	0.69

Figure 4 The yields of perennial rye cv. Gergő according to sites and treatments

The average yield of tall wheatgrass (TW) was 5.94 t.ha^{-1}, whereas perennial rye (PR) 4.65 t.ha^{-1}. As to the nutrition treatments, the highest yield of 7.84 t.ha^{-1} was found under intensive nutrition, while the yield of 5.19 t.ha^{-1} under semi-intensive and the lowest yield of 2.85 t.ha^{-1} was found under an untreated control. The yields of both crops decreased with decreasing nutrition intensity, while the yield decrease of PR was stronger than those of TW. The following yields were found: TW vs. PR – 8.33 vs. 7.35 t.ha^{-1} under intensive nutrition, 5.88 vs. 4.50 t.ha^{-1} under semi-intensive nutrition and 3.61 vs. 2.10 t.ha^{-1} under an untreated control.

When the year as a trial factor is taken into account, the highest yield was found in the first year (season 2016/2017) 5.94 t.ha^{-1}, then followed by 5.86 t.ha^{-1} in 2020 (season 2019/2020), 5.50 t.ha^{-1} in 2019 (season 2018/2019) and the lowest yield in 2018 (season 2017/2018) 3.88 t.ha^{-1}. In general, the yield of TW was higher than that of PR, with the exception of the first season whereas TW vs. PR yields were as follows: 5.13 vs. 6.75 t.ha^{-1} in 2017, 5.62 vs. 2.14 t.ha^{-1} in 2018, 5.88 vs. 5.12 t.ha^{-1} in 2019 and 7.12 vs. 6.60 t.ha^{-1} in 2020.

Yield was mainly affected by nutrition (*F*-ratio 82.84), then less by site (*F*-ratio 16.20), variety (*F*-ratio 10.04) and the year had minimal effect (*F*-ratio 7.85). Generally, crop productivity can be increased by a higher number of utility years or can be decreased during years and a stand can completely disappears especially under insufficient nutrition on unsuitable soil types. According to the results of a multi-factor ANOVA, 14 out of a total of 26 possible interactions were found as statistically significant concerning the first set of 728 yield data and 8 out of 10 possible interactions as statistically significant concerning the second set of 192 (the set without replications).

Yields of trial varieties affected by site and nutrition are displayed in Figures 1-4, whereas the results obtained can be used to formulate several preliminary conclusions of practical importance:

1. Both TW varieties, Szarvasi-1 and Alkar:
   - are slower to reach full fertility in comparison to both varieties of PR,
   - are suitable for all types of tested marginal soils under intensive nutrition,
   - under lowland conditions (sites 1, 2 and 3):
     - when grown on heavy soils, they can tolerate the lack of nutrition to some extent,
     - when grown on light soils, yield response to lack of nutrition was stronger and yield decline is more expressive than on heavy soils,
   - under highland conditions (Site-4), more expressive decrease of yields was noticed in absence of nutrition on the heavy soil.

   When TW varieties were compared, Szarvasi-1 provided a higher yield on average than Alkarl, while:
   - Szarvasi-1 can be more suitable for lowland conditions, where it provided higher yields on light soil (Site-1) as well as on both heavy soils (sites 2 and 3).
   - Alkar can be more suitable for highland conditions, where it provided higher yields on heavy soil (Site-4).

2. Both PR varieties, Kriszta and Gergő:
    - quickly reached full fertility in comparison with both TW varieties, but
    - full fertility could be quickly eliminated under nutrition deficiency,
    - are suitable for all types of tested marginal soils under intensive nutrition,
    - are more suitable for growing on light soils in comparison with both TW varieties and especially with the variety Alkar,
    - are more sensitive to water stress as seen during water-logging (Site-2) in comparison with both TW varieties.

The highest differences in yield between Kriszta and Gergő were recorded on Site-2, where Gergő. was obviously the most damaged variety because of the water-logging. This could be probably more associated with a land profile than with sensitivity of the variety itself to water stress. Concerning the other trial sites, it can be stated, that:

- in highland conditions (Site-4), the yield of Kriszta was higher on heavy soil,
- in lowland conditions without the water-logging:
    - on heavy soil, both varieties had almost the same yield but Kriszta had higher yield on Site-3,
    - on light soil, both varieties had very similar yields but Gergő had higher yield on Site-1.

3.2 Height and coverage

Presented data on plant heights and stand coverage were recorded at harvest. The height of TW stand was 128 cm on average and ranged from 39 to 173 cm, the height of PR stand was 144 cm on average and ranged from 74 to 193 cm. The coverage of TW stand was 76% on average and ranged from 13 to 100%, the coverage of PR was 39% on average and ranged from 1 to 99%.

The yields of tested crops were in a medium correlation with height (r 0.645) and in a stronger correlation with coverage (r 0.704), while the yields of TW were in a medium correlation with height (r 0.669) and in a stronger correlation with coverage (r 0.677), the PR yields strongly correlated with both height (r 0.804) and coverage (r 0.810). Second-order polynomic courses of the dependence of crop yield on plant height are presented in Figure 5. Similar dependences of yield on stand coverage are presented in Figure 6. Both figures show the forming of two homogenous groups identical to the crops and similar to the yield data statistics (Table 4).

Medium and strong relations of plant height and stand coverage on yields support the conclusions outlined in

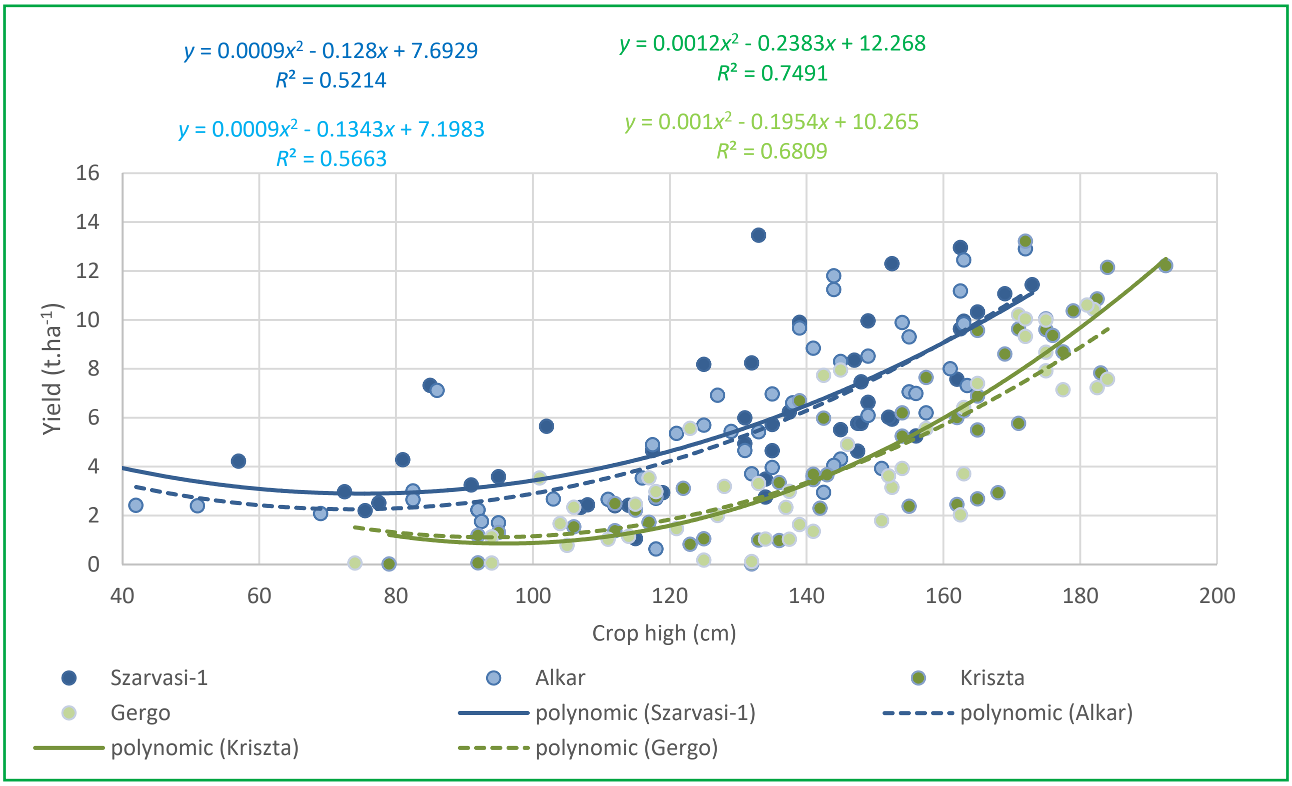


Figure 5 Yield dependence on crop height and its polynomic trend within the experiment with tall wheatgrass cv. Szarvasi-1 and Alkar and perennial rye cv. Kriszta and Gergő

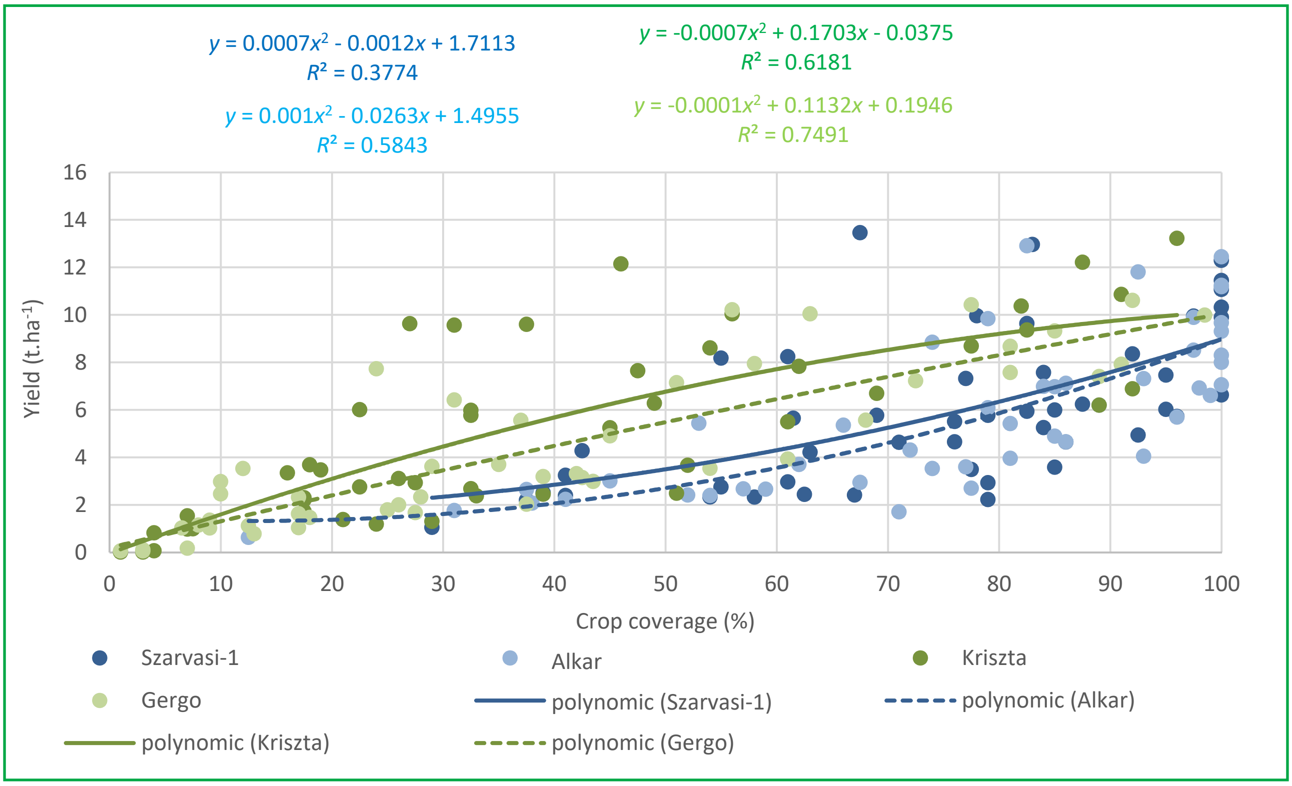


Figure 6 Yield dependence on crop coverage and its polynomic trend within the experiment with tall wheatgrass cv. Szarvasi-1 and Alkar and perennial rye cv. Kriszta and Gergő

Chapter 3.1 hereinbefore. The achieved values of plant height and crop coverage are presented in Tables S5 and S6. The height and coverage of the trial varieties had the following average, minimum and maximum values:

- Szarvasi-1: height 127 – 39 – 173 cm, coverage 75 – 29 – 100%,
- Alkar: height 129 – 42 – 172 cm, coverage 77 – 13 – 100%,
- Kriszta: height 147 – 79 – 193 cm, coverage 39 – 1 – 96%,
- Gergő: height 141 – 74 – 184 cm, coverage 39 – 1 – 99%.

3.3 *DM content at harvest*

Tall wheatgrass and perennial rye stands were harvested with regard to an optimal harvest maturity. During the trial years, TW had quite variable harvest date, whereas PR reached the harvest maturity earlier than TW, and in the first half of July regularly (Table S4). TW was harvested usually a month or two later than PR, in the middle of August to middle of September. TW shoots contained 56.8% of dry matter on average at harvest, the content ranged from 48.8% to 70.0%. PR shoots contained 56.8% of dry matter on average, within the range of 51.9 to 71.1%.

The values of DM content at harvest are presented in Table TS7 and suplementary Figure S1. The results of DM content at harvest can draw some practical conclusions, important for timing of single or two-phase method of harvest:

- PR stands, especially if left longer non-harvested, will dry out during a sunny summer. Hot and dry weather can reduce the moisture content of green phytomass. On the other hand, humid and cold weather can promote sprouting and forming green shoots. This can also complicate a harvest at the accurate DM content.
- TW stands probably can hardly reach the moisture content which is required for a safe storage, even though the crop is harvested later. A two-phase harvest became usual, especially when a harvest is delayed until autumn. At first, a stand is cut, which is then followed by collection after a couple of days after green phytomass has dried sufficiently.

3.4 *Weather and soil conditions*

Both crops were sowed in late summer of 2016. Germination as well as emergence of the crops was favourable because of high-quality pre-sowing soil preparation and enough precipitation. Due to the water-logging on Site-2, certain complications occurred on the heavy clay soil which affected crops not only immediately but also subsequently (soil clay content on this site is presented in Table 1 and weather conditions of this site are displayed in Table S2).

The weather as soil conditions varied even though the crops were grown on same the site due to different time of harvest (Table S3). The differences of weather and soil condition values from early April till harvest time were as follows:

- average daily temperature for PR was lower about 1.9 °C (16.3 vs. 18.2 °C) on average in comparison with TW, the differences varied from 1.3 °C to 2.7 °C,
- sum of precipitation for PR was lower about 148 mm (187 vs. 334 mm) on average in comparison with TW, the differences varied from 62 mm to 257 mm,
- average soil moisture for PR in comparison with TW was:
    - higher in a topsoil about 1.2% (30.5 vs. 29.3%) on average, the differences varied from -1.7% to +3.9%,
    - higher in a subsoil about 2.4% (34.2 vs. 31.8%) on average, the differences varied from -1.4% to +6.5%,
- average soil temperature for PR in comparison with TW was:
    - lower in a topsoil about 2.2 °C (16.4 vs. 18.7 °C) on average, the differences varied form 1.3 °C to 2.9 °C,
    - lower in a subsoil about 2.4 °C (14.7 vs. 17.1) on average, the differences varied from 1.7 °C to 2.9 °C,
- average soil electrical conductivity for PR in comparison with TW was:
    - higher in a topsoil about 0.018 mS.cm^{-1} (0.277 vs. 0.259 mS.cm^{-1}) on average, the differences varied from -0.041 mS.cm^{-1} to +0.101 mS.cm^{-1},
    - higher in a subsoil about 0.030 mS.cm^{-1} (0.445 vs. 0.414) on average, the differences varied from -0.057 mS.cm^{-1} to +0.131 mS.cm^{-1}.

The correlation coefficients of yield on weather condition and yield on soil condition relations are presented in Figures S2 and S3. It is evident that nutrition intensity was proven as an important modifying yield factor. The strongest negative effect (r -0.595) of higher temperature on the yield of Kriszta under intensive nutrition was ascertained, whereas higher precipitation under the same nutrition had the weakest positive effect (r 0.018) on the variety yield. In general, weather had different response on TW in comparison with PR, whereas the variety of Szarvasi-1 was more resistant to higher temperatures. The relations of yield on weather and soil conditions are presented in Figures S4 A to S7 D. Second-order polynomic trends (linear trend in the case of precipitation, respectively) are used to support crop suitability conclusions described in Chapter 3.1. Due to dense content of these figures, reliability indexes (R^2) of the polynomic or linear relations are presented separately in Table S8.

Figures S4 A – D present yield dependence on weather conditions, while it is evident a higher tolerance to air temperature of Kriszta variety in comparison with Gergő (Figure S4 C). Moreover, Figures S5 A – S6 D present the dependence of yield on soil-climate conditions, while it is ascertained that each variety had higher tolerance to unfavourable soil conditions when growing under intensive nutrition (Figures S7 A – C).

3.5 Main soil chemical properties and soil nutrient content

The main chemical soil properties as well as nutrient content were determined for each of the 48 plots (4 sites × 4 varieties × 3 treatments). Laboratory analyses were done in two replications for both initial (2016) as well as terminal status (2020). The data of initial status are presented in Table S1. Finally, initial vs. terminal status, the change respectively, was calculated for each soil parameter. The change is presented in Figures S8 and S9.

The highest negative change was recorded for soil Ca content, while the change was especially high on Site-2. Probably, this change can be associated with increased Ca leaching due to the accident with water-logging. The changes related to nutrition treatment are fully in accordance with nutrition intensity and consumption by green phytomass yield. The further can be stated:

- Positive change in the content of total nitrogen (N_t) apparently indicates that the production potential of marginal soil conditions was achieved.
- The only negative change of Nt was achieved on the most productive Site-3, which has the least marginal soil character. It can indicate a higher production potential of the crops if not grown in marginal soil conditions, however, but not necessarily under Central European climate.
- The highest positive change of Nt was achieved with the variety of Alkar. This probably indicates that the variety reached full production capacity and nitrogen remained in the soil is in excess.
- Macro nutrients of P and K, even Mg, did not limit crop production on treated variants despite a positive or negative change because of the content of soil P and K is relatively high.
- Soil pH was changing the least in comparison with the other parameters.
- In general, soil total organic carbon (C_{ox}) content was increased by 0.233% on average, when the minimum change of 0.019% and maximum change of 0.365% C_{ox} content was recorded.

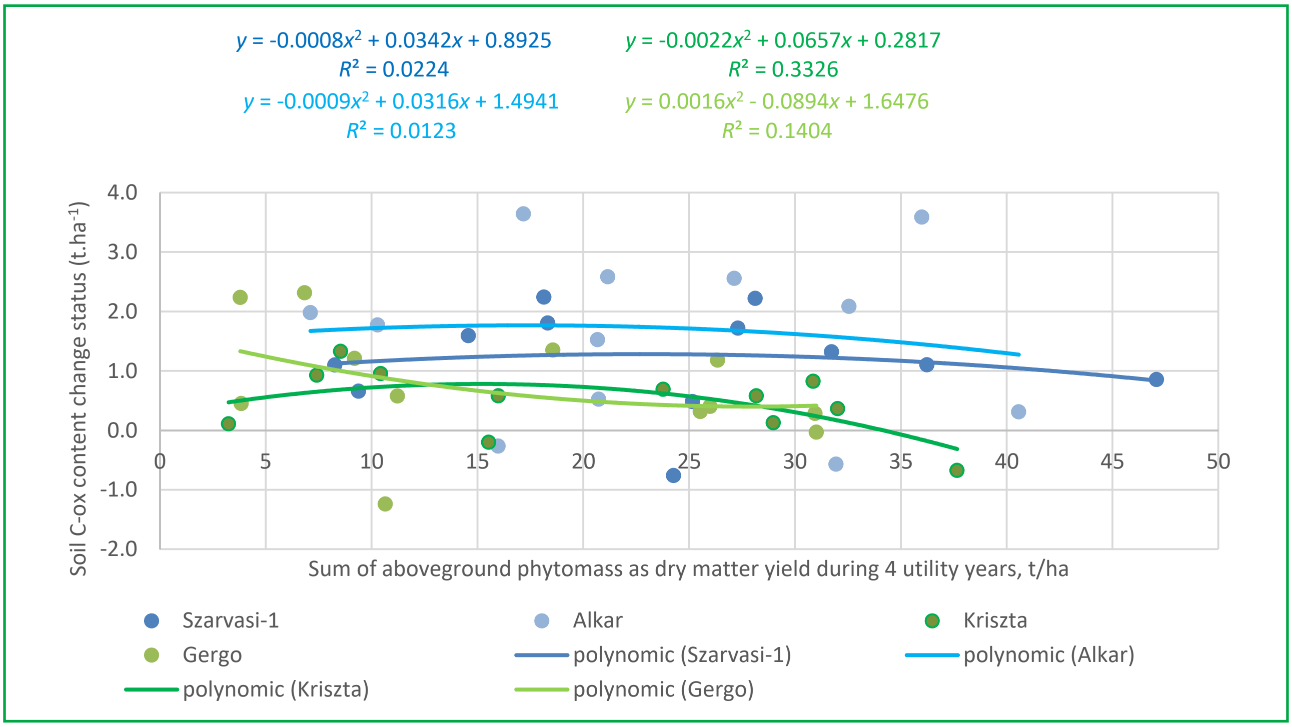


Figure 7 The polynomic course of dependence of soil C_{ox} change on yield of tall wheatgrass cv. Szarvasi-1 and Alkar and perennial rye cv. Kriszta and Gergő during 4 growing years

As mentioned before, the average change of C_{ox} content was 0.233%; it means the increase of 1.048 $t.ha^{-1}$ C_{ox} during a 4 year period or increase of 0.262 $t.ha^{-1}$ C_{ox} per year; C_{ox} content ranged from 0.021 $t.ha^{-1}$ to 0.495 $t.ha^{-1}$ per year. If each of the 48 basic plots are evaluated, the change of C_{ox} content range is much wider and values vary from -0.242 $t.ha^{-1}$ to +3.641 $t.ha^{-1}$ C_{ox} per year, as presented within basic points of the polynomial courses in Figure 7.

3.6 Perennial rye (PR)

In Hungary in the 1960s, Szőke-Pázsi et al. (2021) studied crosses between *Secale cereale* and *S. montanum* to combine favorable agronomic characteristics of these rye species. Based on artificial hybrid production, three perennial rye *S. cereanum* cultivars were developed: Kriszta and Perenne registered in 1998 and Gergő registered in 2009. The presented research is focused on the varieties of Kriszta and Gergő, while it can be stated that the work is probably one of the first papers, if not the first, which recognized PR as a crop suitable for energy purposes and is studied based on large-scale experiments as well.

According to Sipos and Halász (2007), a stand of PR established on acid sandy soil (pH/KCl 4.35) using a sowing rate of 1.8 and 2.7 million plants per hectare achieved the yield of 6.87 and 7.07 $t.ha^{-1}$ DM during the second utility year when cultivated as a fodder crop. Within the presented paper, the trials with PR was established on marginal light and heavy soils with weakly to strongly acidic soil reactions (pH/KCl 4.82–5.80) using a sowing rate of 4.15 million of germinating seeds per hectare, whereas it was achieved dry matter (DM) yield of 4.65 $t.ha^{-1}$ in average, 13.21 $t.ha^{-1}$ as maximum respectively.

Based on the conclusions of similar study of Sipos and Halász (2007) PR can be introduced into sustainable agricultural systems because unfavourable soil conditions can be alleviated by growing perennial rye. Its fibrous root system can contribute to the improvement of soil conditions. Moreover by them, being a perennial plant, it can also play a great role in soil protection against soil erosion. Root and stem residues ploughed into the soil increase soil organic matter in sandy soils and improve some other soil properties. According to Schneider et al. (2016) and Szakács et al. (2020), PR has a large gene pool that can be exploited even in wheat breeding. As specified by the authors, the crop is also tolerant to frost and drought, therefore, it adapts well to disadvantageous soil and weather conditions. This studied only confirmed that PR can overcome cold/frost winters comman in continental climates of central Europe.

The presented research is equate with the conclusions of Sipos and Halász (2007) as well Schneider et al. (2016) and Szakács et al. (2020), especially with those focused on improvement of some of the soil conditions, as well as adaptivity to disadvantageous soil and weather conditions. However within marginal soil conditions, the achieved results, in particular development of DM yield of this perennial crop and the followed basic chemical parameters of soil, clarify the very strong influence of nutrition and therefore all the mentioned above is relative to crop management practices and the environmental conditions respectively.

3.7 Tall wheatgrass (TW)

According to an extensive study of Csete et al. (2011), an average yield of Szarvasi-1 is as much as 10–15 $t.ha^{-1}$ DM with great spatial and temporal variation depending on weather and habitat conditions. Based on some conclusions of Pál and Csete (2008), on each experimental plot covered by Szarvasi-1 decreased significantly, not only weed cover but also weed species number. Till the second year, the average weed cover dropped from 48 to 17% and in the third year it did not exceed 4%. Bernas et al. (2019) indicated that Szarvasi-1 is an alternative and promising energy crop introduced in some European countries (mostly in Hungary and Germany) and it has good yield potential. Szarvasi-1 had an average yield of 6.1–8.6 $t.ha^{-1}$ in the 4-year trial conducted in the Czech Republic. Based on the conclusions of the study aimed at the effect of mineral and digestate fertilization on the yield of TW (Kopecký et al., 2021), it was achieved an average yield of 7.4 $t.ha^{-1}$ under digestate fertilization. The findings of Csete et al. (2011), Pál and Csete (2008), Bernas et al. (2019) and Kopecký et al. (2021) are parallel to the results presented within the paper, TW achieved DM yield of 5.94 $t.ha^{-1}$ in average, 13.46 $t.ha^{-1}$ as maximum respectively. The coverage of the crop stand was 76% on average, while ranged from 13 to 100%.

Jafari et al. (2014) tested 17 populations of TW on clay loam to silty clay loam soils with alkaline pH 7.7 and reached an average yield of 1.482 and 3.053 $t.ha^{-1}$ dry matter under two and one cutting management, respectively. Based on the findings of Vergiev (2019), TW belongs to key species even for dune stabilization for its high tolerance to sea water immersion and high viability. In contrast with the environmental conditions of Jafari et al. (2014) and Vergiev (2019) with alkaline pH or saline dunes, the presented research was based on the field trials established on soils with weak to strong acidic soil reactions (pH/KCl 4.82–5.80). The obtained results confirmed the suitability of TW growth on acidic soils, which is complementary to the findings concerning alkaline environment. The results achieved at Site-1, which is characterized by erosion-threatened light soil, loamy-sandy soil respectively, are favourable and in accordance with the conclusions of Vergiev (2019) for dune stabilization.

However, Csete et al. (2011) described TW as particularly drought resistant, there is no general consensus about the most favorable soil conditions for TW. Liu et al. (2008) described adaptation or tolerance against poorly drained soils for TW. A study of Ruf et al. (2019) aimed on water-logging treatment indicates that TW can better cope with drier soil conditions than with excessive wet ones, which is in line with the morphological features of TW. Certain studies of Borrajo and Sanches-Morreiras (2018) show stability of TW for DM production under any level of water stress. Possibly, it can be related to a higher tiller number. Due to this plasticity, TW should be studied as a species with great potential to drought stress resistance. Their studies evaluated four populations of TW from different soil-climatic conditions under different water stress: 100 – 50 – 30% of field capacity. According to the procured results DM production dependences on soil-climate parameters and presented within the paper, TW's resistance to drought is site-specific and strongly influenced by the intensity of plant nutrition. The results obtained on Site-2, where water-logging occurred on heavy soil, confirm the better regenerative ability of TW than PR.

According to results of this paper, earlier harvested PR had less precipitation available about 148 mm on average, when compared to TW, whereas average daily temperature was lower about 1.9 °C on average respectively. According to study of Ciria et al. (2020), TW variety ALKAR achieved a yield of 4.8 $t.ha^{-1}$ DM under Mediterranean marginal rainfed conditions. Low yields below 0.5 $t.ha^{-1}$ were obtained when rainfall was lower than 150 mm between March and June. Based on the results presented within the paper, Alkar can be more suitable for highland conditions, where it provided higher yields in comparison with Szarvasi-1on the Site-4 with heavy soil. The polynomial trend of yield dependence on precipitation indicates that the variety of Alkar tolerated much better higher precipitation than Szarvasi-1. On the contrary, Szarvasi-1 tolerated higher air temperatures better than Alkar.

3.8 Miscellaneous

Martyniak et al. (2017) tested some wild populations of TW including Szarvasi-1 and found out that a high biomass yield can also be connected with relatively high quality of production. This corresponds with previous similar findings when testing other energy crops according to the way phytomass is used (Kron et al., 2017, Porvaz et al., 2012 and others). However, some detailed analysis of quality aspect should be also done.

Based on the conclusions of Agostini et al. (2015), the annual net soil organic C storage change exceeds the minimum mitigation requirement (0.25 t.ha^{-1} C per year) under herbaceous and woody perennials by far (1.14 to 1.88 and 0.63 to 0.72 t.ha^{-1} per year, respectively). However, long-term series of field data are needed to verify sustainable soil organic C enrichment, as the physical and chemical stabilities of soil organic C pools remain uncertain, although they are essential in defining the sustainability of C sequestration (half-life >25 years). Furtherly, according to Agostini et al. (2015) the C inputs and turnover can now be specifically parameterised in whole perennial energy crops system models, whilst dependencies on soil texture, moisture and temperature remain empirical.

Based on our results it was found that the average change of C_{ox} content was 0.233% which means an increase of 1.048 t.ha^{-1} C_{ox} during 4 years or 0.262 t.ha^{-1} C_{ox} per year. More detailed soil C_{ox} data (described in Chapter 3.4) confirmed the conclusions of Agostini et al. (2015), although it can be assumed that there is an apparent disparity between C_{ox} in soil and C content in green phytomass (Figure 7), whereas only a low correlation (reliability) was found, however there is an assumption of high causality. Therefore, the main issue of C sequestration measuring is much broader and also includes a method of soil sampling. An ordinary method of soil sampling was used as noninvasive and non-terminative for a crop stand, when the fibrous root system of both crops (Csete et al., 2011; Sipos and Halász, 2007) was not violated.

4 Conclusions

The influence of marginal soil condition on the yield of green phytomass of tall wheatgrass and perennial rye was verified. Moreover, the effect of mineral nutrition was also tested on 4 contrasting sites during 4 trial years. Despite the contrasting soil as climatic conditions, the yield was affected mainly by nutrition, then by sites followed by varieties and finally by years. The productivity of both the crops can increase by an ascending number of utility years or the crops stand can completely disappear especially under nutrition absence on unsuitable soil types. It can be concluded:

a) under intensive or semi-intensive nutrition both crops are suitable for all types of tested marginal conditions,
b) when some unexpected water-logging occurred on Site-2 with heavy clay soil, tall wheatgrass better tolerated these conditions of excessive soil moisture, so this crop species proved itself as higher moisture tolerant, while consequently, perennial rye can be recommended for light sandy soils.

This study focused on Kriszta and Gergő is probably one of the first original research papers published, so more agronomic studies are required, especially due to the marginal conditions of different nature and with strong potential to affect the cropping success, growing possibilities respectively. Although tall wheatgrass is a relatively better-known energy crop than perennial rye, further mutual comparisons of these crops are required, because to the crops seem to be similar as well as complementary.

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