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Growth and development of six cover crops in the Czech Republic

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ABSTRACT

The cultivation of cover crops brings a number of benefits and a range of species that can be used as cover crops is relatively wide. In our research, we studied the growth and development of six cover crop species: purple tansy (*Phacelia tanacetifolia* Benth.), crimson clover (*Trifolium incarnatum* L.), safflower (*Carthamus tinctorius* L.), buckwheat (*Fagopyrum esculentum* L.), Hungarian vetch (*Vicia pannonica* Crantz.) and cultivated rye (*Secale cereale* L. var. multicaule) in a field experiment carried out in 2021–2024 on a conventional farm. The main goals were (a) to assess the cover crops in terms of their emergence rate, phenological development, height and growth intensity, stand closure and weed infestation, production of above-ground biomass and damage by cold, and (b) to answer the question what performance can be expected from the investigated species in terms of biomass production, ensuring soil cover and reduced occurrence of weeds. The cover crop species exhibited significant ($P < 0.05$) differences in the phenological development, growth intensity, rate of stand closure, weed infestation and production of biomass. The most rapid growth and development was shown by buckwheat which achieved the stage of fruit development and ripening. Height of plants ranged as of the last evaluation date on average from 76.4 mm in crimson clover up to 538.8 mm in purple tansy, and 555.2 mm in buckwheat. The best stand closure was recorded in purple tansy (99.2% of leaf coverage). The greatest production of above-ground fresh biomass was recorded in purple tansy (41.4 Mg ha⁻¹) and safflower (26.4 Mg ha⁻¹), but the greatest production of above-ground dry biomass was in purple tansy (4 Mg ha⁻¹) and rye (3.82 Mg ha⁻¹). With respect to effective good stand closure and competitiveness, rye and purple tansy are suitable for being grown as pure crops.

ARTICLE HISTORY

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BBCH stages; biomass production; clover; coverage; purple tansy; weeds

1. Introduction

The main objective of today's agriculture is to increase the productivity of plants and ensure environment protection (Fageria et al. 2005; Hunter et al. 2017; Song et al. 2021), i.e. to enhance sustainability of agricultural production (Arora 2019). Crop rotation and the diversity of crops being grown are very important for a sustainable system of growing plants. The number of plants grown in the region or on individual farms is a significant indicator of diversity in agriculture (Boháč et al. 2006), which is one of the basic prerequisites of sustainability and stability of agricultural production (Chloupek 2008). However, farmers often prefer several dominant crops (Meynard et al. 2018) and the current diversity of grown crops is low. There are about 7 thousand crop species, but only ca. 120 crop species are of major importance, and a half of the global production of agricultural commodities consists of four main crops (FAO Statistics 2022).

Diversity of crops is affected by a great number of factors from ecological (altitude, size and slope of sites) to socio-technical ones. Increasing diversity is not always simple; it is very often a complex process that

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includes changes in crop cultivation technologies, for example increased diversity of crop rotation (Shah et al. 2021). Compared to this, introduction of the cultivation of cover crops is a relatively easy change. Cover crops included in the crop rotation increase crop diversity and play a great role in the sustainability of cultivation systems (Teasdale 1996; Lu et al. 2000; Kaspar and Singer 2011), particularly in narrow rotations of just several crops (Kwiatkowski et al. 2016). Such crops are not for sale (receipts) and are grown in the period between harvesting and sowing the main crops (Fageria et al. 2005). Cover crops are cultivated worldwide (Koudahe et al. 2022) and bring a number of benefits to the environment: cover the soil and fill it with roots, make the uptake of nutrients easier, can increase SOC sequestration (Singh et al. 2024; Helfrich et al. 2024), increase the soil microbial activity through the supply of biomass into the soil (Gentsch et al. 2020; Koudahe et al. 2022), and increase the content of organic matter in the soil (Adetunji et al. 2020). The increase in soil organic matter (SOM) supports the formation and stability of soil aggregates (Kaspar and Singer 2011; Sharma et al. 2018) and enhances soil aeration (Mohammadi et al. 2011).

Thus, cover crops can mitigate the potentially negative impacts of low diversity crop structure. The most serious manifestations of low diversity crop rotation include soil compaction, reduced content of SOM and depletion of soil nutrients (Bowles et al. 2020; Vanino et al. 2022). A very important function of cover crops is discontinuation of crop rotation and reduced spread of diseases and pests (Creamer and Dabney 2002; Fageria et al. 2005; Koudahe et al. 2022). The cultivation of cover crops can also suppress weeds (Lu et al. 2000; Creamer and Dabney 2002). An important weed occurring in cover crops is often the volunteer pre-crop (Brant et al. 2009) which competes with cover crops and can promote the spread of pests and diseases.

A factor significantly affecting the influence of cover crops on the environment (content of SOM) is the capacity of cover crops to create a sufficient amount of above-ground and under-ground biomass (Tiessen et al. 1994). The growth intensity of cover crops and their capability of developing a sufficiently closed stand is then entirely crucial e.g. for erosion control or suppression of weeds (Samarappuli et al. 2014).

Furthermore, the influence of cover crops depends on the plant species used. Legumes (such as clover or vetch) for example, have a capacity to fix atmospheric nitrogen, increase availability and efficiency of nitrogen use in the soil (Blesh 2017; De Notaris et al. 2021). Root systems of (cover) crops also improve soil structure (Yogendra and Raut 2020) and cover crops with the extensively developed root systems (such as *Carthamus tinctorius* L. etc.) can be used for bio-drilling, i.e. for the disruption of compacted soil layers and hence for the improvement of soil structure (Shaheb et al. 2021). A great role in cover crops is also played by their properties similar to those of main crops used in rotations. As to the occurrence of pests and diseases, main crops very sensitive to cover crop selection are those from the family of Brassicaceae (rape, cruciferous vegetables) which includes a number of cover crops. Best cover crops for the discontinuation of rotations are then those that are not related to other crop species such as purple tansy or buckwheat (Fageria et al. 2005; Riviere et al. 2022).

The growing of cover crops does not bring only advantages but can have some cons as well. During the periods of drought for example their production can be reduced, the supply of ground water for subsequent crops can be depleted (Hunter et al. 2021), which will reflect in the reduced production of the market crop (Hunter et al. 2021; Dong 2022). The use of an inappropriate method or timing of cover crop growth end can also adversely affect the yield of the main crop (Balkcom et al. 2015; Adetunji et al. 2020). This is caused by situations where interspecific competition can arise or germination of main crop seeds can slow down (Alonso-Ayuso et al. 2014). When the termination of cover crop growth is too late, the cover crops can form seeds which may subsequently infest the main crop with weeds (Jacobsen et al. 2010; Scholberg et al. 2010; Keene et al. 2017). This can be prevented by the timely termination of cover crop growth (Osipitan et al. 2018). Therefore, when using cover crops, it is important that they are not only sown in time after the harvest of the main crop, but also at the timely end of their cultivation before seeding the main crop. The growth of cover crops can be ended in a natural way, e.g. by winter kill due to sensitivity to cold (Evans et al. 2016), use of herbicides (Creamer and Dabney 2002) or mechanically (Scholberg et al. 2010), for example by rolling or cutting the stand of cover crops by means of cutting rollers (Ashford and Reeves 2003).

Individual cover crop species can exhibit considerable differences in growth dynamics, which then affect not only the production of biomass, but also the capability to withstand weed infestation and risks of seed production. The choice of a cover crop requires knowledge of the performance that can be expected from individual cover crop species both in terms of biomass production and in terms of soil cover and reduced occurrence of weeds. A decisive criterion can also be the risk of subsequent crop weed infestation with

respect to the development rate (risk of seed formation) and susceptibility to frost (risk of overwintering). The main objective of our research was to evaluate the growth and development of six cover crop species from the viewpoint of: (a) development characterised by means of BBCH codes (codes of BBCH scale, the BBCH abbreviation is derived from the names of institutions where the scale was developed – Biologische Bundesanstalt, Bundessortenamt and Chemical industry), (b) growth intensity, (c) biomass production, (d) stand closure, (e) competitiveness to weeds.

The presented paper was prepared for a detailed comparison of emergence, development and growth of some cover crops with a potential for wide application in conditions of Central Europe. The novelty of our experiment consists in the large number of cover crops tested directly in operating conditions rather than in the form of commonly used pot or small-scale experiments as well as in the complex study of the development of individual cover crop species in relation to other important parameters (growth, coverage, biomass production), growth dynamics and development of cover crops in time and their effect on the growth of weed plants. Our goal was to find out whether the cover crop species and time from sowing (the date of evaluation/sampling) improve the soil cover and suppress the occurrence of weeds through forming a sufficient amount of biomass which covers the soil and creates a strong competitive environment that limits the growth of weed plants. We set up two null hypotheses (H_{0A} and H_{0B}). First, the influence of the cover crop species was examined, and a null hypothesis (H_{0A}) was tested that the plant species used as cover crop has no effect on the monitored parameters. Second, the effect of time (the date of evaluation/sampling) was evaluated, and we verified a null hypothesis (H_{0B}) that the date of evaluation/sampling has no effect on the monitored parameters.

Material and methods

Site characteristics

Field experiments were conducted to study the development of six cover crop species with a focus on the rate of growth and development, above-ground biomass production, degree of cover and capacity to suppress weeds with respect to the risk of weed infestation to the subsequent crop. The experiments were carried out between 2021 and 2024 in the municipality of Nová Ves as a part of semi-operational testing of selected crop species. As to agro-ecological division, the experimental plots were situated in the beet production region and the location of the site in the Czech Republic (CZE) (part of the European Union – EU) is shown in the map (Figure 1). Geographic coordinates of the experimental fields are 49.098498N, 16.313883E (2021; experimental field no. 0901/8) and 49.109583N, 16.332938E (2022; experimental field no. 9701/16), 49.110080 N, 16.331470 E (2023; experimental field no. 0901/8) and 49.101287 N, 16.310569 E (2024; experimental field no. 1801/8). The mutual distance of individual experimental plots was 750 m and there were no essential differences between the plots with respect to soil and agrochemical characteristics (Table 1). The selected experimental sites were situated at altitudes ranging from 275 to 300 m a.l.s., above all the area of interest has a North East exposition. Mean annual temperature is with 7.9 °C mean annual precipitation 677 mm for period 1991–2020 (more information is provided in Annex 1 and 2). According to information provided by the Czech Research Institute for Soil and Water Conservation (VUMOP), pedological characteristics of the experimental plots are identical with Cambisols occurring mainly or exclusively on the flat terrain, with omnidirectional aspect and total skeleton content of up to 10%. Based on the pedological survey made by VUMOP using soil pits, three soil pits were dug out in the experimental area, in which four main soil horizons were identified of different thickness and soil texture: (1) topsoil horizon 0–28 cm; (2) humus horizon 28–48 cm; (3) illuvial horizon 48–64 cm and (4) substrate horizon 64–74 cm. The topsoil and subsoil horizons consisted of loam (USDA classification), the share of clay particles was increasing with the increasing soil profile depth, and clay-loam soils were found in the illuvial horizon (USDA classification). As to soil structure, the topsoil horizon exhibited optimal granular structure while the structure of deeper soil horizons was more aggregated from blocky subangular up to prismatic in the deepest parts of the soil profile. Geological bedrock in the area is loess and loess loam of the Bohemian Massif, a smaller part of the area is built of calcareous clay, at some places with the positions of sands falling into the system of Carpathians. Soil type is Haplic Cambisol.

The basic agro-chemical parameters (contents of plant available nutrients and soil reaction) Table 1 were similar without any significant differences. Soil reaction was neutral and contents of all basic nutrients were high on both plots.

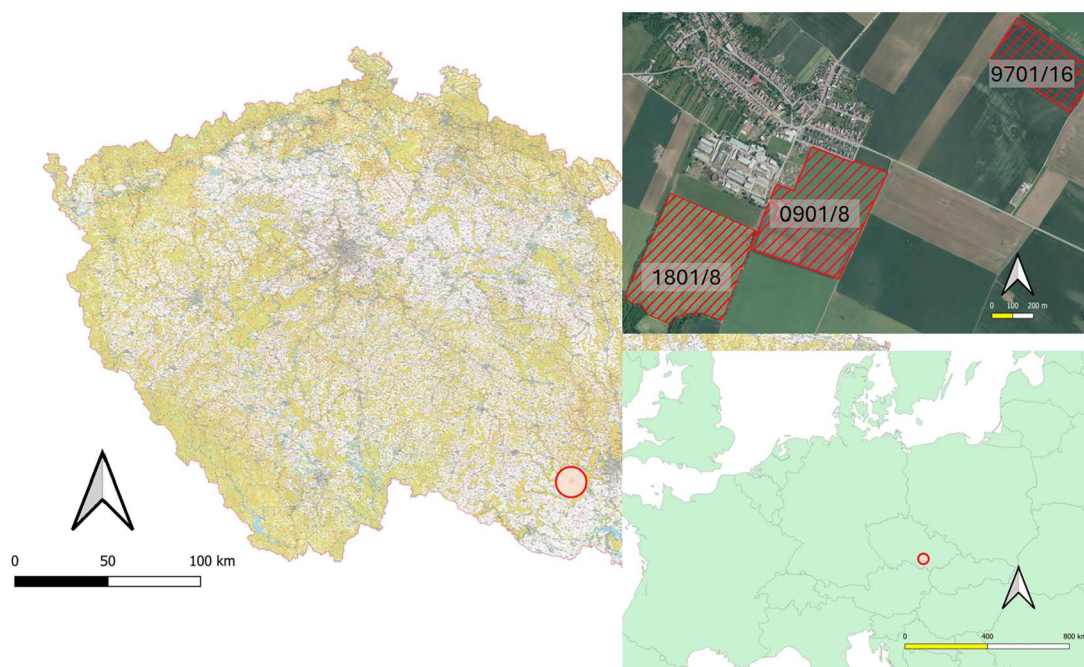


Figure 1. Map of field experiment sites in CZE.

Table 1. Content of plant available nutrients in soil and soil reaction.

Season/date	2020/2021	2021/2022	2022/2023	2023/2024
Soil reaction and plant available nutrients content	Experimental field no. 0901/8	Experimental field no. 9701/16	Experimental field no. 0901/8	Experimental field no. 1801/8
pH (CaCl ₂)	6.7	6.4	6.7	7.4
P (mg kg ⁻¹)	256	232	256	259
Ca (mg kg ⁻¹)	4 067	3 620	4 067	7 993
Mg (mg kg ⁻¹)	379	381	379	302
K (mg kg ⁻¹)	599	388	599	492

Comment: Presented values were recorded within Agrochemical testing of agricultural soils in the Czech Republic carried out by the Central Institute for Supervising and Testing in Agriculture of the CZE. Contents of available nutrients were determined in Mehlich III extract, exchange soil reaction was determined in CaCl eluate. All analyses were performed in line with the Regulation of Czech Republic No. 275/1998: Decree of the CR Ministry of Agriculture on agro-chemical testing of agricultural lands and detection of soil properties in forest lands.

The field experiment was implemented in operational conditions on a conventional farm within standard crop rotation. In all years, experiments with cover crops followed the same pre-crop of winter wheat (*Triticum aestivum* L.) to curb a possible influence of another pre-crop. As the field experiment was conducted in operational conditions on the farm, winter wheat could not be grown on the same plot in consecutive years. Therefore, the experiments were established different fields in the same locality (Figure 1) with identical soil conditions described above. Field experiment organisation (Figure 2) was always the same. When the wheat was harvested, stubble-tillage to a depth of 8 cm took place, and the post-harvest residues were shallowly incorporated into the upper soil layer.

Field experiment description

The experimental comparison (Figure 2) included six species in pure seeding (cover crop variants): safflower (*Carthamus tinctorius* L.), buckwheat (*Fagopyrum esculentum* L.), purple tansy (*Phacelia tanacetifolia* Benth.), crimson clover (*Trifolium incarnatum* L.), rye *Secale cereale* L. var. *multicaule*, Hungarian vetch (*Vicia pannonica* Crantz). The species are not part of the family of *Brassicaceae* and are therefore suitable also in crop rotations with rape or cruciferous vegetables. Two species (crimson clover and Hungarian vetch) are leguminous plants fixing atmospheric nitrogen. Two other species (purple tansy and buckwheat) belong to families that are not related to commonly cultivated crops, safflower belongs to the family of *Asteraceae* and rye belongs to the family of *Poaceae*. Safflower, buckwheat and phacelia are spring species while rye, crimson clover and Hungarian vetch are winter species.

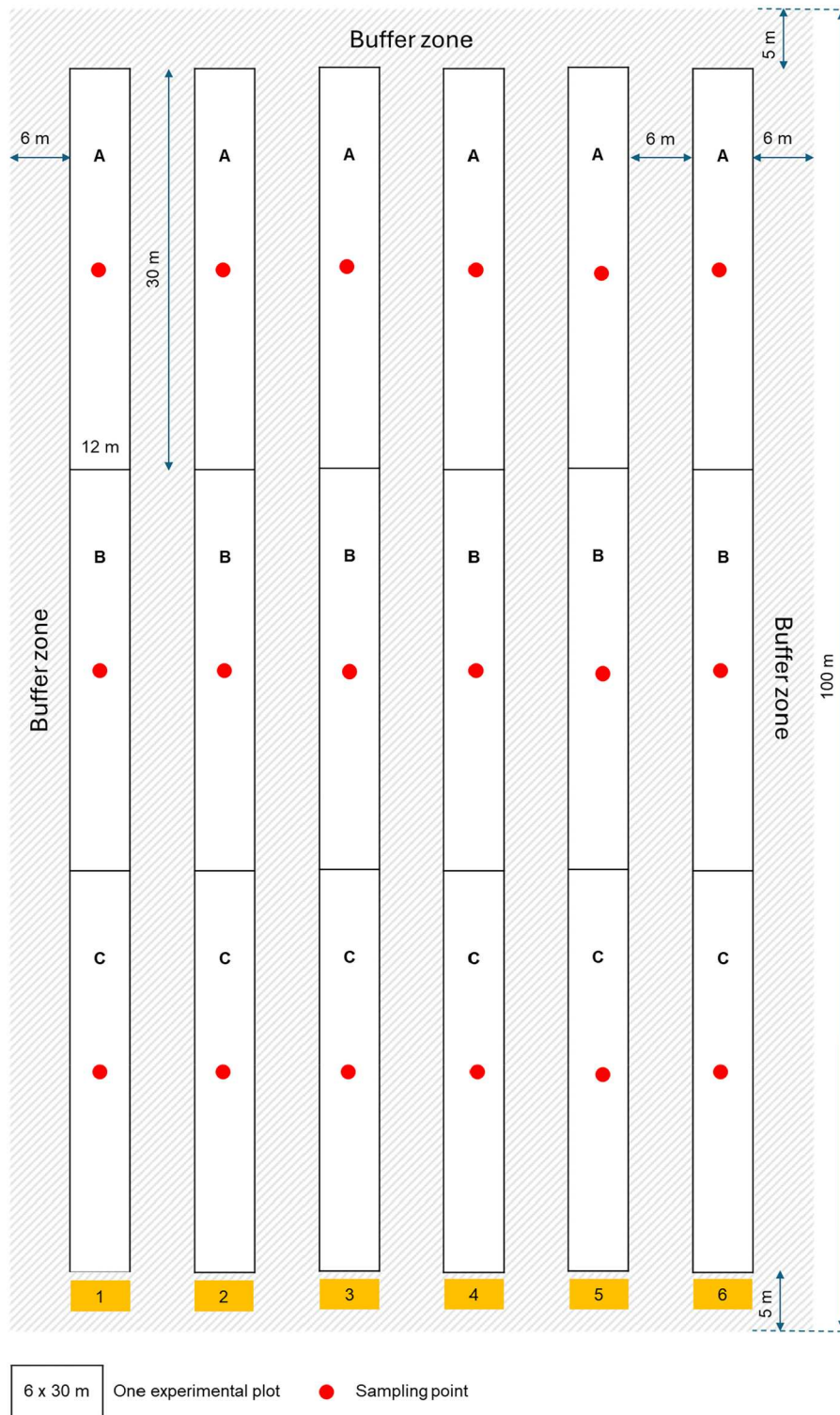


Figure 2. Illustrative representation of field experiment organisation and principle of plant sampling. Comment to [Figure 2](#): Individual variants were divided into three blocks, and collection points were established in each block by means of GPS, from which plant biomass was sampled according to methodology described in Kintl et al. (2024). On the respective experimental plots (1–6), following intercrops were grown according to the above scheme which was identical for the entire time of the field experiment (2021–2024): (1) *Phacelia tanacetifolia* Benth. (2) *Trifolium incarnatum* L. (3) *Fagopyrum esculentum* L. (4) *Carthamus tinctorius* L. (5) *Vicia pannonica* Crantz. (6) *Secale cereale* L. var. *multicaule*.

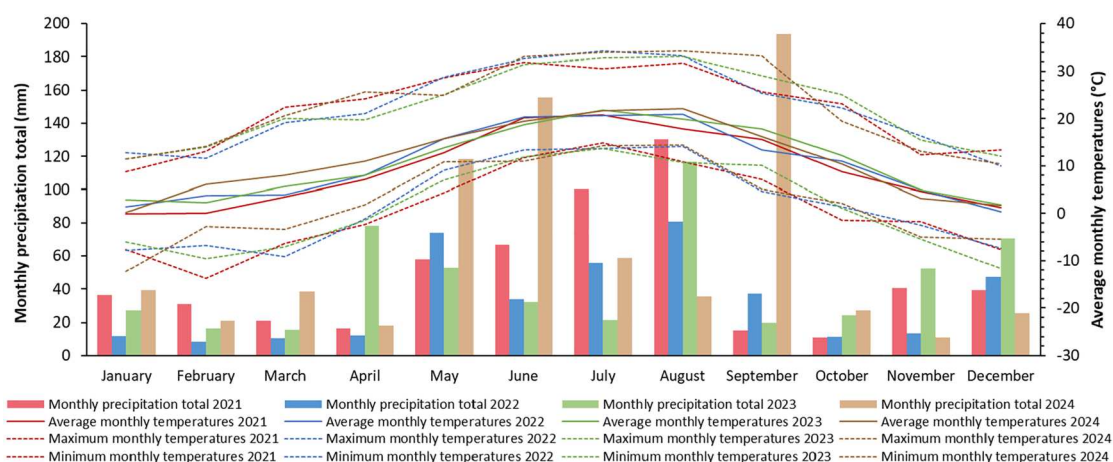


Figure 3. Weather course in 2021–2024. Comment to Figure 3: The diagram shows mean temperatures and total precipitation amounts in the respective years of the experiment. Parameters are arranged always from June to May of the following year so that they reflect the growth of individual cover crops (between the growing seasons). Weather conditions were measured using a professional meteorological station (rain gauge: MR3H-FC, METEOSERVIS Ltd., CZE; wind-gauge: WAA151, VAISALA Ltd., FIN; temperature and humidity sensor: HMP35D, VAISALA Ltd., FIN) operated by the Czech Hydrometeorological Institute.

Cover crops were sown (Figure 2) on 16 August 2021 using the AMAZONE AD-P Special 3000 machine, and on 10 August 2022; 21 August 2023 and 25 August 2024 using the Lemken Solitair 9 seeding machine. Based on recommendations from the seed producer (PRO SEEDS Ltd., Czech Republic), sowing rates for the given crops and locality were as follows: safflower and buckwheat 30 kg ha^{-1} , purple tansy 12 kg ha^{-1} , crimson clover 12.5 kg ha^{-1} , rye 100 kg ha^{-1} , vetch 40 kg ha^{-1} . The growing season of cover crops lasted from August to the end of autumn, or until spring of the next year according to cover crop species (susceptibility to frost kill); however, weather conditions in diagrams and tables are recorded from June to May. The course of weather in the 2021/2022 to 2024/2025 growing seasons are documented by a survey of basic meteorological parameters (Figure 3 and Annex 1) and by the climate diagram (Annex 2). The growing periods of cover crops in 2021 and 2023 was characterised in August by lower temperatures and high precipitation. In August 2022 and 2024, temperatures were higher and precipitation was lower. October was the coldest month in 2021 when the lowest measured temperatures dropped below zero.

Cover crops were sown in strips (Figure 2). Strips with cover crops were divided into three blocks. In each block, collection points were established by means of GPS, from which plant biomass was sampled according to methodology described in Kintl et al. (2024) and measured.

Evaluation and sampling of plants

The evaluation was focused on the growth and phenological development of plants. Emergence was assessed after one week. From the second week, development stages were recorded using a two-digit code according to the general extended BBCH scale (Hack et al. 1992). Growth BBCH stages were described according to the extended BBCH scale for cereals (Witzenberger and Hack 1989; Lancashire et al. 1991). The last assessment of the development of plants and frost damage was made in spring before the spring term of spading into the ground when the wintering of plants was assessed (frost kill in % of dead plants) and the BBCH stage of development.

During the vegetation period, photographs were taken, and plant cover was recorded; an example of coverage evaluation is presented in Annex 3 and Annex 4. The cover of grown cover crops, cover of weeds and percentage of bare ground were evaluated. The evaluation was made visually. In addition, plant height was measured in mm in 21 plants. The evaluation was made on eight dates (T1–T8) in autumn (from August to November) and on one spring date (T9), when only the development stage and frost kill were evaluated. The first assessment of development, growth and cover was made two weeks after sowing and further assessments were made once a week (T1 to T8). The spring assessment (T9) was made from the end of March

Table 2. Dates of evaluation during the field experiment from 2021 to 2024.

Evaluation date (term)	Days from sowing
T0 (sowing)	
T1	16
T2	24
T3	31
T4	38
T5	46
T6	57
T7	66
T8	77
T9	March/April

Table 3. Dates of above-ground biomass sampling during the field experiment from 2021 to 2024.

Sampling date (term)	Days from sowing	Evaluation date (term)
TO 1	38	T4
TO 2	57	T6
TO 3	77	T8

to the beginning of April depending on the course of winter (see Table 2). The spring assessment was made only in the period from 2022 to 2024.

The shoot biomass (fresh and dry) was established by sampling from an area sized 0.25 m x 0.25 m and then converted to 1 ha for each cover crop separately. As to weeds, the total biomass of all weeds was evaluated in each cover crop. Plant biomass was collected on three sampling dates (TO 1–TO 3; see Table 3). The plants were collected from the given area, depending on the specific species and sowing rate. The number of plants differed in the individual cover crops and ranged on average from 36 up to ca. 186 plants per square meter. Plant biomass was dried in the laboratory using a chamber drying kiln (model HS62A, manufacturer Chironax, spol. s r.o.) at 50°C to constant weight. Then the samples were left to cool down for 24 hours at a laboratory temperature of 18°C. An example of the development and growth of individual plants in the second year (2022) of a field experiment is listed in Annex 5.

Processing of measured data

Heights and time differences between the measurements were used to calculate daily height increments for individual time periods according to the following Equation (1).

$$DHI = (H_n - H_{n-1}) / (t_n - t_{n-1}) \quad (1)$$

where: DHI = daily height increment, H_n = height in t_n , H_{n-1} = height in t_{n-1} , $t_n - t_{n-1}$ = number of days between the dates of measurements; and growth intensity changes were detected during the vegetation periods (Kubíková et al. 2022b).

Detected degrees of coverage and time differences between the dates of evaluation were used to calculate daily increments of cover for individual time periods according to the following Equation (2).

$$DCI = (C_n - C_{n-1}) / (t_n - t_{n-1}) \quad (2)$$

where DCI = daily cover increment, C_n = cover in t_n , C_{n-1} = cover in t_{n-1} , $t_n - t_{n-1}$ = number of days between the measurements; and changes were detected in the intensity of stand closure during the vegetation periods (Kubíková et al. 2022b).

Differences recorded in biomass production between the respective dates of sampling and time differences between the samplings served to establish the average daily increment of biomass between the individual dates of sampling according to the following Equation (3).

$$DBI = (B_n - B_{n-1}) / (t_n - t_{n-1}) \quad (3)$$

where: DBI = daily increment of above-ground biomass, B_n = production of above-ground biomass in t_n , B_{n-1} = production of above-ground biomass in t_{n-1} , $t_n - t_{n-1}$ = number of days between the measurements; and

average daily increments were established between the individual dates of sampling. A modified formula was used to calculate the periodical annual increment (PAI) according to Ábri and Rédei (2022).

Data analyses were performed using the programme STATISTICA 12 (Dell, Round Rock, Texas, U.S.A.) the Real Statistics Resource Pack software (Copyright 2025 REAL STATISTICS USING EXCEL – Charles Zaiontz). As the dates of evaluation and sampling could not be completely identical in all years, data transformation was used according to the formula $y = x - tp$, where y is the converted value, x is the measured value, t is the difference in the number of days from sowing on the given date compared with the same evaluation/sampling date in 2021, and p is an average daily increment for the given date where correction was necessary. Mean values of individual parameters, dispersion of measured values and significance of differences in the mean values of individual parameters were established. A Shapiro–Wilk test was conducted to assess the distribution normality, revealing a deviation from normality. After failing to correct these using data transformations, differences between cover crops (six variants) and years (four years) were analysed using the Scheirer–Ray–Hare extension of the Kruskal–Wallis test, a non-parametric alternative of ANOVA (Dytham 2011), and Dunn’s post hoc test with Bonferroni correction ($P < 0.05$) (Wang et al. 2019). Friedman test, a non-parametric alternative of repeated measure ANOVA (Wang et al. 2019; Tenuzzo et al. 2012), was performed to evaluate differences among the eight dates of evaluation (or three dates of above-ground biomass sampling in case of biomass production). When the differences were statistically significant (with $P < 0.05$), we used the post-hoc Nemenyi test to find out which differences were significant. All analyses were performed at a significance level of $P < 0.05$.

Results

The Scheirer-Ray-Hare test showed that the factors of year and cover crop (variant) were statistically significant ($P < 0.05$). The effect of year did not show in the daily change of crop coverage (see Annex 6). The effect of variant, i.e. cover crop species was recorded in all evaluated characteristics. The effect of year is presented in tables (Annexes 6–9). Significant differences ($P < 0.05$) between the years are expressed by indices ‘a–c’. The effect of cover crop (variant) is presented in tables (Annexes 6–9) and shown in diagrams by letter indices. Significant differences ($P < 0.05$) between the variants (cover crop) are expressed by indices ‘a–d’. The Friedman test showed that the factor date of evaluation/sampling was statistically significant ($P < 0.05$). The effect of evaluation/sampling date was given by the number of days from sowing and different development stage of crops and was recorded in all evaluated characteristics. The effect of evaluation/sampling date is shown in diagrams by letter indices. Significant differences ($P < 0.05$) between the variants (cover crop) are expressed by indices ‘a–d’ and the effect of time (date of evaluation/sampling) by indices ‘e–k’.

Emergence, development and end of vegetation

All species began to emerge a week after sowing. Two weeks after sowing, (Date T1) they developed first true leaves (BBCH 11–14). Only vetch and *Secale cereale* L. var. *multicaule* reached the stage of the formation of side shoots/tillering (maximum BBCH 21 and 22) (Table 4). Differences were observed between the cover crop species development. *Fagopyrum esculentum* L. was the most rapidly developing crop and the only species with the recorded development of fruits. It reached the stage of fruit development (BBCH 73–30% of fruits achieved final size) to the stage of seed ripening (BBCH 85–50% of ripe fruits), then the vegetation ended due to cold weather, and development stages recorded in the last dates of evaluation were BBCH 96–98. Inflorescences developed also in *Carthamus tinctorius* L. which achieved the stage of bud formation (BBCH 51) and in *Phacelia tanacetifolia* Benth. which started to flower (BBCH 61). *Secale cereale* L. var. *multicaule* was the most variable cover crop and achieved the development stages of tillering (BBCH 29) to ear formation (booting, BBCH 45) and ear emergence (inflorescence emergence, BBCH 54). The development stage affected the frost kill of the *Secale cereale* L. var. *multicaule* stand. More than 90% of *Secale cereale* L. plants survived winter (only on average 8% were killed by frost) in the season when *Secale cereale* L. achieved the stage of tillering, but the stand was killed by frost (99% of plants) in the seasons when *Secale cereale* L. achieved higher stages of development (BBCH 45–59). In *Vicia pannonica* Crantz. and *Trifolium incarnatum* L., wintering was recorded in almost all years. *Phacelia tanacetifolia* Benth., *Fagopyrum esculentum* L. and *Carthamus tinctorius* L. were completely killed by frost. Results are presented in Table 4.

Table 4. Differences in BBCH stages.

Variant	Cover crop	Year	T1	T2	T3	T4	T5	T6	T7	T8	T9	Frost damage in %
1	<i>Phacelia tanacetifolia</i> B.	2021	12	14	24	31	33 (50)	50 (51)	53 (61)	58 (61)	98	100
		2022	12	17	17	32	32	33 (51)	50 (53)	50 (56)	98	100
		2023	12	14	19	31	32	50 (55)	54 (59)	56 (61)	98	100
		2024	12	14	14	16	19	31	32	34	98	100
		Min/max	10/14ab	10/19a	12/30ab	14/32ab	16/50ab	30/55bc	31/61bc	33/61bc	98/98a	100/100a
2	<i>Trifolium incarnatum</i> L.	2021	11	13	15	23	26	27	27	29	29	0
		2022	11	12	21	25	27	29	29	29	98	70
		2023	11	13	14	23	25	27	29	29	29	10
		2024	11	13	15	15	23	26	27	29	29	–
		Min/max	10/13a	10/15a	12/23a	13/27a	21/29a	23/29a	24/29a	29/30a	29/98b	0/80b
3	<i>Fagopyrum esculentum</i> L.	2021	11	14	61 (62)	64 (65)	65 (66)	70 (73)	96	98	98	100
		2022	11	13	54 (61)	62 (65)	63 (64)	64 (65)	67 (73)	73 (74)	98	100
		2023	12	51 (55)	58 (63)	63 (65)	65 (67)	77 (81)	90 (83)	95 (85)	98	100
		2024	11	12 (50)	50 (61)	50 (61)	61 (63)	65 (71)	76	98	98	100
		Min/max	10/13a	10/55ab	12/63c	14/65b	55/67b	63/81c	65/97 (83)c	65/98 (85)b	98/98a	100/100a
4	<i>Carthamus tinctorius</i> L.	2021	12	14	17	30	31	33	35	35	98	100
		2022	12	15	16	31	31	33 (50)	33 (50)	37 (50)	98	100
		2023	12	15	18	19	33	37 (50)	50 (51)	50 (51)	98	100
		2024	12	13	14	15	17	19	19	30	98	100
		Min/max	10/12a	10/17a	10/31ab	12/32a	15/36a	18/50ab	19/51ab	19/51ab	98/98a	100/100a
5	<i>Vicia pannonica</i> Crantz.	2021	14	14	21	21	23	28	29	30	98	90
		2022	15	24	25	29	29	29	30	30	29	10
		2023	14	22	25	29	30	31	31	31	30	15
		2024	13	13	14	23	24	26	28	29	30	5
		Min/max	12/21b	12/27ab	13/30ab	15/30a	15/32a	23/33a	25/33a	25/33a	25/98b	0/100b
6	<i>Secale cereale</i> L. var. <i>multicaule</i>	2021	13	23	29	27	29	29	29	30	30	8
		2022	15	23	25	31	32	33 (45)	34 (50)	49 (54)	98	100
		2023	14	23	27	29	31	32	33 (45)	33 (45)	98	100
		2024	–	–	–	–	–	–	–	–	–	–
		Min/max	11/22b	13/27b	23/31bc	25/32ab	25/33a	25/45ab	25/50ab	25/54ab	30/98ab	5/100ab

Notes: The table presents characteristic (most often) codes of BBCH stages in individual years and dates of evaluation. Min/max = total variation range of BBCH stages for the period from 2021 to 2024 on individual dates of evaluation. The maximum achieved generative BBCH stage is shown in parentheses (bud formation, flowering, fruit formation and ripening – codes 50 - 89). Different letter indices indicate significant differences between the variants on individual dates at a significance level $P < 0.05$ (post hoc Dunn's test with Bonferroni correction). T1 – T9 indicate individual dates of evaluation that are closer characterised in Table 2. Frost damage parameter expresses the percentage of killed plants. Colours are used to indicate important development stages: inflorescence formation was achieved (pink), fruit formation was achieved (orange) and vegetation end was achieved (red).

Height of plants and growth intensity

Cover crops were measured on eight evaluation dates. Significant differences in height and growth intensity were found both between cover crops and between evaluation dates. The differences are shown in [Figures 4](#) and [5](#). The total height of cover crops reflected growth intensity. The most rapid initial growth was recorded in *Secale cereale* L.. Two weeks after sowing, *Secale cereale* L. reached an average height of 102 mm. The average height of other cover crops ranged from 15 to 55 mm. From the second week after sowing, the most rapid elongation of plants was recorded in *Fagopyrum esculentum* L. in which the growth was very intensive. Its greatest increments were recorded between week 3 and 5 (T2–T4). After 5 weeks, *Fagopyrum esculentum* L. reached the stage of full bloom, and then the growth intensity decreased. The greatest height (354–668 mm) was recorded in *Fagopyrum esculentum* L. after 8–9 weeks from sowing. Then it exhibited the end of vegetation (see [Table 4](#)). In *Phacelia tanacetifolia* Benth. and *Carthamus tinctorius* L., the intensive stem elongation started later than in *Fagopyrum esculentum* L. (after four to five weeks), and none of them reached the stage of full bloom when the growth intensity in plants slows down (Kubíková et al. 2022a) and more intensive extension was recorded also on later dates. *Phacelia tanacetifolia* Benth. reached a height of 367–732 mm and *Carthamus tinctorius* L. achieved a height of 147–791 mm. The most variable height was recorded in *Secale cereale* L., where the height ranged from 257 to 958 mm (Annex 6). The lowest growth intensity was recorded in *Trifolium incarnatum* L. and *Vicia pannonica* Crantz. with a relatively low total height of plants (on average 76 and 90 mm, respectively).

Coverage and intensity of stand closure

The studied cover crops exhibited differences in both the intensity of stand closure and the total stand closure ([Figures 6](#) and [7](#)). The most rapid stand closing was recorded in *Phacelia tanacetifolia* Benth. and *Secale cereale* L. which also exhibited high daily increment of coverage. The most intensive stand closure was recorded between week 2 and 5 after sowing in *Phacelia tanacetifolia* Benth. (1.25–8.63% of leaf coverage per day) (see Annex 8). For *Secale cereale* L., average daily increment of coverage in the same period ranged from 1.2 to 3.9% of leaf coverage per day. Coverage over 90% was reached after 6–8 weeks in *Phacelia tanacetifolia* Benth. and after 8–9 weeks in *Secale cereale* L.. Maximum stand closure was 98.4–100% in *Phacelia tanacetifolia* Benth. and 92.5–100% in *Secale cereale* L.. Leaf coverage of crimson clover was (57.2–90%) and leaf coverage of *Carthamus tinctorius* L. was 62.3–82.1%. The stand closure of the other crops was even lower.

In addition to leaf coverage of the crop, leaf coverage of weeds was also monitored ([Figure 5](#) and Annex 9). The most frequently occurring weeds included volunteer wheat (*Triticum aestivum* L.), white goosefoot (*Chenopodium album* L.) and shepherd's purse (*Capsella bursa-pastoris* L. MED.) which occurred namely in *Vicia pannonica* Crantz. and *Trifolium incarnatum* L.. Other weed species were observed at a lower extent, for example field penny-cress (*Thlaspi arvense* L.), red dead-nettle (*Lamium purpureum* L.), groundsel (*Senecio vulgaris* L.), *Veronica* ssp., etc. The lowest leaf coverage was recorded in weeds growing in *Phacelia tanacetifolia* Benth. and *Secale cereale* L., which exhibited the best stand closure. In *Phacelia tanacetifolia* Benth., the highest coverage of weeds was in the period of stand closing 3–4 weeks after sowing (on average 6.6–7.5% of leaf coverage). Then the crop was overgrowing, and the weeds were suppressed. In *Secale cereale* L., a maximum coverage of weeds ranged from 5.6% to 9.2% of leaf coverage between week 4–7.

At the end of the autumn evaluation, the average percentage of area covered only by weeds ranged from 0.2 to 14.6%, depending on the crop. Weeds affected the total coverage, particularly in crops with the lower cover (see [Figures 5](#) and [7](#)). Total coverage was lower than the sum of the cover of crop and weeds together, as there was a certain overlapping of weeds and the crop. The percentage of area covered only by weeds, i.e. by how much the weeds reduced the percentage of bare ground not covered by the crop growth is presented in [Figure 8](#) and in Annex 9. A larger area was occupied by weeds in crops with the lower stand closure, i.e. in clovers, vetch, *Fagopyrum esculentum* L. and *Carthamus tinctorius* L., in which the area of bare ground without vegetation would increase by more than 16% to 22% without weeds. Spearman's coefficient (r_s) was calculated and the very strong negative correlation (according to Evans 1996) between the crop coverage and percentage of soil covered only by weeds was found ($r_s = -0.83$; $P < 0.001$). The

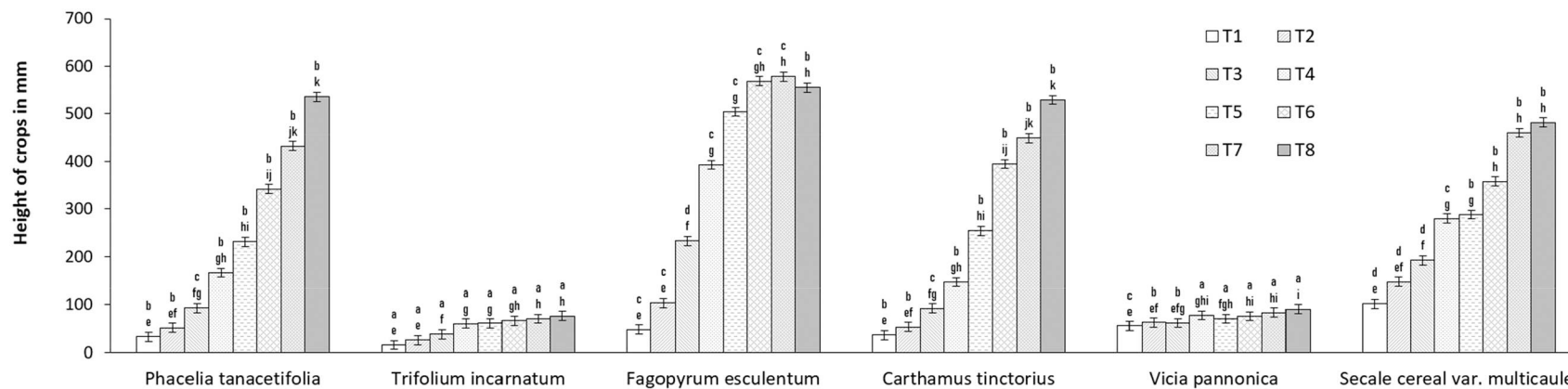


Figure 4. Height in mm. Comment to [Figure 4](#): Mean values ($n = 84$) of crop height (columns) for each crop and evaluation dates \pm SD for the whole time of experiment duration from 2021 to 2024. T1–T8 indicate autumn evaluation dates that are closer characterised in [Table 2](#). Different letter indices indicate significant differences between the variants (cover crops) at a significance level $P < 0.05$ (post hoc Dunn's test with Bonferroni correction) and significant differences between the individual dates at a significance level $P < 0.05$ (post hoc Nemenyi test). Significant differences between the variants are expressed by letter indices a \rightarrow d (a, b, c, d); Significant differences between the evaluation dates are expressed by letter indices e \rightarrow k (e, f, g, h, i, j, k).

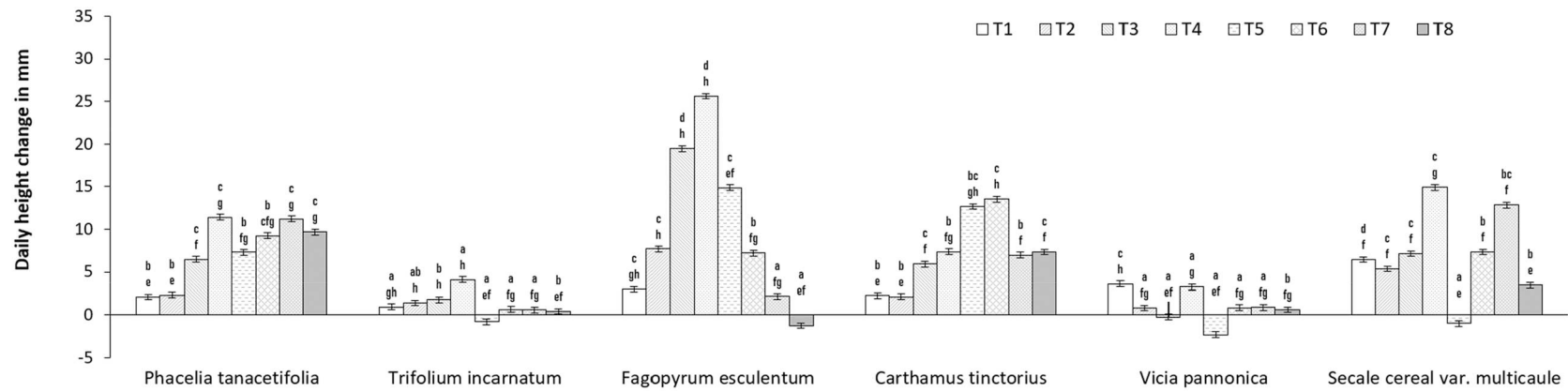


Figure 5. Growth intensity (daily height increment in mm). Comment to Figure 5: Mean values ($n = 84$) of daily height increment (columns) for each crop and evaluation dates \pm SD for the whole time of experiment duration from 2021 to 2024. T0 indicates the date of sowing, T1 – T8 indicate autumn evaluation dates that are closer characterised in Table 2. Different letter indices indicate significant differences between the variants (cover crops) at a significance level $P < 0.05$ (post hoc Dunn's test with Bonferroni correction) and significant differences between the individual dates at a significance level $P < 0.05$ (post hoc Nemenyi test). Significant differences between the variants are expressed by letter indices a → d (a, b, c, d); Significant differences between the evaluation dates are expressed by letter indices e → k (e, f, g, h, i, j, k).

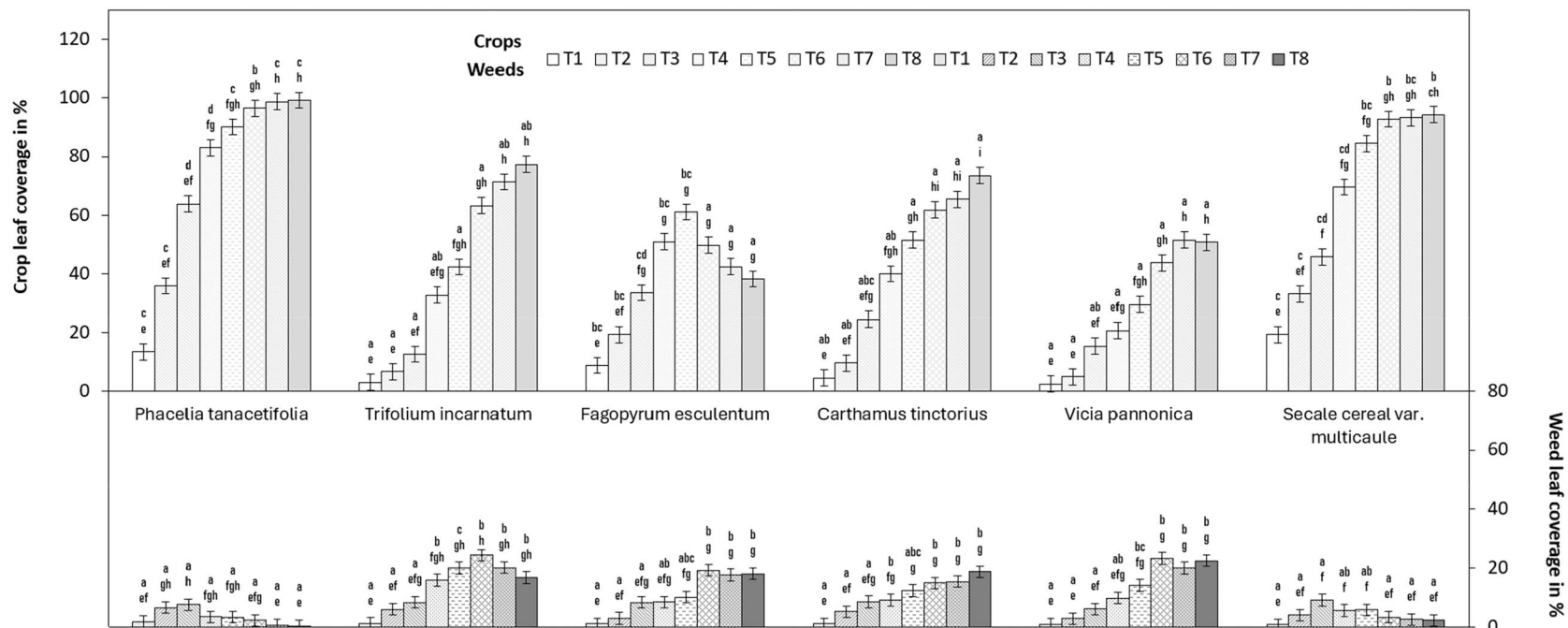


Figure 6. Coverage in %. Comment to Figure 6: Mean values (n = 12) of weed coverage in individual cover crops for each crop and evaluation dates ± SD (lower part of diagram) for the whole time of field experiment duration from 2021 to 2024. T1 – T8 indicate autumn evaluation dates that are closer characterised in Table 2. Different letter indices indicate significant differences between the variants (cover crops) at a significance level $P < 0.05$ (post hoc Dunn's test with Bonferroni correction) and significant differences between the individual dates at a significance level $P < 0.05$ (post hoc Nemenyi test). Significant differences between the variants are expressed by letter indices a → d (a, b, c, d); Significant differences between the evaluation dates are expressed by letter indices e → k (e, f, g, h, i, j, k).

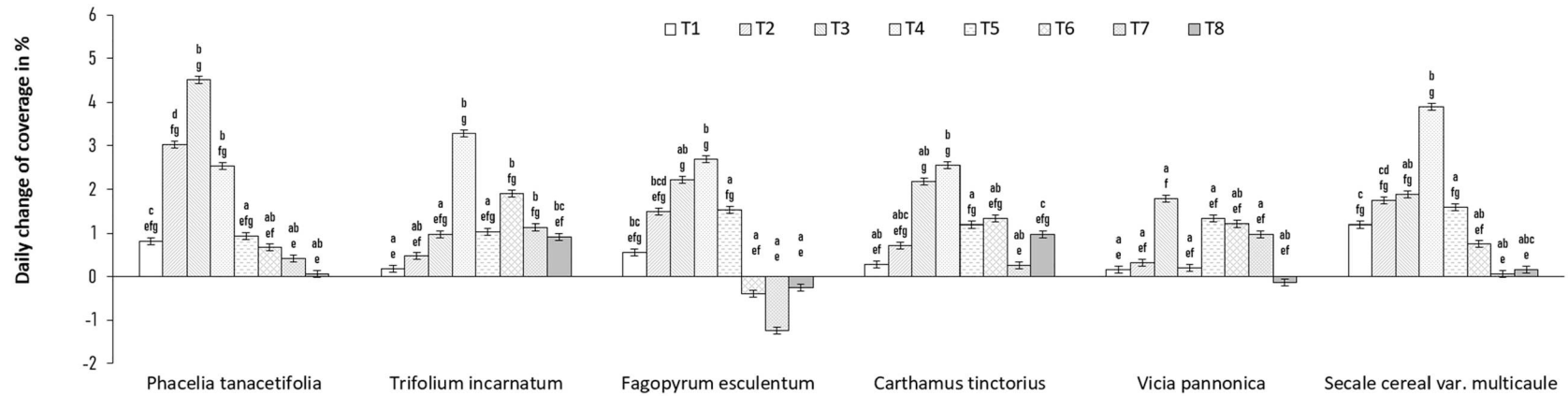


Figure 7. Mean daily change of crop coverage. Comment to Figure 7: Comment to Figure 6: Mean values ($n = 12$) of crop coverage and the evaluation dates \pm SD for the whole time of experiment duration from 2021 to 2024. T0 indicates the date of sowing, T1–T8 indicate autumn evaluation dates that are closer characterised in Table 2. Different letter indices indicate significant differences between the variants (cover crops) at a significance level $P < 0.05$ (post hoc Dunn's test with Bonferroni correction) and significant differences between the individual dates at a significance level $P < 0.05$ (post hoc Nemenyi test). Significant differences between the variants are expressed by letter indices a \rightarrow d (a, b, c, d); Significant differences between the evaluation dates are expressed by letter indices e \rightarrow k (e, f, g, h, i, j, k).

strong negative correlation (according to Evans 1996) between the soil surface coverage by cover crops and weeds was found ($r_s = -0.71$; $P < 0.001$), i.e. the potential influence of the cultivation of cover crops to suppress weeds was confirmed also by the correlation analysis.

Biomass production

There were in total three samplings of above-ground biomass during the autumn evaluation. Total production of shoot matter was formed both by crops and weeds, but the weight of crops and weeds was assessed separately. Significant differences in the production of green (or fresh) matter were found both between the cover crops and between the sampling dates. The lowest green matter production was in most crops in the first collection date, but *Fagopyrum esculentum* L., on the contrary, had the lowest green matter production in the last collection date. This was due to the fact that *Fagopyrum esculentum* L. ended its vegetation because of cold weather and its plants were dry during the last sampling. Crops with a higher production of green matter (Figure 9) were *Phacelia tanacetifolia* Benth. (on average 13.1–41.4 Mg ha⁻¹, depending on sampling date), *Carthamus tinctorius* L. (5.9–26.4 Mg ha⁻¹, depending on sampling date) and *Secale cereale* L. (8.1–19.5 t ha⁻¹, depending on sampling date). In *Phacelia tanacetifolia* Benth. and *Carthamus tinctorius* L., green matter had a higher moisture content and average dry matter production after drying was 1.3–4.0 Mg ha⁻¹ in *Phacelia tanacetifolia* Benth. and 0.5–2.9 Mg ha⁻¹ in *Carthamus tinctorius* L.. A lower moisture content in green matter was recorded in *Secale cereale* L. in which a maximum yield of dry matter was 1.4–4.0 Mg ha⁻¹.

Biomass yields were used to calculate mean daily increments (Figure 10) and to evaluate the intensity of above-ground biomass growth between the samplings. In the initial period of growth, daily biomass increments were lower, similar as the production of biomass, then the increments increased. *Fagopyrum esculentum* L. was exception, in which the daily biomass increment was significantly higher in the period between sowing and the first sampling date. The lowest daily change of biomass production was recorded in *Fagopyrum esculentum* L. between the 2th and 3th sampling date (TO2 and TO3) (see Figure 10).

The above-ground biomass of weeds was assessed along with the production of above-ground biomass in crops (Figure 9 and Annex 10). No significant differences in the fresh weight of weeds between the variants (cover crops) were found, but there were significant differences between the dates of sampling. Differences in the dry weight of weeds were recorded only on the last sampling date, when significantly (Figure 9) more weeds occurred in vetch (0.96 Mg DM of weeds per ha⁻¹) than in *Phacelia tanacetifolia* Benth. (0.33 Mg DM of weeds per ha⁻¹). No significant differences were recorded among the other crops (see Figure 9).

Discussion

Emergence and development

Liu et al. (2015) and Tribouillois et al. (2018) propose that the emergence rate of cover crops and their subsequent development and growth, can be considered as traits affecting the positive environmental effects of cover crops on arable land. In our experiments, the development of cover crops was studied not only from the viewpoint of emergence rate and initial growth but also in relation to the risk of seed formation. The emergence and development of *Phacelia tanacetifolia* Benth. were studied by Kubíková et al. (2022a) and Thrasyloulou and Tsirakoglou (1998). They observed that under favourable temperatures, *Phacelia tanacetifolia* Benth. emerges within 6–14 days and starts to bloom after ca. five to nine weeks from sowing. In our experiments, *Phacelia tanacetifolia* Benth. emerged within a week, but due to lower temperatures in the autumn months, it began to bloom only within ten to eleven weeks (see Table 4). The development of *Carthamus tinctorius* L. was studied by Flemmer et al. (2015) who found out that the crop emerged within 11–24 days and reached the stage of butonization (BBCH 55) within approximately 13 weeks. In our experiments, *Carthamus tinctorius* L. emerged more rapidly (within a week), but buds only began to form (BBCH 50) after 11 weeks (see Table 4), which shows that the onset of bloom is slow in this crop. Hairy vetch and *Trifolium incarnatum* L. are winter species sown in autumn and they usually bloom in spring of the following year (Georgieva and Kertikov 2006; Petraitytė et al. 2007; Moore et al. 2020). *Secale cereale* L. is another winter species; in our experiments, however, it reached up to the stage of ear formation (BBCH 54), which was

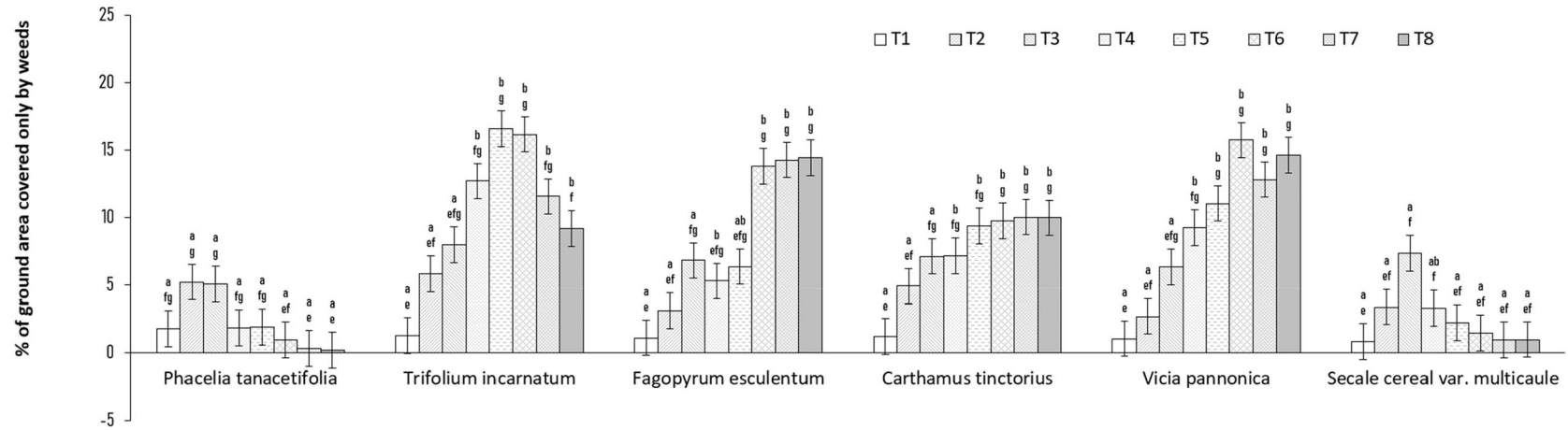


Figure 8. Effect of weeds on total coverage (% of soil covered only by weeds). Comment to [Figure 8](#): Mean values ($n = 12$) of % of soil covered only by weeds for each crop and evaluation dates \pm SD for the whole time of field experiment duration from 2021 to 2024. T1 – T8 indicate autumn evaluation dates that are closer characterised in [Table 2](#). Different letter indices indicate significant differences between the variants (cover crops) at a significance level $P < 0.05$ (post hoc Dunn's test with Bonferroni correction) and significant differences between the individual dates at a significance level $P < 0.05$ (post hoc Nemenyi test). Significant differences between the variants are expressed by letter indices a \rightarrow d (a, b, c, d); Significant differences between the evaluation dates are expressed by letter indices e \rightarrow k (e, f, g, h, i, j, k).

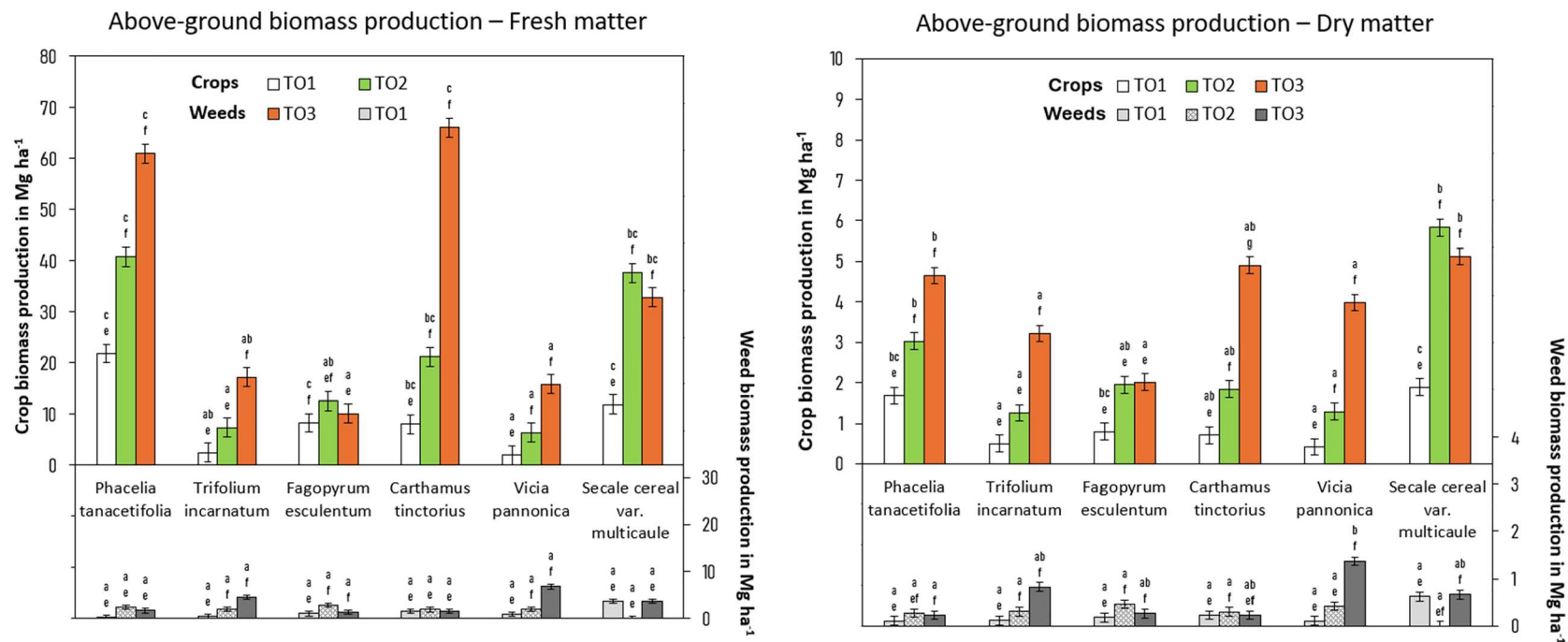


Figure 9. Above-ground biomass production in Mg ha^{-1} . Comment to Figure 9: Mean values ($n = 12$) of the production of crop above-ground biomass for each crop and evaluation dates \pm SD for the whole time of experiment duration from 2021 to 2024. (upper part of diagram). Mean values ($n = 12$) of the production of weed above-ground biomass in individual cover crops for each crop and evaluation dates \pm SD (lower part of diagram). The diagram on the left shows fresh biomass and the diagram on the right shows dry biomass. TO1–TO3 indicate dates of above-ground matter sampling, which are closer characterised in Table 3. Different letter indices indicate significant differences between the variants (cover crops) at a significance level $P < 0.05$ (post hoc Dunn’s test with Bonferroni correction) and significant differences between the individual dates at a significance level $P < 0.05$ (post hoc Nemenyi test). Significant differences are expressed by letter indices $a \rightarrow d$ (a, b, c, d); Significant differences between the evaluation dates are expressed by letter indices $e \rightarrow k$ (e, f, g, h, i, j, k).

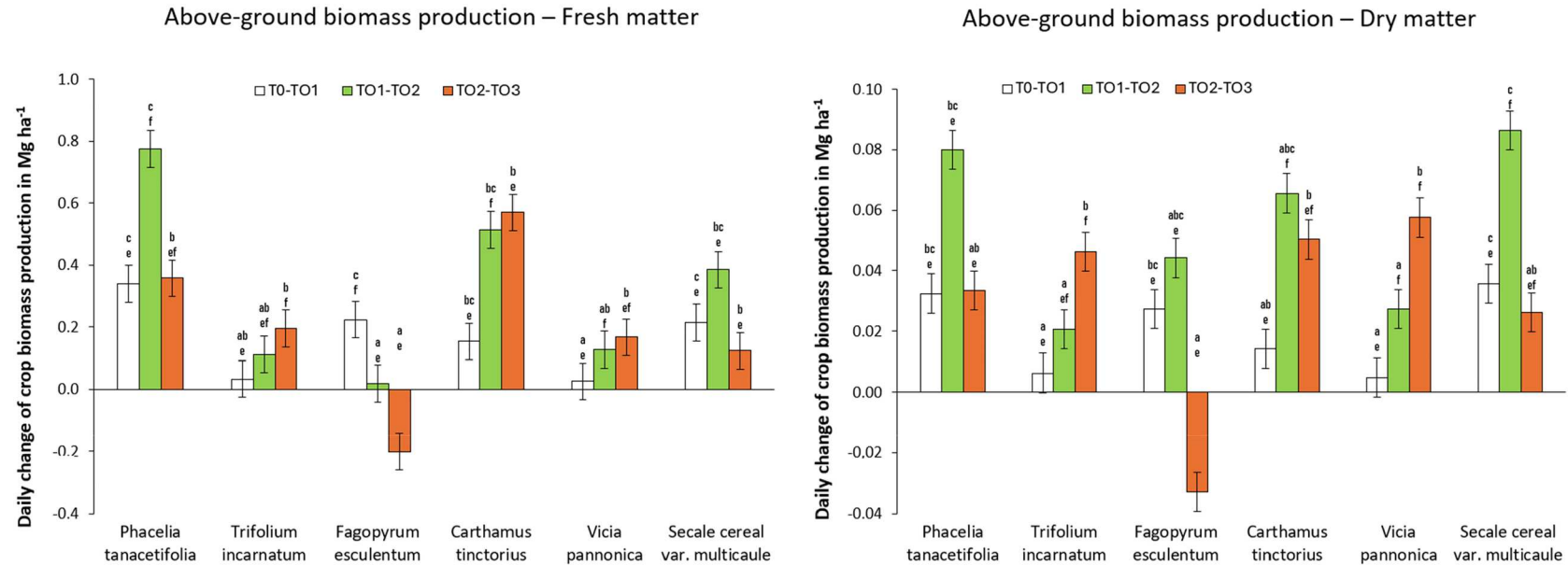


Figure 10. Above-ground biomass production daily change in Mg ha^{-1} . Comment to Figure 10: Mean values ($n = 12$) of the daily change of above-ground biomass for each crop and evaluation dates \pm SD for the whole time of field experiment duration from 2021 to 2024. T0 indicates sowing date, T01–T03 indicate dates of above-ground matter sampling, which are closer characterised in Table 3. Different letter indices indicate significant differences between the variants (cover crops) at a significance level $P < 0.05$ (post hoc Dunn's test with Bonferroni correction) and significant differences between the individual dates at a significance level $P < 0.05$ (post hoc Nemenyi test). Significant differences between the variants are expressed by letter indices $a \rightarrow d$ (a, b, c, d); Significant differences between the evaluation dates are expressed by letter indices $e \rightarrow k$ (e, f, g, h, i, j, k).

related to the early sowing date (Pomortsev et al. 2019, Szuleta et al. 2022) and the course of weather. In the Czech Republic, a date recommended for sowing *Secale cereale* L. on sites up to 400 m a.s.l. is around 5 October (Šarapatka et al. 2006). The development stage of *Secale cereale* L. influenced the stand frost kill. Susceptibility to frost kill at the stage of stem elongation and flowering was observed also in other species (Rapacz et al. 2001; Jacobsen et al. 2005; Frederiks et al. 2015; Wu et al. 2022). The frost kill of cover crops does not need to be considered always to be a disadvantage. It even may be desirable since frost kill is a natural elimination of cover crops without using herbicides. *Fagopyrum esculentum* L. was the most susceptible to frost but it was also the only species in which the formation of seeds was observed. Koyama et al. (2019) recorded the flowering of *Fagopyrum esculentum* L. within six weeks. *Fagopyrum esculentum* L. flowering within four to seven weeks was also reported by other authors (Quinet et al. 2004; Michiyama et al. 2005), which matches our results when *Fagopyrum esculentum* L. bloomed four to five weeks from sowing (see Table 4). From an agronomic point of view, the data obtained on plant emergence and development of plants are of great importance as emergence affects the production of plant biomass, which has a great influence on the capacity to suppress weeds (Florence et al. 2019). The knowledge of development is also very important for the timely end of cover crops when seed formation and ripening have to be taken into account.

Plant height

Plant height changes during the growth and development of plants. It is usually affected not only by the stage of development, but also by the species as well as other factors such as variety, sowing date, year, availability of soil nutrients etc. (Liu et al. 2015; Vujić et al. 2021). Kubíková et al. (2022b) state that the height of *Phacelia tanacetifolia* Benth. in spring sowing dates ranged from 357 to 830 mm at a stage of the beginning of flowering (BBCH 61). In Bowie et al. (1995), a height at the time of flowering was 15–70 cm. Lermi and Palta (2017) recorded that at the time of flowering an average height of plants sown in mid-August was 61 cm. In our experiments, the highest developmental stage of *Phacelia tanacetifolia* Benth. was the beginning of flowering (BBCH 61) and an average height was 536 mm. The next studied crop was *Carthamus tinctorius* L.. Mokhtassi Bidgoli et al. (2006) monitored the effect of soil water availability (water regime) on the growth of *Carthamus tinctorius* L. sown in May, which reached a height of 232–619 mm at full maturity (BBCH 89). *Carthamus tinctorius* L. plants in our experiments reached a height of 147–791 mm (see Figure 2 and Annex 7), with the limiting factor being not soil water availability but temperature. The height of *Fagopyrum esculentum* L. plants sown at the end of summer was studied by Omidbaigi and De Mastro (2023) and Bowie et al. (1995) and average height of *Fagopyrum esculentum* L. in their experiments was 321 mm and 350 mm, respectively. That was less than in our experiments in which the maximum height of *Carthamus tinctorius* L. ranged from 400 to 681 mm (see Annex 7), probably due to lower temperatures and higher precipitation. In Ross et al. (2001), *Trifolium incarnatum* L. reached a height of 28–53 cm after 10 weeks from sowing and in Uchino et al. (2011) vetch reached a height of 42 cm, but in our experiments, clover and vetch belonged to cover crops of lower build. They were growing at lower temperatures and reached a maximum height of 28–116 mm and 29–127 mm, respectively, after a similar time (see Annex 7). The ability of cover crops to reach sufficient height is important for them to compete for resources in the given locality with weed plants (Hatfield and Stewart 1997; Moore et al. 1994). In our experiment, the average height of weeds seven weeks after sowing was 167 mm (*Chenopodium* ssp.) and 242 cm (volunteer wheat), which means that weeds were overgrowing the lowest cover crop species (clovers and vetch), which was a competitive advantage for them.

Coverage and weed infestation

The importance of cover crops as a source of nutrients from crop residues was corroborated by Kincl et al. (2021). The height of plants is an important quality indicator for cover crops. However, if this parameter is interpreted without further qualitative and quantitative indicators (e.g. coverage), it cannot express suitability of a specific crop for being used as cover crop objectively enough (Prabhakara et al. 2015; Szuleta et al. 2022). Coverage combined with plant height is a basis for the potential positive influence of growing cover crops on selected soil properties – SOM, soil aeration, restriction of non-productive

evaporation, resistance to erosion phenomena etc. (Duval et al. 2016; Daryanto et al. 2018). Coverage in *Phacelia tanacetifolia* Benth. and *Trifolium incarnatum* L., was studied by Brant et al. (2009). Mean coverage detected by them from the end of October to the beginning of November was 49.8% in *Phacelia tanacetifolia* Benth. and 45.7% in clover. The coverage was lower than in our experiments, in spite of the fact that the sowing date was also in mid-August. As in our experiments, the coverage of weeds was significantly higher in clover (22.6%) than in *Phacelia tanacetifolia* Benth. (12.3%) (See Figure 6). Schappert et al. (2019) assessed the coverage of *Phacelia tanacetifolia* Benth. and vetch and their influence on weed infestation. The coverage ranged from 25% to 65% in vetch and from 60% to 80% in *Phacelia tanacetifolia* Benth.. As in our research, the coverage was also significantly higher in *Phacelia tanacetifolia* Benth. than it was in vetch (See Figure 6). The composition of weeds was also similar as in our experiment. Volunteer wheat was the most frequently occurring weed. Similar to our work, weeds increased the total ground cover in their experiments, which shows that weeds can have a favourable influence on the soil coverage.. In the experiments by Handlířová et al. (2017), the coverage ranged after 70 days from sowing from 46 to 88% in *Phacelia tanacetifolia* Benth., from 7% to 61% in *Fagopyrum esculentum* L., from 52 to 81% in *Secale cereale* L. and from 66% to 75% in *Carthamus tinctorius* L.. In all crops, the coverage was lower than in our experiments, but *Fagopyrum esculentum* L. coverage was significantly lower than for *Carthamus tinctorius* L., *Phacelia tanacetifolia* Benth. and *Secale cereale* L.. Similar results were recorded in *Phacelia tanacetifolia* Benth. and *Secale cereale* L. in our experiments. In our experiments, the coverage of *Fagopyrum esculentum* L. was comparable with that of *Carthamus tinctorius* L. after 70 days from sowing.

Biomass production

Higher growth with good coverage is prerequisites for high biomass production which is also a significant benefit in the cultivation of cover crops. Kwiatkowski et al. (2016) found that the yield of above-ground dry matter in *Phacelia tanacetifolia* Benth. was 4.01–4.06 Mg ha⁻¹, which is close to our results. On the other hand, Brant et al. (2009) reported the yields of purple tansy (ca. 1.19 Mg DM per ha) lower than those in our experiments (see Figure 9 and Annex 1). It could not have been due to sampling date since the sampling of biomass was made at the beginning of November, similarly as in experiments. In *Trifolium incarnatum* L. they recorded a dry matter yield of 1.09 t per ha. An average yield of crimson clover in our experiments was higher (1.63 Mg DM per ha). Lower yields in experiments conducted by Brant et al. (2009) were most likely related to coverage that was also lower than in our experiments. Brant et al. (2009) also recorded the dry matter of weeds, which was 0.25 Mg ha⁻¹ in *Phacelia tanacetifolia* Benth. and 0.45 Mg ha⁻¹ in *Trifolium incarnatum* L.. In our experiments, higher values were detected (see Figure 9 and Annex 2). Schappert et al. (2019) report a production of dry matter in *Phacelia tanacetifolia* Benth. (0.8–1 t ha⁻¹) and in weeds (0.05–0.15 t ha⁻¹) seven weeks after sowing, which is similar as in our experiments. Thorup-Kristensen (2001) recorded a total weight of dry biomass in *Phacelia tanacetifolia* Benth. to be 4.7 Mg ha⁻¹ (of this 0.5 Mg ha⁻¹ of roots) and 4.3 Mg ha⁻¹ in vetch (of this 0.6 Mg ha⁻¹ of roots). Compared to our experiments, the production of vetch and *Phacelia tanacetifolia* Benth. did not exhibit a significant difference, as the production of vetch was higher than in our experiments. Mokhtassi Bidgoli et al. (2006) assessed *Carthamus tinctorius* L. yields. In their experiments, *Carthamus tinctorius* L. reached a dry matter yield of up to 11 Mg ha⁻¹. The yield was higher than in our experiments because *Carthamus tinctorius* L. was harvested at a higher stage of development (BBCH 89). Danieli et al. (2011) recorded dry shoot matter yields of *Carthamus tinctorius* L. in the period of butonization to be 1.8–2.7 Mg ha⁻¹ depending on the nitrogen dose. The average yield of 2.5 Mg ha⁻¹ at the beginning of butonization was recorded in our experiments (see Annex 10). According to Cazzato et al. (2011), *Carthamus tinctorius* L. yields of dry shoot matter ranged in different development stages from 4.5 Mg ha⁻¹ (at the beginning of butonization) to 11.6 Mg ha⁻¹ (at the time of flowering). Yields were higher but similarly as in our experiment, the biomass production was increasing during the development. Arslan et al. (2007, 2012) studied biomass production in *Carthamus tinctorius* L. and accompanying weeds. Dry matter yields in *Carthamus tinctorius* L. were 7.9–8.8 Mg ha⁻¹ (fresh matter yields 28.5–30.1 Mg ha⁻¹). The dry matter production was higher, but the experiments were harvested at full bloom. This stage of development was not reached by *Carthamus tinctorius* L. in our experiments. Arslan et al. (2007, 2012) also report the amount of dry matter of weeds ranging from 0.27 to 0.58 Mg ha⁻¹ in *Carthamus tinctorius* L., similar to our experiments (see Annex 10). Buckwheat seems to be a very variable crop. In our experiments, the yields of dry matter were

from 0.8 to 1.7 Mg ha⁻¹ in *Fagopyrum esculentum* L. at the stage of flowering, but Omidbaigi and De Mastro (2023) reported yields of above-ground biomass in *Fagopyrum esculentum* L. from 0.11 to 0.25 Mg of dry matter per hectare, Brunori et al. (2005) report yields of dry matter in *Fagopyrum esculentum* L. at harvest in full maturity to range from 0.63 to 1.43 Mg ha⁻¹, and Romanovskaja et al. (2022) state *Fagopyrum esculentum* L. yields at the beginning of flowering stage to be 2.8–5 Mg of dry matter per hectare. Handlířová et al. (2017) monitored dry matter yields in *Secale cereale* L., *Fagopyrum esculentum* L., *Carthamus tinctorius* L., and *Phacelia tanacetifolia* Benth. 70 days after sowing and the yields were lower than in our experiments.

In the context of results published by other authors, the production of biomass clearly depends not only on the crop species, but also on external conditions and the development stage of the crop. It is impossible to make general recommendations, but an important precondition for high yield is good stand closure and growth intensity. The best results can be expected from *Phacelia tanacetifolia* Benth. and *Secale cereale* L. in conditions similar to our experiment. Maximum biomass production has to be considered also from the viewpoint of plant development, when the shifting of the end of vegetation growth may be beneficial for production. However, if the cover crop forms seeds, this may adversely affect weed infestation of the subsequent crop.

Conclusion

The presented study was conducted in operational conditions of a conventional farm and aimed to find out the potential of several plant species for use as cover crops. The main objective of the research was to evaluate the growth and development of six cover crop species from the viewpoint of their: (a) development, (b) growth intensity, (c) biomass production, (d) stand closure, (e) competitiveness to weeds. A hypothesis was tested that the chosen species of the cultivated cover crop has an influence on biomass production, improves soil coverage and suppresses the occurrence of weeds. Based on the measurements undertaken, it is possible to state that the hypothesis was confirmed. The main findings are as follows:

- The studied cover crop species exhibited differences in growth and development, plant height, coverage, biomass production as well as in the proportion of weeds occurring in the stands of individual cover crops.
- *Fagopyrum esculentum* L. was the most rapidly developing cover crop and fruit development was recorded in it. This poses a risk in the use of this species that the subsequent crop may be infested by weeds due to crumbled seeds. It is therefore important to pay attention to the timely end of vegetation, optimally at the time of flowering, i.e. some 4 or 6 weeks after sowing depending on the course of weather.
- Overwintering was observed in clover, *Vicia pannonica* Crantz and *Secale cereale* L. Nevertheless, *Secale cereale* L. plants overwinter until the beginning of stem elongation stage. Although rye is a winter species, frost kill occurred if it had overgrown before winter and reached the stage of intensive stem elongation, ear formation or flowering. Plants of purple tansy, buckwheat and safflower did not hibernate. Thus, these cover crops are suitable for freezing mixtures used by farmers in regions with the similar climatological characteristic.
- Buckwheat was the most intensively growing species and reached the greatest height especially at the beginning of development. By contrast, species exhibiting the slowest growth were clover and vetch. Safflower and purple tansy showed a very even growth and because of their similar development and susceptibility to frost kill they can be used in mixtures.
- The most rapid stand closure was recorded in purple tansy which showed low occurrence of weeds and reliable frost kill of the plants (as a spring crop). Good stand closure was observed also in cultivated *Secale cereale* L. which was effective in suppressing weeds. In the cover crops of lower coverage, the soil was considerably covered by weeds.

The production of above-ground matter was affected by the growth and development of cover crops over the course of time, and higher production of biomass was usually recorded at later sampling dates when the plants were reaching greater heights and better stand closure. The highest yields of the studied species were recorded in *Phacelia tanacetifolia* Benth. tansy and *Secale cereale* L.. Regarding the fact that both species also exhibited good coverage, they can be considered as perspective cover crops. Good production of biomass was also recorded in *Carthamus tinctorius* L. which has lower

competitiveness similarly to clover, vetch and *Fagopyrum esculentum* L.. With respect to their lower competitiveness, these species do not appear appropriate as monoculture cover crops.

As to the practical use of our research findings it can be stated that the species most suitable for cultivation in pure seeding (cover crop monocultures) are *Phacelia tanacetifolia* Benth. and *Secale cereale* L. with the highest biomass production, the best coverage and the best competitiveness. The other tested cover crop species (*Carthamus tinctorius* L., *Fagopyrum esculentum* L., *Trifolium incarnatum* L. and *Vicia pannonica* Crantz.) are not much suitable for cultivation in pure seeding (cover crop monocultures) but they can be good for use in mixtures with other cover crop species. Further research should be focused not only on the monitoring of individual cover crop species, but also on their development in mixtures in which the development of plants may differ to a certain extent. Research should be also focused on the rate of seed development in various cover crop species with respect to the risk of weed infestation for the subsequent crop.

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