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ORIGINAL RESEARCH PAPER

Aboveground dry biomass partitioning and nitrogen accumulation in early maturing soybean 'Merlin'

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Abstract

The aim of the study was to determine the biomass and nitrogen accumulation in early maturing soybean plants experiencing contrasting weather conditions. Soybean (*Glycine max*) is a species of agricultural crop plant that is widely described in scientific publications. During 2014–2016, a field experiment with early maturing soybean 'Merlin' was carried out at Grodziec Śląski, Poland (49°48′01″ N, 18°52′04″ E). Results showed that the morphological traits of the plants, the yield of individual plants, and the soybean crop were all closely related to the climatic conditions. A high amount of precipitation stimulated seed development, resulting in a high production potential. The harvest index calculated for soybean 'Merlin' was high and exceeded 0.5 g g^{-1}. The nitrogen content of the aboveground biomass increased during ontogenesis. The maximum yield of dry matter was noted at the green maturity phase, which subsequently decreased at the full maturity phase because of the loss of the leaf fraction. The variation in the effectiveness of nitrogen accumulation in seeds between 2015 and 2016 was 30%. The nitrogen harvest index values were high in each year of the experiment and exceeded 0.92 g^{-1}. For the production of 1 ton of seeds with an adequate amount of soybean straw, plants needed, on average, 68 kg of nitrogen.

Keywords

morphological traits; HI; growth stage; NHI

Introduction

In the terms of its economic importance, soybean [genus: *Glycine* Willd, species: *Glycine max* (L.) Merr.] is the leading crop species in the bean family (Fabaceae). According to Liu et al. [1], the number of papers related to soybean physiology published between 1990 and July 2014 amounted to 1572. Soybean is the dominant crop legume; 50% of global crop production is of legumes and 68% of this is soybean [2].

The multifaceted use of soybean products as a food for humans or feed for livestock determines its very high economic rank [3]. In recent years, Poland has been importing 2 million tons of soybean meal, costing about €1 billion, annually [4]. Over the past 10 years, the import of soybean meal has doubled. It should be emphasized that the soybean meal imported into the country is derived from the processed seeds of GMO (genetically modified organism) cultivars. Soybean meal imported into European countries, including Poland, contains genetically modified protein, therefore this product is not welcomed by a part of the society [5]. On a global scale, soybean cultivation extends over 121 Mha. At the same time, the seed yield production reaches 340.8 Mt. There are big differences in yields, since in the United States the average yield is 3.5 t ha^{-1}, whereas in China it is only 1.79 t ha^{-1} [6]. Of all the high-protein legumes, soybean is characterized by a relatively high protein content and high digestibility. Herridge et al. [2] showed that soybean fixed 16.4 Tg of nitrogen annually, which corresponds to 77% of the total N amount fixed by leguminous plants.

Currently, four countries, the USA, Brazil, Argentina and China, produce as much as 89% of the global soybean seed production [4]. Most of these are GMOs. Other countries have a small share of the total soybean seed production. It is postulated that the successful implementation of soybean for a broader scale of cultivation in Poland, using nongenetically modified cultivars, will improve the country's food security. The presence of soybean, as a leguminous plant in the structure of arable cropland will help to improve the organic matter balance in the soil profile, which may then increase the yield of cereal crops in a successive crop rotation. The cultivation of soybean also has a positive effect on the "greenfield" requirements for implementation on large-scale farms. In Europe, it is suggested to cultivate early-maturing soybean varieties between the forty-second and fiftieth latitudes north. Under these climatic conditions, the varieties of the "000" and "00" earliness groups are primarily cultivated. Therefore, such cultivars should be grown in Poland because the crop they produce lasts for about 120–130 days [7]. In the list of COBORU (Centralny Ośrodek Badania Odmian Roślin Uprawnych – Research Centre for Cultivar Testing in Poland) cultivars, eight early-maturing soybean cultivars were registered in 2014. Most of them have been included in the "Common catalogue of varieties of agricultural plant species" of the European Union. Saatbau offers a large number of soybean cultivars, including the non-GMO soybean 'Merlin', which is valued for its exceptional earliness ("000") and high, stable yields. In the official experiment of 2008, it yielded 3.96 t ha^{-1}. However, another cultivar from this company, 'Lissabon', produced an even higher yield of 4.26 t ha^{-1}.

The changing climate, as a result of a progressive global warming, requires continuous adaptation of the production agrotechnology of agricultural plants. The pursuit of maximum agricultural production under new environmental conditions indicates the high potential for soybean. As shown by Falloon and Betts [8], the unfavorable effects of climate change on agriculture in the temperate zone may result in an increase in the water deficit during summer, which will increase the need for soybean irrigation in traditional regions of cultivation. Changing climatic conditions may result in a shifting of traditional regions of thermophilous plants (i.e., soybean and maize) to the northern parts of the temperate zone, beyond the fiftieth latitude [9,10].

Due to the widespread use of soybean products for feeding poultry and swine, there is a much interest for farmers to increase the acreage of soybean cultivation. However, based on the existing research data, there is a strong influence of weather conditions on soybean yield potential [11,12]. Consequently, there is a need for a precise understanding of the agrobiological determinants of productivity at the individual plant and soybean crop levels. Crucial for this is the precise understanding of nitrogen accumulation in plant parts at specific growth stages. Soybean, as a leguminous plant, has high nutritional requirements for nitrogen. In the USA, 1 t of seeds (+ straw) requires ca. 80 kg of nitrogen for proper growth and development [13].

The aim of this study was to determine the participation of the specific parts of plants in the dry matter production of the whole plant and resulting soybean crop at different stages of its development. We determined nitrogen content in individual parts of the plants. We also estimated the nitrogen harvest index (NHI) and nitrogen consumption for the production of 1 t of seeds (+ straw) by an early maturing soybean cultivar over three growing seasons.

Material and methods

The morphological development and seed yield of an early maturing soybean cultivar, 'Merlin', were investigated at Grodziec Śląski (Silesian Province, southern Poland) over three growing seasons, 2014–2016. The town is located in the piedmont region of Silesian Beskids at an altitude of 373 m a.s.l. The soil here is classified as Class IIIa of the good wheat complex. The crop preceding soybean was wheat in all years. The

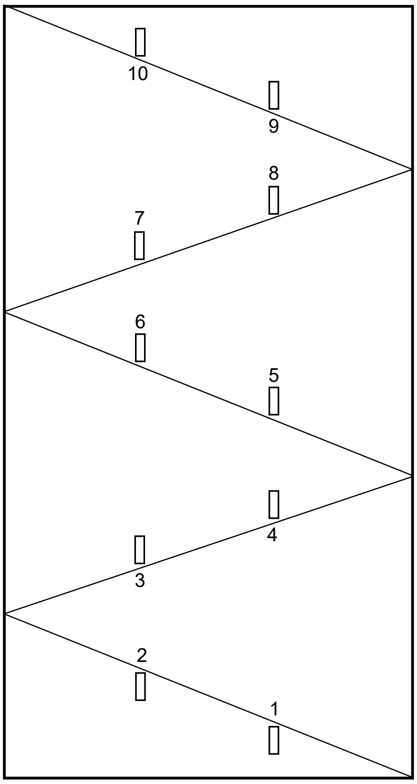

Fig. 1 The location of 10 experimental plots of soybean in the production field.

cultivated soil was characterized by a high or medium content of available forms of phosphorus, potassium, and magnesium in the rooting zone and pH of 6.6 to 7.0. Before planting, the plots were fertilized with 46 kg ha^{-1} of P_2O_5 and 80 kg ha^{-1} of K_2O, with the exception of potassium fertilization in 2014. The starting dose of nitrogen was 18 kg ha^{-1}. Experimental measurements were conducted on the production fields in all 3 years, which amounted to 3.0, 6.0, and 8.0 ha in 2014, 2015, and 2016, respectively.

Soybean seeds were sown on the following dates (yyyy-mm-dd): 2014-05-08, 2015-05-10, and 2016-05-09 at a seeding rate of 70 seeds m^2 and in rows spaced 25 cm apart.

Dicotyledonous weeds were controlled in all growing seasons using a mixture of Afalon 450 SC 1.0 dm^3 ha^{-1} (linuron) + Command 400 EC 0.17 dm^3 ha^{-1} (clomazone) herbicides. Insects and diseases were not observed during vegetative growth. Before harvesting, soybean plants were desiccated with Basta 150 SL. Harvesting of mature plants was conducted on: 2014-10-10, 2015-10-07, and 2016-09-30.

After seed germination, 10 plots (replicates) were designated from the large field in a completely randomized block design, as shown in Fig. 1. Each plot had dimensions of 3 × 7 m. Biometric measurements of the soybean plants were conducted in these plots at three developmental stages: flowering (BBCH 69), green maturity (BBCH 79), and full maturity (BBCH 89) [14]. Ten individual plants at each stage were analyzed from each plot to give a total of 100 sample plants. The harvested plants were dried in an airflow dryer for 3–4 days. At each stage of development, the following morphological characteristics and yield of soybeans were evaluated: plant height (cm), plant weight (g), shoot weight (g), number of leaves (pcs.), flower weight (g), juvenile pod weight (g), pod weight (g), pod wall weight (g), number of pods (pcs.), seed weight (g), number of seeds (pcs.), plant density (pcs. m^2). For the green maturity and full maturity stages, an evaluation of the pod characteristics was also made. After sampling soybean plants from the production field, the experimental plots were harvested with a Wintersteiger Seedmaster Universal plot combine. Water content was determined in the seed yields. The latter were calculated on the basis of a 9% water content.

The harvest index (HI; g g^{-1}) was calculated at the green and full maturity stages, according to formula proposed by Donald and Hamblin [15]:

$$HI = \frac{Seed\ yield}{Biological\ yield}$$

Total nitrogen content was determined in the dried parts of the soybean plants. Based on these data, the NHI (g g^{-1}) was calculated according to formula proposed by Salado-Navarro et al. [16]:

$$NHI = \frac{N\ seed}{N\ total}$$

Analyses of variance (ANOVA) (Statistica 10.0 software) were performed for evaluation of the experimental data. Tukey's honestly significant difference (HSD) test was used for mean separation at the $p < 0.05$ significance level.

Results

A summary of the weather conditions at Grodziec Śląski each year of the soybean cropping is presented in Tab. 1. The growing seasons in 2014 and 2015 were characterized by a similar total precipitation; in July and August 2015 it was less than those months in 2014. Dry and warm weather during soybean maturation in 2015 reduced the weight of a single seed and consequently decreased the yield (Tab. 2, Tab. 3).

The climatic conditions prevailing during the term of the experiment influenced the morphological traits of soybean plants at the full flowering stage (Tab. 4). Dry conditions, which occurred in June 2015, along with the higher air temperatures, reduced

Tab. 1 Monthly precipitation totals (A) and the average air temperature (B) at the experimental location in Grodzieniec Śląski during 2014–2016.

Specification	Year of vegetation	Month						Total (A); average (B)
		Apr	May	Jun	Jul	Aug	Sep	
Precipitation – A (mm)	2014	51.0	85.0	40.0	48.0	76.0	68.0	368.0
	2015	58.0	111.0	40.0	75.0	15.0	58.0	357.0
	2016	80.0	70.0	80.0	190.0	90.0	55.0	565.0
Air temperature – B (°C)	2014	9.3	12.1	16.8	19.1	17.4	16.0	16.0
	2015	10.5	14.0	18.0	20.5	20.5	16.0	16.0
	2016	9.0	13.0	18.0	20.0	18.0	16.0	15.7

Tab. 2 Morphological characteristics of pods in response to growth stage and growing season.

Trait	Growth stage BBCH	Year			$HSD_{\alpha = 0.05}$	ρ
		2014	2015	2016		
Pod length (cm)	79[1]	4.4 ±0.4[3]	3.7 ±0.6	4.3 ±0.3	0.07	***
	89[2]	4.5 ±0.5	3.6 ±0.6	4.5 ±0.4	0.09	***
Pod weight (g)	79	0.440 ±0.105	0.260 ±0.095	0.730 ±0.151	0.021	***
	89	0.717 ±0.161	0.349 ±0.135	0.937 ±0.201	0.029	***
Seed weight in pod (g)	79	0.280 ±0.082	0.138 ±0.073	0.507 ±0.120	0.016	***
	89	0.529 ±0.126	0.183 ±0.089	0.697 ±0.163	0.022	***
Pod wall weight (g)	79	0.159 ±0.033	0.121 ±0.037	0.223 ±0.050	0.007	***
	89	0.188 ±0.044	0.171 ±0.050	0.240 ±0.081	0.010	***
Number of seeds per pod (pcs.)	79	2.8 ±0.5	2.3 ±0.9	3.0 ±0.3	0.106	***
	89	3.0 ±0.6	2.0 ±0.8	2.9 ±0.5	0.111	***
Single seed weight (g)	79	0.100 ±0.020	0.066 ±0.041	0.169 ±0.031	0.005	***
	89	0.177 ±0.027	0.099 ±0.036	0.241 ±0.045	0.006	***

[1] 79 – green maturity. [2] 89 – full maturity. [3] Mean ± standard deviation. Significant effects at $p < 0.001$ (***).

Tab. 3 Yielding, plant density, and the height of the first pod on the soybean stem.

Specification	Year			$HSD_{\alpha = 0.05}$	ρ
	2014	2015	2016		
Yield (t ha^{-1})	2.55 ±0.26	1.75 ±0.21	2.04 ±0.15	0.223	**
Plant density (pcs. m^{-2})	30.3 ±2.4	26.7 ±5.4	20.5 ±4.8	5.2	*
Height of first pod (cm)	12.5 ±2.5	4.3 ±1.1	10.6 ±3.3	1.2	***

Significant effects at $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***).

Tab. 4 The characteristics of the morphological traits of soybean plants in the flowering stage (BBCH 69).

Trait	Year 2014	Year 2015	Year 2016	HSD $_{\alpha = 0.05}$	ρ
Plant height (cm)	64.5 ±6.6[1]	45.5 ±4.9	76.0 ±7.8	3.1	***
Plant weight (g)	7.92 ±1.60	7.95 ±1.56	13.51 ±4.26	1.32	***
Shoot weight (g)	3.70 ±0.89	2.54 ±0.52	5.20 ±1.66	0.54	***
Number of leaves (pcs.)	13.8 ±3.4	56.6 ±13.3	20.3 ±9.3	4.5	***
Flower weight (g)	0.119 ±0.050	0.183 ±0.094	0.254 ±0.093	0.039	***
Juvenile pod weight (g)	0.091 ±0.089	0.037 ±0.044	0.103 ±0.071	0.034	*

[1] Mean ± standard deviation. Significant effects at $p < 0.05$ (*) and $p < 0.001$ (***).

Tab. 5 Leaf DM and its proportion in total plant DM at the two growth stages.

Trait	Growth stage BBCH	Year 2014	Year 2015	Year 2016	HSD $_{\alpha = 0.05}$	ρ
Plant leaves weight (g)	69[1]	4.01 ±0.77	5.19 ±1.31	7.95 ±2.55	0.81	***
	79[2]	4.44 ±1.5	2.71 ±0.7	6.63 ±1.6	n.s.	0.98
Proportion of leaves in plant weight (%)	69	50.9 ±3.5	64.7 ±6.5	58.8 ±2.9	2.2	***
	79	26.4 ±2.2	27.5 ±4.4	20.7 ±5.7	1.25	***

[1] 69 – flowering. [2] 79 – green maturity. Significant effects at $p < 0.001$ (***); n.s. – nonsignificant.

plant height and, consequently, shoot dry matter (DM) in comparison to 2014 and 2016. When compared with other growing seasons, plants in 2015 developed the greatest number of leaves. The tallest and the heaviest plants along with the greatest flower DM and young pod weights were formed during the more humid season of 2016. In 2016, plants produced the largest leaf DM per plant during the flowering phase. This tendency was also noted at the green maturity stage when compared to 2014 and 2015 (Tab. 5). The proportion of leaves in the plant DM was high at the flowering stage and varied between the growing seasons. The greatest proportion of leaves in the plant DM, varying around 64.7%, was observed in 2015 during the flowering stage (BBCH 69), when the stems of soybean plants were profusely leafy. However, between stages BBCH 69 and BBCH 79, the decline in the proportion of leaf DM was twofold. Such large declines were not observed in other years of the experiment. The leaf DM of a single plant at the green maturity phase of development did not differ significantly between growing seasons (Tab. 5). Fig. 2 shows the relationship between soybean leaf and plant DM. During the flowering phase the correlation was linear with a strong relationship as evidenced by the high correlation coefficient $R^2 = 0.93$. For the next stage of plant development, green

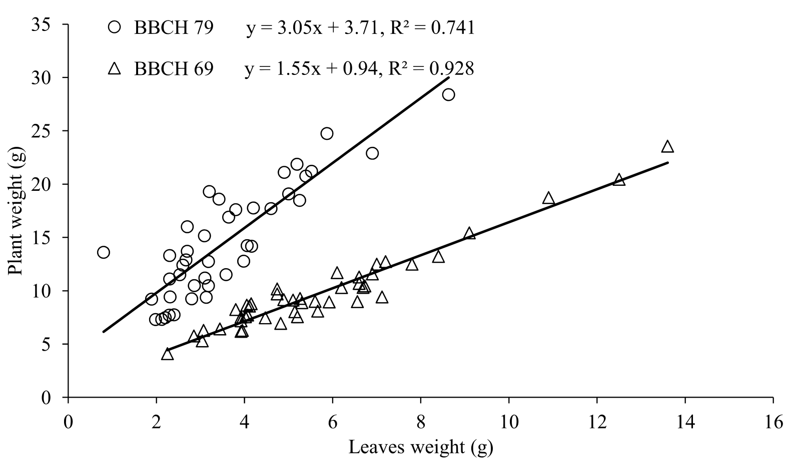

Fig. 2 The correlation between plant weight and leaf weight at two growth stages of soybean: flowering (BBCH 69), and green maturity (BBCH 79).

Tab. 6 The characteristics of soybean plants in two growth stages depending on the location.

Traits	Growth stage BBCH	Year			HSD $_{\alpha = 0.05}$	ρ
		2014	2015	2016		
Plant height (cm)	79[1]	78.5 ±10.2[3]	48.0 ±6.2	68.0 ±11.5	4.5	***
	89[2]	76.7 ±5.4	47.9 ±8.1	66.1 ±3.3	2.8	***
Plant weight (g)	79	16.88 ±5.35	10.05 ±2.69	17.04 ±3.95	3.74	**
	89	15.38 ±2.82	13.04 ±4.90	18.88 ±4.89	2.04	**
Shoot weight (g)	79	4.19 ±1.70	1.77 ±0.70	2.66 ±1.10	n.s.	0.070
	89	3.22 ±0.39	2.20 ±0.82	4.68 ±2.15	0.64	***
Number of pods (pcs.)	79	23.3 ±6.2	20.2 ±2.3	28.5 ±4.3	3.9	*
	89	20.8 ±4.8	19.0 ±6.7	20.8 ±8.3	n.s.	0.706
Pod weight (g)	79	8.24 ±2.43	5.57 ±1.94	10.75 ±1.97	2.47	***
	89	12.17 ±2.77	10.84 ±4.49	14.19 ±3.62	1.74	*
Seed weight (g)	79	5.21 ±1.53	3.38 ±0.68	7.36 ±1.28	1.73	***
	89	8.96 ±2.04	7.23 ±3.04	10.26 ±2.54	1.21	**
Pod wall weight (g)	79	3.03 ±0.89	2.19 ±1.46	3.40 ±1.11	0.84	***
	89	3.21 ±0.73	3.61 ±1.86	3.93 ±1.18	n.s.	0.316
Harvest index (g g^{-1})	79	0.310 ±0.031	0.343 ±0.050	0.442 ±0.076	0.029	***
	89	0.578 ±0.032	0.555 ±0.095	0.550 ±0.057	n.s.	0.453

[1] 79 – green maturity. [2] 89 – full maturity. [3] Mean ± standard deviation. Significant effects at $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***); n.s. – nonsignificant.

maturity, the correlation weakened and showed a moderate strength for the relationship, $R^2 = 0.74$. This pattern of correlation was determined by the smaller proportion of leaves in the total weight of a plant.

At the ripening phase, morphological traits differed between the growing seasons (Tab. 6). For example, the smallest plants were developed in 2015 when compared to 2014 and 2016, which was likely a result of extended drought during summer. A similar pattern was also observed during the green maturity phase in 2015. At the full maturity phase, the plant DM varied significantly between growing seasons: 15.38 ±2.82 g, 13.04 ±4.90 g, and 18.88 ±4.89 g, respectively for 2014, 2015, and 2016.

Soybean plants developed variable numbers of pods for all growing seasons – from 19 to 28 pcs. The highest seed yield per plant was harvested in 2016, and the lowest in 2015, which was a result of insufficient soil moisture during the ripening phase in summer. The HI of soybean 'Merlin' was favorable and exceeded 0.55 at full maturity, indicating a high proportion of seed weight in the total plant DM.

The potential of soybean production in relation to weather conditions is presented in Tab. 2. During the dry season of 2015, plants developed significantly shorter pods when compared to the other growing seasons. As a result, pod weight was also significantly lower, both because of lower single seed weight and the lower seed number per pod in the both phases of development (green and full maturity). The number of seeds per pod was more variable in 2015 than that in other seasons, as evidenced by higher standard deviation values for this trait.

Soybean yield varied significantly between growing seasons (Tab. 3). The highest yield was recorded in 2014, when climatic conditions were favorable for plant growth. Under the wetter conditions during the summer of 2016, seed yield was lower compared to 2014. It is likely that reduced seed yield resulted from extended periods of overcast

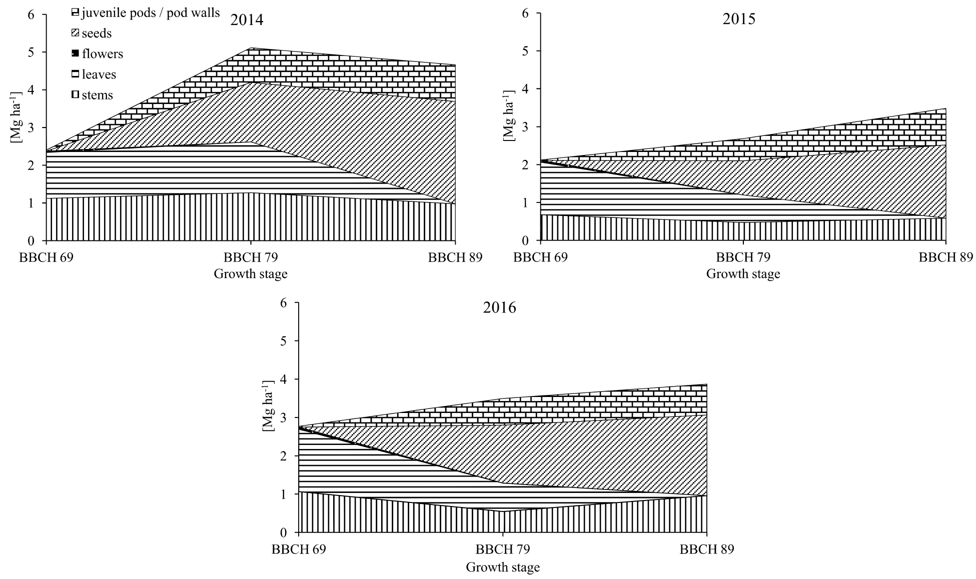

Fig. 3 The proportion of individual plant organs in aboveground biomass as affected by the growth stage and growing season.

skies, especially in July (Tab. 1), which could have reduced the amount of photosynthetically active radiation needed for soybean crop production. The height of the first pod setting on a stem was the greatest in 2014, which might have significantly reduced the loss of the seed yield during harvest. The opposite was observed in 2015, when plants established pods very low on the stems.

The proportions of individual plant parts in the total weight of the soybean plants are presented in Fig. 3. The most stable fraction in relation to other individual plant organs in aboveground biomass was the stem. The proportion of leaves was high at the flowering stage (BBCH 69), and then gradually decreased in the following stages. At full maturity (BBCH 89), plants did not have any leaves. The proportion of seeds in the total yield of the aboveground biomass as well as the proportion of pod walls were stabilized when the plants reached green maturity. The loss of leaves caused a decrease in total plant biomass estimated at full maturity.

The nitrogen content of the plant parts and in the aboveground biomass increased with progressive plant development (Tab. 7). Regardless of the growing season, the whole soybean plants had the lowest nitrogen content at the flowering stage. It was increasing as the plant was developing, mainly because it was accumulated in the seeds in the

Tab. 7 Nitrogen content (g kg^{-1} DM) in the soybean plants components depending on the growth stage: flowering (BBCH 69), green maturity (BBCH 79), full maturity (BBCH 89) and the year of research.

Plant part and whole plant	Growth stage BBCH 69				Growth stage BBCH 79				Growth stage BBCH 89			
	2014	2015	2016	HSD $\alpha = 0.05$	2014	2015	2016	HSD $\alpha = 0.05$	2014	2015	2016	HSD $\alpha = 0.05$
Stems	15.10	15.00	15.40	0.39	9.90	13.66	14.26	0.04	4.50	4.67	7.14	0.02
Leaves	20.90	19.70	20.40	0.33	23.9	22.46	27.26	0.87	-	-	-	-
Flowers	28.50	30.70	31.70	0.19	-	-	-	-	-	-	-	-
Juvenile pod	33.50	28.70	28.70	0.30	-	-	-	-	-	-	-	-
Pod walls	-	-	-	-	9.10	7.83	6.90	0.06	5.20	4.30	5.81	0.05
Seeds	-	-	-	-	63.50	72.80	64.80	0.63	62.70	50.37	66.15	0.57
Whole plant	18.47	18.44	19.13	0.32	30.14	34.87	36.99	1.58	38.26	29.93	39.30	1.62

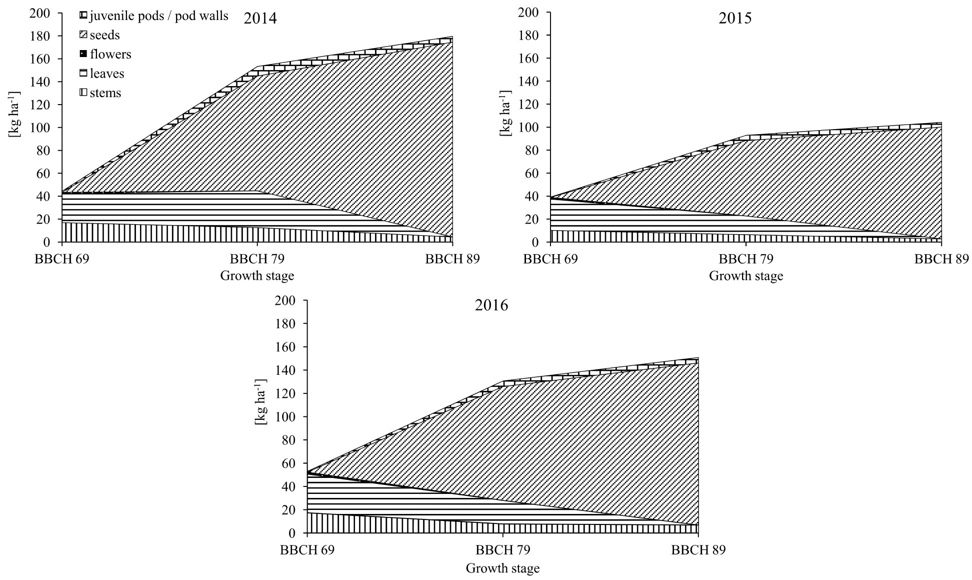

Fig. 4 Nitrogen accumulation (kg ha^{-1}) in soybean plant organs, as affected by growth stage and growing season.

form of proteins. The highest nitrogen contents were found in flowers and young pods during the flowering stage; the most accumulated during the flowering stage in 2014 when climatic conditions were favorable of plant growth (Fig. 4). In contrast to 2014, the amount of nitrogen accumulated in the aboveground biomass of flowering plants in 2016 was small. In that year, there was a significant reduction in nitrogen accumulation during the maturation stage. Regardless of the growing season, the accumulation of nitrogen was higher in leaves and lower in stems during the flowering phase. At the green maturity stage, the nitrogen content in leaves was higher than that measured at the flowering stage. During the dry year of 2015, there was a reduction of nitrogen content of stems and seeds as well as the whole plant at the full maturity phase.

Discussion

Growth

Extensive observations of the development of the soybean 'Merlin' have allowed an assessment of the production potential of plants and the crop at the critical stages of growth. The morphological characteristics of this early maturing cultivar were strongly affected by climatic conditions during the flowering stage in each of the growing seasons recorded in this study. The important information which emerged was the fact that the harvest could be conducted from the third decade of September through to the first decade of October. According to Kaczmarek and Pawlak [4], early maturing cultivars of "000" and "00" soybeans, which have a short vegetative period, reach maturity in Poland before mid-October. Thus, our results suggest that soybean production can be successfully accommodated in Poland. In the Northern Hemisphere, the fiftieth parallel is considered the northern boundary for soybean production.

Analysis of the development dynamics of soybean plants showed that the proportion of leaves in the whole plant biomass was very high at the flowering stage. The highest proportion of leaves in the whole plant biomass (64.7%) was found at the green maturity stage during the dry year of 2015, when the shorter soybean stems were very abundantly foliaged. At the flowering phase, the correlation between the whole plant and leaf biomass was linear and highly significant (R^2 = 0.93). At the green maturity stage, the leaf fraction in the whole plant biomass decreased significantly. In 2015, the reduction in the proportion of leaf DM was marked, and declined from 64.7 ±6.5% at the flowering stage to 27.5 ±4.4% at the green maturity stage. This was likely a result of an extended drought during that growing season.

Impact of weather on total dry matter and seed yield

The maximum total dry matter (TDM) yield of the very early soybean 'Merlin' was found at the green maturity stage and it systematically decreased thereafter due to the loss of foliage. In more favorable weather conditions (2016), there was a significant increase in single seed weight (2.5-fold) and seed weight per pod (3.8-fold), which had a significant impact on seed yield in comparison to the previous dry year (2015).

The effects of a short period of water deficiency stress on leaf senescence and duration of seed filling, and the resulting soybean yield are not well understood [17]. Cregan and Yaklich [18] emphasized that seed yield was correlated with TDM ($r = 0.61$, $p < 0.05$). In our studies, soybean seed weight was higher in 2016 as a result of excessive precipitation during the vegetative period. Board and Maricherla [19] provide evidence that seed yield in soybean is controlled by TDM accumulation and its partitioning into seed yield as measured by the HI. These authors suggested a concept of plant component contribution in the soybean seed yield for the warm regions of the USA.

Water is a key factor in agricultural production, especially in the zones with warm and dry climates. Water shortages can reduce food production and adversely affect global security [20,21]. The onset of drought in regions of global food production, including Europe and the USA, contributes to disturbance of macroeconomic market rights [22]. One way of solving local water shortages is to use irrigation systems [23]. As reported by Hanjra and Qureshi [24], lands cultivated with the support of irrigation supply 40% of the world's food production. Thus, irrigation will become a significant factor in food safety under a changing climate. According to Fedoroff et al. [25], in some parts of the world water security has become of critical concern for agriculture. Excessive irrigation, however, often reduces the water use efficiency of soybean seeds, and there is a linear relationship between changes in this and annual temperature [26]. Many climate models have been developed to simulate the impact of climate change on crop yields, including soybean. Parry et al. [27] used the dynamic crop model IBSNAT-ICASA (International Benchmark Sites Network for Agrotechnology Transfer) to estimate soybean yield in response to climate change. They found that the changing climate would increase yields at high and midlatitudes and decrease yields at lower latitudes (traditional soybean growing regions). Challinor and Wheeler [28] showed that average and high temperatures during the growing season were not the main determinants of soybean seed yield, but extreme temperatures had a negative effect on yield. A similar approach to climate change and soybean yield has been presented by Vasselin et al. [29], indicating the effectiveness of soybean adaptation in western parts of Europe. Using the CROPGRO model, these authors showed that incremental warming, in combination with an increase in precipitation, leads to higher soybean yield. An increase in simulated soybean yield for the twenty-first century was because of the positive impact of warming and especially of the beneficial influence of the direct CO_2 effect. Liu et al. [30] proved that seed weight is modified by environmental conditions. This indicates that, by redistributing the available resources across the main stem to other organs, soybean can maintain or even improve yield in a constantly changing environment. This suggestion was supported by our results in the more favorable weather conditions of the 2016 soybean cropping season.

Nitrogen – content and accumulation

In this paper, the nitrogen content data for soybean plant parts and the dynamics of nitrogen accumulation by the soybean crop have been assessed for the period of generative growth. In addition, our study included a calculation of NHI. Nitrogen fixation by soybean plants can contribute to the accumulation of large amounts of N during seed development [31]. The NHI of soybean was very high during the growth period, suggesting that soyabean 'Merlin' accumulated nitrogen almost exclusively in the seeds. The calculated values of NHI were very high, exceeding 0.92 g g^{-1}. This indicates that soybean, as a leguminous plant, does not dissipate nitrogen compounds into the soil environment. For the production of 1 Mg ha^{-1} of seeds + an adequate amount of straw, soybean plants needed, on the average, 68 kg of nitrogen regardless of the growing season (Tab. 8). This result is in agreement with data presented by Shiraiwa and Hashikawa

Tab. 8 Nitrogen accumulation in the aboveground biomass yield depending on the year of research and the growth phase, as well as nitrogen harvest index (NHI) and accumulation of nitrogen by 1000 kg of seeds along with straw.

Year	N accumulation (kg ha^{-1}) in three growth stages			NHI (g g^{-1})	N accumulation by 1000 kg of seeds
	flowering	green maturity	full maturity		
2014	44.30	153.20	179.60	0.9460	70.43
2015	39.10	92.90	104.20	0.9310	59.54
2016	52.90	130.60	150.80	0.9240	73.92
HSD $_{\alpha = 0.05}$	5.56	11.30	18.96	0.0084	4.27

[32], who reported that NHI was significantly higher for modern soybean cultivars (0.95 g g^{-1}) when compared to older cultivars (0.91 g g^{-1}). These results suggest that soybean carefully deposits fixed nitrogen in the seeds. For some reason, lower values of NHI were reported by Mastrodomenico and Purcell [33]. In their studies, the NHI amounted to only 0.89 and 0.85 g g^{-1} in 2008 and 2009, respectively. Other legume crop plants, such as *Phaselous* sp., can also efficiently deposit nitrogen in their seeds. This species expressed NHIs of 0.89 and 0.83 g g^{-1} in 1998 and 1999, respectively [34].

Nitrogen accumulation in the total dry matter of the soybean crop is correlated with seed yield [18]. In seasons with suboptimal temperatures and high precipitation during the seed-filling phase, nitrogen fixation may be reduced, resulting in low protein content in the seed [35]. However, similar responses of reduced nitrogen fixation and nitrogen content in soybean seed were observed during a warm and dry summer by Śliwa et al. [12] in the Greater Poland region. This region is known for its typically low precipitation along with low temperatures during the summer period. Those climatic conditions had an impact on the seed protein content, resulting in a lower value in 2015 compared to that measured in seeds collected in 2016 when precipitation was much higher. Salvagiotti et al. [36] found that a high-yielding soybean, with yields of 5 t ha^{-1} on the average, has a nitrogen uptake resulting from biological nitrogen fixation varying from 50% (in control plots with no presowing nitrogen fertilization) to 46%, 32%, and 38%. In their study, treatments with varying rates of nitrogen were applied with two doses: 0 (control) and 180 kg N ha^{-1} at various times of application – late-release urea; early applied ammonium nitrate; late-applied ammonium nitrate. Under these fertile soil conditions (high N content), the contribution of nitrogen fixation during the period of seed development varied from 25% to 50% of the total amount of nitrogen accumulated [37]. In contrast, at a low nitrogen content in the soil, the amount of nitrogen from biological fixation may range from 80% to 94%.

In the hot climatic conditions of a savanna in southern Guinea, the contribution of nitrogen from biological fixation in the total nitrogen accumulated in the seed was reported to be on the average 70% [38]. It was estimated that a soybean crop yielding 5 Mg ha^{-1} accumulates about 400 kg N ha^{-1} in its aboveground biomass and about 50–80% of that nitrogen requirement usually comes from biological nitrogen fixation [13].

Soybean is a pulse crop of a major agricultural, nutritional, and economic importance. It is of great importance for all the agricultural science community of the world. The use of legumes in cropping has effects that range from field to the global scale. The impacts on a global scale are particularly relevant in Europe as a driver of efforts to restore the use of legumes [39].

Conclusions

- The HI calculated for soybean 'Merlin' was high and annually amounted to >0.5 g g^{-1}, indicating a very favorable distribution of aboveground biomass between plant organs.
- The nitrogen content of the aboveground biomass of soybean 'Merlin' increased through its stages of growth. Leaves and seeds had the highest nitrogen accumulation.

Weather conditions at the time of maturity strongly determined the accumulation of nitrogen in the aboveground biomass.

- The maximum yield of plant dry matter of this very early soybean was found at the green maturity stage, and it declined as the growing season progressed due to leaf senescence and subsequent loss of foliage. Nitrogen accumulation continued until the end of the growing season, when nitrogen was primarily accumulated in seeds, which is characteristic for legume plants.
- The NHI values were high and exceeded 0.92 g g^{-1} in each year of the study. For the production of 1 t of seeds, including straw, soybean plants require on average 68 kg of nitrogen.

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Udział części roślin oraz gromadzenie azotu w plonie nadziemnej biomasy wcześnie plonującej soi odmiany 'Merlin'

Streszczenie

Celem badań było określenie akumulacji biomasy i azotu we wcześnie dojrzewającej odmianie soi [*Glycine max* (L.) Merr.] w zmiennych warunkach pogodowych. W latach 2014–2016 w Grodźcu Śląskim (49°48′01″ N, 18°52′04″ E) przeprowadzono eksperyment polowy z wcześnie dojrzewającą odmianą soi 'Merlin'. Wykazano, że cechy morfologiczne roślin soi oraz plonowanie były ściśle związane z warunkami klimatycznymi. Wysoka ilość opadów stymulowała rozwój nasion, dając w rezultacie wysoki potencjał produkcyjny. Indeks żniwny (HI) obliczony dla odmiany 'Merlin' był wysoki i przekraczał 0.5 g g^{-1}. Zawartość azotu w nadziemnej biomasie wzrastała wraz z rozwojem generatywnym roślin. Maksymalną wydajność suchej masy odnotowano w początkowej fazie dojrzewania. W fazie pełnej dojrzałości wydajność suchej masy spadła, z powodu utraty frakcji liści. Zróżnicowanie w efektywności akumulacji azotu w nasionach w latach 2015–2016 wyniosło 30%. Wartości indeksu żniwnego azotu (NHI) były wysokie w każdym roku doświadczenia i przekraczały 0.92 g g^{-1}. Do produkcji 1 tony nasion z odpowiednią ilością słomy rośliny potrzebowały średnio 68 kg azotu.