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A MINERAL PROFILE OF WINTER OILSEED RAPE IN CRITICAL STAGES OF GROWTH – NITROGEN

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Abstract

Winter oilseed rape is the key oil crop in temperate climate regions of the world. Yield of seeds depends the most on nitrogen management throughout the season. The evaluation of N status in the oil-seed rape canopy was studied in 2008, 2009, and 2010 seasons. The one factorial experiment to verify the formulated hypothesis, consisting of six treatments, was as follows: absolute control (AC), NP, NPK, NPK + MgS - $^1/_3$ rate of total planned rate applied in Spring (NPKMgS1), NPKMgS - 1.0 rate in Autumn (NPKMgMgS2), NPK+MgS - $^2/_3$ in Autumn + $^1/_3$ in Spring (NPKMgS3). Plant samples were taken at three stages: i) full rosette (BBCH 30), ii) the onset of flowering (BBCH 61), iii) maturity (BBCH 89). The total plant sample was partitioning in accordance with the growth stage among main plant organs such as leaves, stems, straw, and seeds. Yield of biomass, nitrogen concentration and content were determined in each part of the plant. The study showed an existence of two strategies of dry matter and nitrogen accumulation by oil-seed rape throughout the season. In 2008, and partly in 2010 revealed the strategy of yield formation relying on relatively slow, but at the same time a permanent increase in nitrogen and biomass accumulation during the season. This strategy resulted in a high seed density in the main branch. The size of this yield component significantly depended on nitrogen content in leaves at the onset of flowering. In 2009 revealed the second strategy of yield formation by oilseed rape. Its attribute was a very high rate of nitrogen accumulation during the vegetative growth, resulting in a huge biomass of leaves at the onset of flowering. This growth pattern, as corroborated by yield of seeds, was not as effective as the first one. The main reason of its lower productivity was the reduced seed density, especially in pods of the secondary branch, resulting from an excessive nitrogen content in leaves at the onset of flowering. Irrespectively on the strategy of nitrogen management by the oilseed rape canopy, the best predictor of the final yield was nitrogen content in seeds. It can be concluded that any growth factor leading to the nitrogen sink decrease, such as reduced plant density and/or disturbed N management throughout the season, can be considered as a factor negatively impacting yield of seeds.

Key words: nitrogen, plant parts, N partitioning, yield structural components, yield of seeds.

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PROFIL MINERALNY RZEPAKU OZIMEGO W KRYTYCZNYCH FAZACH ROZWOJU – AZOT

Abstrakt

Rzepak ozimy jest kluczową rośliną oleistą w umiarkowanych pod względem klimatu regionach świata. Plon nasion w największym stopniu zależy od gospodarki azotem w okresie wegetacji. Ocenę gospodarki azotem w łanie rzepaku przeprowadzono w latach 2008-2010. Hipotezę badawczą weryfikowano w 1-czynnikowym doświadczeniu, obejmującym 6 kombinacji: kontrola absolutna (AC), NP, NPK, NPK – $^{1}/_{3}$ całkowitej planowej dawki MgS wiosną (NPKMgS1), NPK + 1,0 dawka MgS jesienią (NPKMgS2), NPK + MgS – $^{2}/_{3}$ dawki jesienią i $^{1}/_{3}$ – wiosną (NPKMgS3). Próbki roślin pobierano w 3 stadiach: i) rozety (BBCH 30), ii) początku kwitnienia (BBCH 61), iii) dojrzałości fizjologicznej (BBCH 89). Pobrane próbki roślin dzielono, zależnie od fazy rozwoju rzepaku, na główne części, jak liście, łodygi, słoma + plewy, nasiona. Plon biomasy, koncentrację i akumulację azotu oznaczano w każdej części rośliny. Wykazano funkcjonowanie dwóch strategii akumulacji biomasy i azotu przez łan rzepaku. W 2008 r., a w mniejszym stopniu w 2010 r., ujawniła się strategia formowania plonu, polegająca na względnie powolnej, lecz ciągłej akumulacji azotu i biomasy w okresie wegetacji. Ta strategia formowania plonu przez rzepak przejawiła się dużą liczbą nasion w łuszczynach pędu głównego. Ten element struktury plony wykazał istotną i dodatnią reakcję na ilość zakumulowanego azotu w liściach na początku kwitnienia rzepaku. W 2009 r. ujawnił się drugi model formowania plonu przez rzepak. Plonotwórcza istota tej strategii przejawiała się bardzo intensywną akumulacją azotu, a tym samym biomasy przez łan rzepaku w okresie przed kwitnieniem. Strategia ta, jak wynika z plonu nasion, nie była tak efektywna jak pierwsza, dominująca w 2008 roku. Główną przyczyną mniejszej efektywności tej strategii była zredukowana liczba nasion w łuszczynach, zwłaszcza pędów bocznych, wynikająca z nadmiaru azotu w liściach na początku kwitnienia. Niezależnie od strategii gospodarki azotem w łanie rzepaku, najważniejszym wskaźnikiem finalnego plonu nasion był potencjał nasion do akumulacji tego składnika. Stwierdzono, że jakikolwiek czynnik wzrostu prowadzący do spadku potencjału ujścia fizjologicznego azotu, jak zbyt mała liczba roślin lub też zakłócona gospodarka azotem w łanie w okresie wegetacji, może być traktowany jako ujemnie kształtujący plon.

Słowa kluczowe: azot, części rośliny, rozdział azotu , elementy struktury plonu, plon nasion.

INTRODUCTION

Winter oilseed rape is the most important oil crop in temperate regions across the world. As documented by SUPIT et al. (2010), the yield potential of this crop in the Central European countries like the Czech Republic, Germany and Poland as evaluated during the period 1996-2005 was at the level of 3.6, 4.1, and 3.7 t ha^{-1}. Whereas, the actual yields in this period were lower, presenting the level of 2.5, 2.7 and 2.2 t ha^{-1}, respectively. In the period, 2006-2012 actual yields in these three countries raised up, achieving the level of 2.940 ± 0.153, 3.466 ± 0.430, 2.618 ± 0.272 t ha^{-1} (FAOSTAT 2013). There are numerous factors responsible in the yield gap development. In the present farming practice, the domination of nitrogen fertilizer over potassium and phosphorus fertilizers is an obvious matter. The superfluous role of nitrogen in plant growth is well documented, taking into account its physiological functions (RUBIO et al. 1993). However, an efficient exploitation of fertilizer nitrogen requires its balancing using a broad set of nutrients.

In the primary step, it refers to phosphorus and potassium (Grzebisz et al. 2010*a*; Grzebisz et al. 2013). In the period 1989-2005, as documented by Grzebisz et al. (2012), the ratio of N:P_2O_5:K_2O consumption in Central European countries underwent a significant extension, resulting in a high sensitivity of broad-leafed crops, like oilseed rape to the course of weather. Therefore, the key reason of the existing yield gap in oil-seed rape production is the imbalanced fertilization of crops due to N excess, leading during Spring's vegetation to an increased sensitivity of winter oilseed rape to water shortages (Abbasian, Rad 2011, Albert et al. 2012). The second step in an efficient usage of externally applied nitrogen requires is its balancing by secondary nutrients, like sulfur and magnesium (Spychaj-Fabisiak et al. 2011, Szczepaniak et al. 2013).

The yield of winter oilseed rape is a result of development processes, which efficiency is decisive for development of yield component. Two of four key yield components, such as the number of pods per plant, numbers of seeds per pod are highly sensitive to nitrogen supply during spring growth of oilseed rape (Diepenbrock 2000). However, the impact of in-season management of nitrogen taken up by the crop during both a vegetative and reproductive period is weakly recognized. The objective of the conducted study was to evaluate an impact of nitrogen accumulation and its partitioning among the main plant organs of winter oilseed rape in two critical stages such as the rosette and the beginning of flowering on development of structural yield components, and consequently, on final yield of seeds.

MATERIALS AND METHODS

Studies on nitrogen status of winter oil-seed in critical stages of yield formation were carried out during three consecutive growing seasons 2007/08, 2008/09, and 2009/10 at Donatowo in the private farm. The field experiment was established on a soil originated from a loamy sand underlined by a sandy loam, classified as Albic Luvisol. Soil fertility level as indicated by the main agrochemical characteristics was satisfactory for producing high yield of seeds (Table 1). The one factorial trial, replicated four times, consisted of six treatments. The detailed description, including the rate and form of fertilizer are given in Table 2.

Each year of study, winter wheat preceded oilseed rape. The size of the individual plot was 100 m^2. The variety *Chagall* was sown in the last decade of August. Phosphorus and potassium were applied prior to sowing in doses adjusted to the soil test rating and treatment. Phosphorus was applied in the form of di-ammonium phosphate and potassium in accordance with the treatment schedule. Magnesium and sulfur were applied to the crop in the form of magnesium sulfate during the season as presented in Table 2. Nitrogen (ammonium saltpeter) was applied at the rate of 27 kg N ha^{-1} before

Table 1

Agrochemical characteristics of the soil

Year	pH (1M KCl)	Content of nutrients (mg kg^{-1} soil)						N_{min}
		P	rating	K	rating	Mg	rating	kg ha^{-1}
2008	6.36	96.3	very high	151.1	high	45	medium	65.6
2009	6.55	89.1	very high	164.3	high	52	high	74.8
2010	5.96	68.4	high	103.8	medium	75	very high	68.0

Table 2

Arrangement of the experiment: composition, rates and timing

Code of the treatment	Treatments	N		P	K		Mg		S	
		time and rate of applied fertilizer (kg ha^{-1})								
		A[**]	S[***]	A	A	S	A	S	A	S
AC	control	0	0	0	0	0	0	0	0	0
NP	N + P[*]	27	187	30.1	0	0	0	0	0	0
NPK	NPK	27	187	30.1	149.4	0	0	0	0	0
NPKMgS1	NPK + MgS1	27	187	30.1	99.6	49.8	0	5.4	0	6.0
NPKMgS2	NPK + MgS2	27	187	30.1	149.4	0	16.3	0	18.0	0
NPKMgS3	NPK + MgS3	27	187	30.1	99.6	49.8	10.8	5.4	12.0	6.0

[*] di-ammonium phosphate, [**] Autumn, [***] Spring

sowing, 102 kg N ha^{-1} before Spring's regrowth and at the remaining part at the end of the rosette stage. Fungicide and insecticide applications were sprayed when required. At maturity, plants were harvested from the area of 15 m^2 using a plot combine harvester. Total seed yield was adjusted to 8% moisture content.

Plant material for assessment of dry mater and nitrogen dynamics were sampled from an area of one m^2 in three consecutive stages of wheat growth according to the BBCH scale: 30, 61 and 89. At each measurement date, the harvested plant sample was partitioning, in accordance with the development stage, into subsamples of leaves, stems, seeds, straw and then dried (65°C). Finally, at each stage, total and sub-sample, dry matter per one m^2 was recorded. At BBCH 89, the whole sub-sample was divided into the main raceme – the principal branch and secondary branches. Number of pods and seeds per pod were counted separately for each sub-group. Nitrogen concentration in plant samples was determined by a standard macro-Kjeldahl procedure, with accuracy of 0.1 mg N (PN-ENISO20483:2007p). Nitrogen content in a particular plant part was calculated by multiplication of its concentration and respective biomass.

The experimentally obtained data were subjected to the conventional analysis of variance using computer programs Statistica 7. The differences between treatments were evaluated with the Tukey's test. In tables and figures, results of the F test (***, **, * indicate significance at the $P < 0.1\%$, 1%, and 5%, respectively) are given. Path analysis was conducted based on correlation coefficients taking yield of seed and/or its structural components as effects and nitrogen accumulation in plant parts as independent variables. The path diagram, showing direct and indirect path coefficients have been elaborated based on the highest value of the correlation coefficient for a particular set of variables. In the second step of diagnostic procedure, the stepwise regression was applied to define the optimal set of variables for a given crop characteristic. In the computing procedure, a consecutive variable was added to the multiple linear regressions in the step-by-step manner. The best regression model was chosen based on the highest *F*-value for the entire model and significance of all independent variables (Konys, Wiśniewski 1984).

Acronyms applied in the paper:

MBY - yield of the main branch (inflorescence),
SBY - yield of secondary branches,
TSY - total yield of seeds,
PD - plant density,
SBP - number of secondary branches per plant,
PMB - number of pods per the main branch,
PSB - number of pods per the secondary branch,
SMB - number of seeds per a pod of the main branch,
SSB - number of seeds per a pod of the secondary branch,
WSM - weight of 1000 seeds of the main branch,
WSB - weight of 1000 seeds of the secondary branch,
STY - yield of straw,
N_{RT} - nitrogen content in oilseed rape at the rosette stage,
N_{LE} - nitrogen content in leaves of oilseed rape at the beginning of anthesis,
N_{SH} - nitrogen content in shoots of oilseed rape at the beginning of anthesis,
N_{ST} - nitrogen content in straw of oilseed rape at maturity,
N_{SE} - nitrogen content in seeds of oilseed rape at maturity.

RESULTS AND DISCUSSION

Yield of seeds and yield forming components

Yield of oilseed rape responded significantly to the increased input of nutrients, balancing the N rate. The optimal composition of applied nutrients was modified by the course of weather, in consecutive years of study (Tables 3, 4). The detailed analysis of the total yield of seeds showed that the main branch constituted around $^1/_3$ of the whole yield. The impact of the principal inflorescence yield, based on the R^2, on the yield of seeds was much lower as found for the yield produced by secondary branches:

Table 3

Distribution of precipitation during oilseed rape vegetation, the synoptic station at Brody

Period	Consecutive months during crop vegetation (mm)											
	VIII	IX	X	XI	XII	I	II	III	IV	V	VI	VII
1957-2010	69.3	41.4	33.0	34.3	40.0	31.0	31.3	35.3	29.9	46.7	59.5	75.4
2007/2008	82.3	27.5	18.4	25.0	27.8	74.4	13.2	45.2	60.4	23.5	15.0	47.9
2008/2009	94.4	14.5	50.7	18.4	36.6	17.5	32.4	37.6	10.0	82.2	99.0	66.0
2009/2010	31.9	58.2	62.8	40.3	49.1	19.1	15.3	38.5	33.4	83.6	21.2	121.6

1) TSY = 2.399MBY + 0.95 for $n = 18$, $R^2 = 0.66$ and $p < 0.001$,

2) TSY = 1.282SBY + 0.508 for $n = 18$, $R^2 = 0.93$ and $p < 0.001$.

Yields of the main branch and secondary branches responded in the different manner to external conditions, i.e., to the weather and applied nutrients. In the first case, weather impact was constant, affecting yield of the principal inflorescence irrespectively on fertilization treatments. In the second case, yield of seeds was a result of interaction of both factors. In 2008, the highest yield of seeds was harvested in the NPKMgS2 treatment, where magnesium and sulfur applied were applied in the full rate in Spring. The same trend was noted in 2010, but yields were much lower. In 2009, the highest yield was achieved in the NPK treatment. The observed year-to-year variability of yield can be partly explained by a high variability of the course of weather. The first year of study was characterized by a mild drought, which prevailed throughout the whole 2007/08 season, except April, which was moist. In contrast, in the 2008/2009 season, distribution of precipitation was normal, except May and June, which were wet, leading to delayed flowering. In the third, 2009/10 season, Autumn was moist and cold, leading to a sharp decrease in plant density (Table 4). Plants of oilseed rape responded to applied magnesium and sulfur the most in 2008, when a mild water stress took place just before the onset of stem elongation. The observed crop response implicitly corroborates the hypothesis by GRZEBISZ (2013), concerning the inductive impact of magnesium and sulfur on N management, under a gentle water stress.

Table 4

Statistical evaluation of seeds yield and yield components

Factor	Factor level	MBY SBY TSY			PD	SBP	PMB	PSB	SMB	SSB	WMB	WSB
		yield (t ha^{-1})			no m^{-2}	no plant^{-1}			no pod^{-1}		(g)	
Fertilization treatments (FT)	AC	1.035^{a}	1.846^{a}	2.881^{a}	35.2	6.21^{a}	45.1	125.0^{a}	12.1^{a}	10.0	5.63	5.23
	NP	1.260^{ab}	2.554^{b}	3.814^{b}	36.4	7.49^{b}	46.8	127.0^{a}	13.5^{ab}	12.7	5.97	5.50
	NPK	1.240^{ab}	3.119^{bc}	4.359^{bc}	33.9	8.00^{b}	48.2	180.8^{b}	13.7^{abc}	10.9	5.92	5.44
	NPKMgS1	1.405^{b}	2.692^{bc}	4.097^{bc}	35.4	7.11^{ab}	44.3	169.2^{ab}	16.9^{c}	9.5	5.88	5.35
	NPKMgS2	1.394^{b}	3.156^{c}	4.550^{c}	37.3	7.41^{ab}	45.0	177.3^{b}	16.2^{bc}	10.1	5.71	5.38
	NPKMgS3	1.339^{b}	3.052^{b}	4.391^{bc}	38.1	7.67^{b}	48.7	168.1^{ab}	13.9^{abc}	9.3	6.02	5.42
Years (Y)	2008	1.454^{b}	3.335^{c}	4.750^{c}	35.7	6.91^{a}	53.2	142.9^{a}	14.4^{b}	14.7^{c}	5.30^{a}	4.73^{a}
	2009	1.535^{b}	2.717^{b}	4.252^{b}	51.2	7.00^{a}	48.5	149.7^{a}	11.5^{a}	6.0^{a}	5.47^{a}	5.11^{b}
	2010	0.887^{a}	2.158^{a}	3.047^{a}	21.3	8.04^{b}	37.4	181.0^{b}	17.3^{c}	10.5^{b}	6.81^{a}	6.31^{c}
Fertilizing treatments (FT)		***	***	***	ns	***	ns	**	***	ns	ns	ns
Years (Y)		***	***	***	***	**	***	**	***	***	***	***
FT x Y		ns	*	*	ns	**	ns	ns	**	ns	ns	ns

F – probability values: *,**, *** of 0.05, 0.01, 0.001, ns – no significantly different; ^{a} the same letters means a lack of significant differences

An analysis of yield forming components is a useful tool for explaining yield of seed variability (Diepenbrock 2000). The course of weather, in consecutive seasons was the principal factor affecting development of yield components. The primary one, number of plants per m^2, showed the highest year-to -year variability, changing from about 20 in the wet 2010 to 50 in the normal 2009. Any effect of fertilizing treatments was observed. The same type of response was observed for the weight of thousand seeds. The compensation effect of low plant density was significant, as documented by much higher TSW in 2010, compared to other years. The same dominating trend has been observed for the number of seeds in pods of the secondary branches. The impact of weather conditions on development of this yield component was highly specific. Plants of oilseed rape produced the highest number of seeds in the semi-dry 2008, followed by 2010, and the lowest in the wet 2009. The next canopy component, the number of secondary branches per plant (SPB) is an important yield forming element, highly responsive to plant density (Diepenbrock 2000). This oilseed rape characteristic significantly depended both on fertilizing treatments, but was modified by the course of weather in consecutive years (Table 4). A detailed analysis of SPB showed that in 2008, it was around 7, independently on the treatment. In the wet, 2010, plants fertilized with NPK produced eight branches per plant, but others around seven. Plants grown in the control plot produced about 5, but those fertilized with NP, NPK and NPKMgS3 on average 9. The top response od SPB was an attribute of the NP treatment. The effect of potassium in the NPK treatment was positive, resulting in the highest, on average, value of this plant characteristic. These results implicitly corroborate an importance of the fresh applied phosphorus as a growth compensation factor under low plant density. Number of pods per plant is an important factor, affecting yield of seeds (Diepenbrock 2000). In the case of the main branch, this component was only affected by the course of weather, decreasing in the order: 2008 > 2009 > 2010. Number of pods developed by secondary branches was on average several times higher, responding to fertilization treatments and years, but not to interaction of both factors. Potassium was the key nutrient impacting positively this plant characteristic, as noted in the NPK treatment. Addition of magnesium and sulfur, averaged over years, did not results in the pod number increase, mainly due to its sharp decrease in 2009. This yield component showed an extremely high flexibility, as affected by plant density, as documented in 2010. Number of seeds per pod showed a quite different response to tested factors, taking into account the principal inflorescence and secondary branches. Number of seeds developed in pods of the main branch responded to applied nutrients, but at the same time was modified by the weather course in consecutive seasons. In the first two years, the highest number of seeds, independently on its real values, was an attribute of the NPKMgS1. In the third year, the effect of MgS was even more pronounced, as documented by 25% increase in the number of seeds as compared to the NPK treatment. This trend indicates on magnesium and sulfur as an important factor for seed set in the pod, especially in low density oilseed crop. In contrast, number of seeds per pod of the secondary branch was much lower, responding only to weather conditions during vegetation. The compensation effect was not observed, because the highest seed pod density was an attribute of the semi-dry 2008 year.

In order to define the key yield forming component, the path and stepwise analyses were used, but evaluated separately for each part of the total yield. The yield produced by the MBY was, as indicated by both, the correlation and path coefficients, significantly affected by the number of plants per unit area (PD, Figure 1a). The straight effects of other variables were small (< 0.1) for SB, PMB, PSB, and WSB, but large and positive (> 0.5) for SMB, SSB, and WMS. These three variables impacted, however, negatively the PD direct coefficient. The stepwise regression showed that yield produced by the principal branch was the best explained by plant density, as a single yield predictor. The improvement of the MBY prognosis accuracy requires an implementation of two other yield forming components, such as the PMB and especially the SMB:

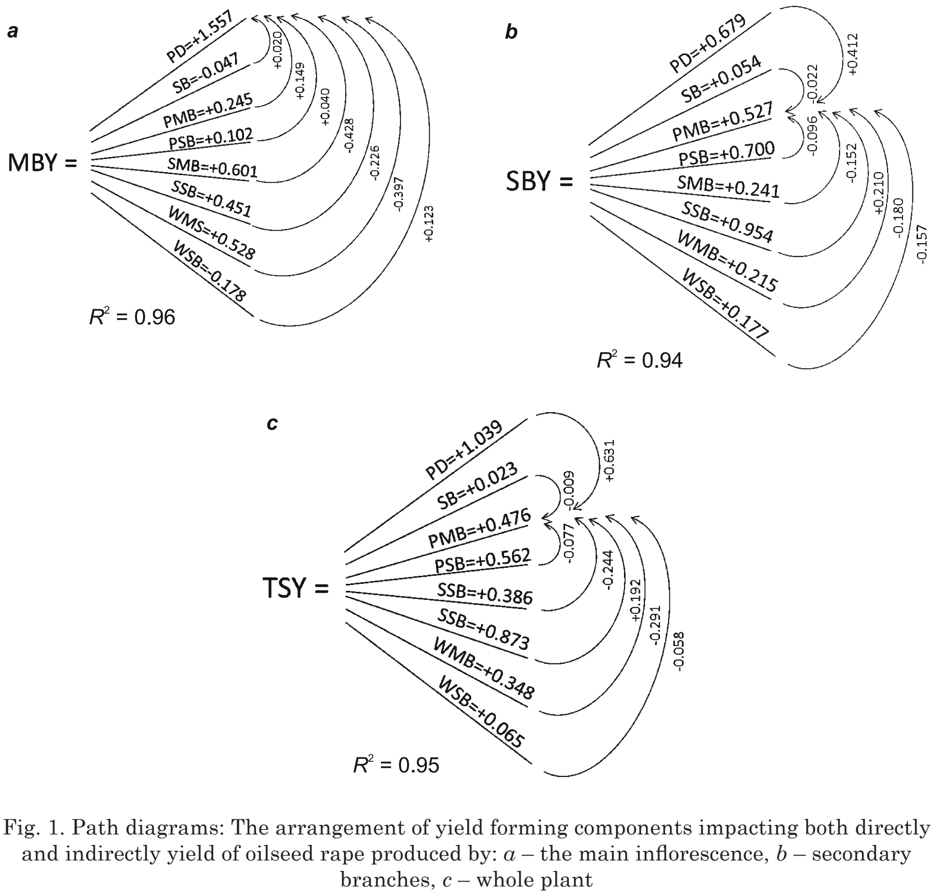

Fig. 1. Path diagrams: The arrangement of yield forming components impacting both directly and indirectly yield of oilseed rape produced by: *a* – the main inflorescence, *b* – secondary branches, *c* – whole plant

1) MBY = 0.507 + 0.021 PD for $n = 18$, $R^2 = 0.70$ and $p < 0.00002$,
2) MBY = -0.491 + 0.03PD + 0.047SMB for $n = 18$, $R^2 = 0.82$ and $p < 0.0000$,
3) MBY = -1.514 + 0.027PD + 0.02PMB + 0.064SMB
for $n = 18$, $R^2 = 0.93$ and $p < 0.00000$.

These three regression models implicitly indicate on a balance between plant density and development of the main inflorescence structural components. Too dense plant canopy results in the lower number of seeds per pod of the principal inflorescence and thousand seed weight (Table 4).

The yield of secondary branches, decisive for the total yield of seeds, was determined by the quite different set of yield forming components. The number of pods per the main branch, as presented in the path diagram, was the single component, discriminating the most yield produced by subordinate branches (Figure 1*b*). Its direct effect was, however, much weaker, compared with several other yield components, which impact decreased in the order: SSB > PSB > PD. The value of the correlation coefficient for PMB was increased mainly due to the indirect but large impact of plant density (PD). The stepwise regression models implicitly showed that the best set of yield forming components is composed by the number of pods and seeds per pod of the main and secondary branch (PMB, PSB, SMB, SSB):

1) SBY = -0.554 + 0.071PMB for $n = 18$, $R^2 = 0.54$ and $p < 0.00054$,
2) SBY = -3.774 + 0.104PMB + 0.116SMB
for $n = 18$, $R^2 = 0.72$ and $p < 0.00008$,
3) SBY = -4.789 + 0.1PMB + 0.007PSB + 0.SMB
for $n = 18$, $R^2 = 0.82$ and $p < 0.00002$,
4) SBY = -3.976 + 0.06PMB + 0.015PSB + 0.036SMB + 0.099SSB
for $n = 18$, $R^2 = 0.89$ and $p < 0.00000$.

The fourth regression model in the spite of the lowest p value was biased by insignificant effect of seed number per the main branch.

The total yield of seeds is a result of productivity of the main and secondary branches. The dominating yield forming effect of the number of pods per the principal stem has been fully corroborated by the path analysis (Figure 1*c*). However, the largest direct impact was an attribute of other components such as PD > SSB > PSB. The first variable was a decisive component for explanation of the final yield of seeds, having a large effect as results from the value of the indirect path coefficient. The best set of prognostic variables is composed of three structural components, such as the number of pods per the principal and subordinate branch and the number of seeds per pod of the main branch:

1) TSY = -0.59 + 0.1PMB for $n = 18$, $R^2 = 0.60$ and $p < 0.00016$,
2) TSY = -4.113 + 0.136PMB + 0.126SMB
for $n = 18$, $R^2 = 0.72$ and $p < 0.00007$,
3) TSY = -5.5 + 0.13PMB + 0.01PSB + 0.131SMB
for $n = 18$, $R^2 = 0.83$ for $p < 0.00001$.

This model is in close agreement with the regression model developed for oilseed rape by Grzebisz et al. (2010*b*). The key exception between both models is plant density as shown above, instead of the number of secondary branches. The last two sets of regression models implicitly show that both yield produced by subordinate branches, and the total yield can be explained at the moderate level of prognosis (ca 70%) by analyzing the response of the main branch components such as the number of pods and number of seed in the pod of the first inflorescence to interaction of seasons and applied nutrients. The best model, allowing to explain above 90% of oil-seed rape variability yield requires a different set of components (Figure 1c), including the number of plants per unit area, number of pods and seeds per pod of the secondary branch. This set of yield forming components is principally affected by year-to-year variability.

Dry matter partitioning

Dry matter yield and its partitioning among main oilseed rape organs was, except the rosette stage, governed by interaction of seasons, as the dominant factor, and fertilization treatments, as the minor one (Table 5). At the rosette stage, plant biomass was only significantly affected by applied fertilizers, showing on average, a considerably higher production in all treat-

Table 5

Statistical evaluation of oilseed rape biomass partitioning among plant parts during growth (g m^{-2})

Factor	Factor level	BBCH 31	BBCH 61		BBCH 89		
		LE[*]	LE	SH	ST	SE	TO
Fertilization treatments (FT)	AC	221.4^{a}	112.8^{a}	384.4^{a}	1007.5^{a}	288.1^{a}	1295.6^{a}
	NP	310.8^{b}	202.9^{b}	534.9^{b}	1269.0^{b}	381.4^{b}	1650.5^{b}
	NPK	298.0^{b}	199.7^{b}	507.0^{b}	1498.7^{b}	435.9^{bc}	1934.6^{b}
	NPKMgS1	304.0^{b}	192.7^{b}	557.9^{b}	1515.1^{b}	409.7^{bc}	1724.8^{b}
	NPKMgS2	296.8^{b}	195.4^{b}	531.2^{b}	1538.5^{b}	455.0^{c}	1933.6^{b}
	NPKMgS3	263.6^{ab}	195.7^{b}	540.6^{b}	1431.6^{b}	439.1^{bc}	1870.6^{b}
Years (Y)	2008	217.3	142.4^{a}	432.7^{a}	1603.2^{b}	475.0^{c}	2078.0^{b}
	2009	290.6	268.0^{b}	659.5^{b}	1205.0^{a}	425.2^{b}	1630.2^{a}
	2010	285.4	139.2^{a}	436.2^{a}	1222.1^{a}	304.5^{a}	1526.5^{a}
Fertilization treatments (FT)		**	**	**	***	***	***
Years (Y)		ns	***	***	***	***	***
FT x Y		ns	*	**	**	*	*

[*] LE, SH, ST, SE, TO – leaves, shoots, straw, seeds, total, respectively;

F – probability values: *,**, *** of 0.05, 0.01, 0.001, ns – no significantly different;

^{a} the same letters means a lack of significant differences ments fertilizing with nitrogen compared to the absolute control. Therefore, it collaborates the hypothesis that, plant density cannot be considered as the decisive yield forming factor (Hűhn 2001). At all subsequent stages of oilseed rape growth, its biomass was significantly affected by interaction of both factors. Its impact was, however, quite different before and after flowering, as resulted from analysis of biomass yield and its partitioning among main plant organs. In 2009, it has been noted during the period extending from the rosette to the onset of flowering an accelerated increase of the whole biomass of oilseed rape. The observed differences in the rate of biomass increase were much stronger for leaves compared to stem. The biomass of leaves doubled in 2009 as compared to other years, whereas it was only by $^{1/}{}_{3}$ higher for shoots. Quite distinct pattern of dry matter yield and distribution has been documented in the period extending from the onset of flowering to maturity. At this stage, the total plant biomass decreased in the descending order: 2008 (100%) > 2009 (78.4%) = 2010 (73.5%). However, its partitioning differentiated significantly for main organs. With respect to seeds, it decreased in the following order: 2010 (100%) > 2009 (89.5%) > 2010 (64%). At the same time, the yield of straw was by $^{1}/_{3}$ higher in 2008 compared to other years. The first model followed the strategy of oilseed crop growth termed by Barłóg and Grzebisz (2005*a*) as “fast biomass accumulation” and the second as “slow but permanent biomass accumulation.” The first strategy, dominating in 2009, resulted in a high biomass increase at the onset of flowering, leading subsequently to dramatic reduction in seed density. The second one, enabled the growth of pods, as underlined by the higher number of seeds per plant, as observed in 2008, up to maturity, resulted in the significant yield increase. This strategy reveals under conditions of the extended period of N uptake, but without a sharp elevation during the pre-anthesis period of growth, as hypothesized by Barłóg and Grzebisz (2005*b*). The higher yield of straw (STY) can be, therefore, considered as the key factor corroborating this hypothesis. The vegetative part of oilseed plants, including both stems and threshed pods, was the most important single factor explaining variability of the final yield of seeds, especially in 2008, characterized by the highest yield of seeds:

1) all years: $\mathrm{TSY} = 0.622 + 0.0025\mathrm{STY}$ for $n = 18$, $R^2 = 0.63$, and $p < 0.001$,
2) 2008: $\mathrm{TSY} = 1.526 + 0.002\mathrm{STY}$ for $n = 6$, $R^2 = 0.87$, and $p < 0.001$.

These two equations implicitly corroborate the hypothesis by Grzebisz (2013), who documented a positive impact of simultaneously application of magnesium and sulfur on yield components and yield of cereals under conditions of the mild water stress. Such conditions prevailed in 2008, in which the highest yield was harvested in the treatment with full rate of Mg and S applied in Autumn. The mode of this two nutrients action has been explained by a significant increase in vegetative biomass of oilseed plants following the beginning of flowering. As shown in Table 4, plants with an elevated dry matter yield at the beginning of lowering, as observed in 2009, impacted negatively the seed density of the secondary branch. This crop yield characteristic was significantly affected by oil-seed rape vegetative biomass production following the beginning of flowering ($DM_{89\text{-}61}$):

$$SSB = 5.639 + 0.732DM_{89\text{-}61} \qquad \text{for } n = 18,\ R^2 = 0.45, \text{ and } p < 0.01.$$

This equation corroborates the hypothesis that development of structural components of oilseed yield depends the most on the course of weather just before and after flowering. The observed increase in the seed density, as observed in 2008, resulted from a prolonged increase in the dry matter yield of vegetative parts. This is a result of pod growth, as a prerequisite of seed density. This is in agreement with Ludlow and Muchow (1990), who documented for cereals an increased growth of vegetative organs during the post-flowering period in response to mild drought. This positive response took place in treatments with MgS rate, applied in Autumn. The action of these nutrients resulted in additional uptake of nitrogen. The same type of crop response was reported by Grzebisz (2013) for cereals, maize and sugar beets. The contrastive growth conditions, resulting in the excess of biomass production during the pre-anthesis period of growth, which took place in 2009, leading finally to reduction in the seed number. This phenomenon indirectly proves the finding by Habekotte (1993), who showed a positive impact of plant biomass production by oilseed plants since the onset of flowering on seed density.

Nitrogen concentration and accumulation

Nitrogen concentration in the main part of oilseed rape plants was variable in consecutive stages of growth (Table 6). At the rosette stage, the

Table 6

Statistical evaluation of nitrogen concentration in parts of oilseed plant in critical stages of growth, (g kg^{-1} d.m.)

Factor	Factor level	BBCH 31	BBCH 61		BBCH 89	
		LE*	LE	SH	ST	SE
Fertilization treatments (FT)	AC	36.2^{a}	31.2^{a}	16.3^{a}	5.2^{a}	30.0^{a}
	NP	50.2^{b}	43.0^{b}	23.3^{b}	8.3^{b}	34.9^{b}
	NPK	52.4^{b}	40.0^{b}	25.1^{b}	8.0^{b}	35.9^{b}
	NPKMgS1	51.0^{b}	42.7^{b}	24.3^{b}	7.7^{b}	35.6^{b}
	NPKMgS2	49.9^{b}	42.2^{b}	24.3^{b}	0.73^{ab}	35.2^{b}
	NPKMgS3	51.6^{b}	41.9^{b}	23.8^{b}	8.1^{a}	34.9^{b}
Years (Y)	2008	44.2^{a}	36.8^{a}	19.7^{a}	5.6^{a}	30.0^{a}
	2009	5.11^{b}	47.7^{b}	23.3^{b}	11.0^{b}	35.9^{b}
	2010	50.4^{b}	36.7^{a}	25.6^{b}	5.7^{a}	37.3^{b}
Fertilization treatments (FT)		***	***	***	***	***
Years (Y)		***	***	***	***	***
FT x Y		*	ns	ns	ns	ns

* see Table 5; F – probability values: *,**, *** of 0.05, 0.01, 0.001, respectively, ns – no significantly different; ^{a} the same letters means a lack of significant differences applied nitrogen fertilizer was the key factor impacting nitrogen concentration in leaves, but modified by the course of weather. Plants fertilized with nitrogen showed its concentration at the level of 5% d.m. This value is considered as an optimal for high-yielding plantation (Wojnowska et al. 1995). It is necessary to focus attention on a much lower N concentration in 2008 compared to other two years. At flowering, this trend underwent a change for leaves, but not for shoots. In leaves, a significantly higher concentration was noted in 2009. At maturity, the same trend as for leaves at anthesis was observed for straw. The almost double concentration of N in straw in plants harvested in 2009 as compared to other years, indirectly indicates on a much lower N remobilization during the post-flowering period. The excess of nitrogen in vegetative plant parts was a result of an insufficient development of the sink capacity as indicated by the reduced seed density per plant.

The content of nitrogen in the oilseed rape canopy, as a result of its concentration and plant biomass, progressed throughout plant development stages. Both experimental factors impacted this crop characteristic only at maturity (Table 7). At the rosette stage the amount of nitrogen in the canopy responded to applied fertilizer N, but the key differences were due to variable weather in consecutive seasons. The most significant changes in nitrogen content took place in the period extending from the rosette up to the onset of flowering. As a rule, the amount of accumulated N raises up, but

Table 7

Statistical evaluation of nitrogen accumulation and partitioning in oilseed plant parts in critical stages of growth (g m^{-2})

Factor	Factor level	BBCH 31	BBCH 61		BBCH 89		NHI
		LE*	LE	SH	ST	SE	%
Fertilization treatments (FT)	AC	8.00^{a}	3.60^{a}	6.57^{a}	4.95^{a}	8.43^{a}	63.0
	NP	15.60^{b}	9.48^{b}	12.43^{b}	10.49^{b}	13.16^{b}	55.6
	NPK	15.75^{b}	8.50^{b}	12.90^{b}	11.96^{b}	15.44^{b}	56.4
	NPKMgS1	15.62^{b}	8.68^{b}	13.49^{b}	9.69^{b}	14.45^{b}	59.9
	NPKMgS2	14.81^{b}	8.52^{b}	13.05^{b}	10.86^{b}	15.87^{b}	56.7
	NPKMgS3	13.59^{b}	8.45^{b}	12.90^{b}	11.36^{b}	15.17^{b}	57.2
Years (Y)	2008	12.12^{a}	5.37^{a}	8.64^{a}	9.16^{b}	14.44^{b}	60.4^{b}
	2009	15.10^{b}	13.16^{b}	15.80^{b}	13.48^{c}	15.42^{b}	53.3^{a}
	2010	14.47^{b}	5.08^{a}	11.23^{a}	7.02^{a}	11.39^{a}	61,8^{b}
Fertilization treatments (FT)		***	***	***	***	***	ns
Years (Y)		***	***	***	***	***	***
FT x Y		ns	ns	ns	*	*	ns

* see Table 5; F – probability values: *,**, *** of 0.05, 0.01, 0.001, respectively, ns – no significantly different; ^{a} the same letters means a lack of significant differences the observed degree of the increase was the year dependent. It was significant in 2008 and 2010, but almost doubled in 2009. Nitrogen partitioning among plant organs also showed year-to-year variability. In 2008, N content in leaves constituted 38%, whereas in 2009 – 45%, and in 2010 – 31% of its total amount in the canopy. At maturity, the pattern of nitrogen accumulation was considerable different. Effect of applied fertilizers was modified by the course of weather. The nitrogen harvest index achieved 60% in 2008 and 2010, but only 53% in 2009, in spite of the highest total N accumulation. These figures indirectly indicate on insufficient size of the sink capacity, as referred to the seed density.

In order to explain the impact of nitrogen management on yield, both paths and stepwise analyses were applied. Yield of seed produced by the main branch was, as indicated by almost equal values of both correlation and direct path coefficients, depended on the amount of N accumulated in seeds (Figure 2*a*). The path coefficient was a result of indirect and large effect of N content in leaves (negative) and in shoots (positive) at flowering. This observation has been corroborated by the stepwise analysis, as presented by the set of equations, taking into account all three sets of variables, including also N accumulated in the rosette:

1) $MBY = 0.257 + 0.074N_{SE}$ for $n = 18$, $R^2 = 0.57$ for $p < 0.001$,
2) $MBY = 0.448 - 0.036N_{RT} + 0.096N_{SE}$ for $n = 18$, $R^2 = 0.65$ for $p < 0.00034$,
3) $MBY = 0.645 - 0.54N_{LE} + 0.036N_{SH} + 0.075N_{SE}$
for $n = 18$, $R^2 = 0.78$ for $p < 0.0007$.

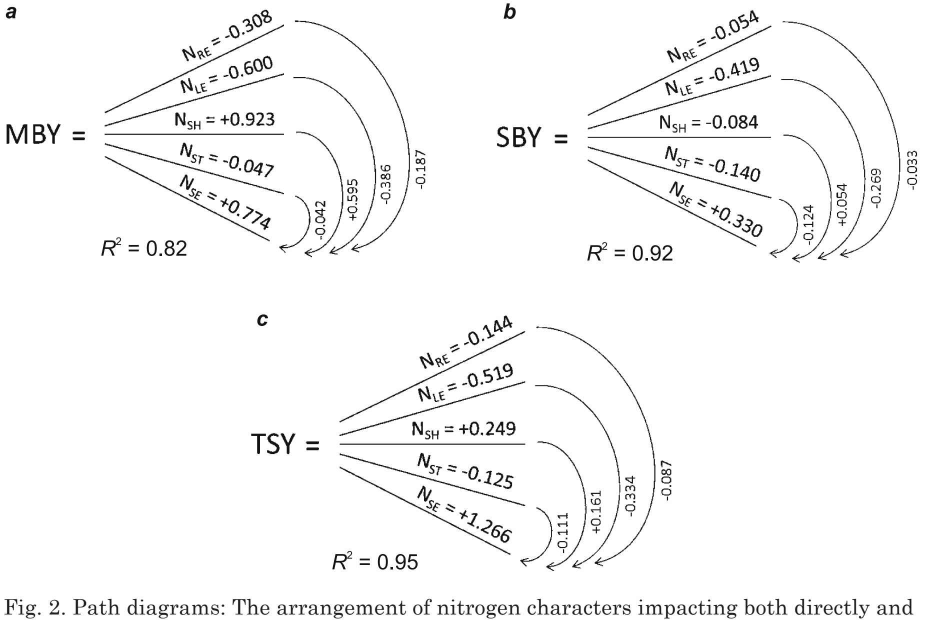

Fig. 2. Path diagrams: The arrangement of nitrogen characters impacting both directly and indirectly yield of oilseed rape produced by: *a* – the main inflorescence, *b* – secondary branches, *c* – whole plant

Yield of seeds produced by secondary branches was the most affected by nitrogen content in seeds (Figure 2*b*). However, its direct impact was significantly, but negatively corrected by all other variables, the most by nitrogen content in leaves. These observations have been fully corroborated by the developed stepwise regression models:

1) $SBY = 0.179 + 0.186N_{SE}$ for $n = 18$, $R^2 = 0.72$ for $P < 0.00001$,
2) $SBY = 0.263 - 0.1N_{LE} + 0.267N_{SE}$ for $n = 18$, $R^2 = 0.92$ for $p < 0.00000$.

The total yield of seeds, as referred earlier, was significantly depended on the yield produced by secondary branches. As results from analysis of both correlation and path coefficients, yield of seeds was governed the most by N content in seeds (Figure 2*c*). It has been, however, corrected by the amount of N accumulated in leaves at anthesis. This entire model has been fully corroborated by the developed stepwise regression models:

1) $TSY = 0.437 + 0.26N_{SE}$ for $n = 18$, $R^2 = 0.80$ and $p < 0.00000$,
2) $TSY = 0.527 - 0.107N_{LE} + 0.346N_{SE}$ for $n = 18$, $R^2 = 0.92$ and $p < 0.00000$.

The presented above three sets of equations clearly show that excess of nitrogen in leaves leads to yield decrease. In order to explain this phenomenon, it has been investigated the impact of nitrogen content in parts of oilseed rape during the growth season on the yield component performance. It has been documented that the number of pods (PMB) and number of seeds per pod (SMB), developed by the first inflorescence, are the key yield components for the moderate level of yield prognosis. The PMB dependency on nitrogen content in plant parts can be explained by the amount of N accumulated in seeds. This conclusion is supported by both correlation and path coefficients (Figure 3*a*). However, the path coefficient has been significantly corrected by N content in leaves and shoots at the beginning of flowering. This dependency has been corroborated by the stepwise regression model as presented below:

$PMB = 40.84 - 2.78N_{LE} + 1.87N_{SH} + 1.74N_{SE}$ for $n = 18$, $R^2 = 0.5$ and $p < 0.003$.

The second variable, SMB has been the most determined by the content of nitrogen in shoots. Its direct impact was negative in contrast to positive and large values of coefficients for N_{LE} and N_{SE} (Figure 3*b*). The N_{SH} coefficient has been positively corrected by nitrogen content in leaves (large indirect impact) and seeds (moderate) but at the same time negatively by its content in straw at maturity (large). The interactional effect of these two major variables has been fully corroborated by the developed regression model:

$SMB = 10.67 + 1.35N_{LE} - 1.25N_{SH}$ for $n = 18$, $R^2 = 0.57$, and $p < 0.0018$.

These two sets of equations implicitly corroborate the hypothesis that the performance of pods and seeds in the main branch was governed by the balance of N content in leaves and shoots at the beginning of anthesis. The excess of nitrogen in shoots at the beginning of flowering and in straw at maturity was the main reason for seed number reduction per pod, leading to decrease a seed capacity for N utilization.

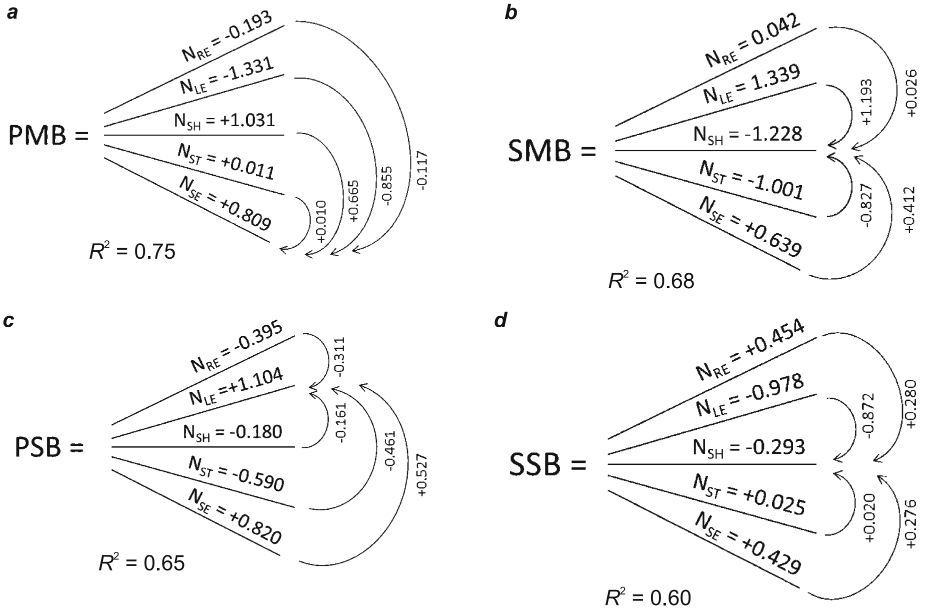

Fig. 3. Path diagrams: The arrangement of nitrogen characters impacting on yield structural components: *a* – number of pods per the main inflorescence, *b* – number of seeds per pod of the main inflorescence, *c* – number of pods per the secondary branch, *d* – number of seeds per the secondary branch

The higher level of yield prognosis requires the different set of data, composed mainly of PSB and SSB. The studied N accumulation variables had almost the same impact on PSB as results from analysis of correlation but not from path coefficients (Figure 3c). The highest values of both coefficients were the attribute of N_{LE}, which impact was significantly corrected by all, except N_{SH}, N variables. However, the significant prognosis can only be conducted using nitrogen content in leaves as the single predictor:

$\mathrm{PSB} = 91.15 + 5.62\mathrm{N}_{LE}$ for $n = 18$, $R^2 = 0.49$, and $p < 0.0013$.

The content of nitrogen in shoots and leaves at the beginning of anthesis showed, as results from values of correlation coefficients, the highest but negative impact on the seed density of secondary branches, SSB. This yield the structural components have been controlled the most by N content in leaves (Figure 3*d*). However, based on the developed stepwise regression model the highest accuracy of prognosis can be achieved, introducing only N content in shoots as the single significant variable:

$\mathrm{SSB} = 14.54 - 0.525\mathrm{N}_{SH}$ for $n = 18$, $R^2 = 0.31$, and $P < 0.01$.

Both equations implicitly indicate on the contrastive effect of N content in leaves at the beginning of flowering on the number of pods and seeds per pod of the secondary inflorescences. Plants following the strategy "slow by permanent biomass accumulation" showed the tendency to develop more pods of high seed density. This trend revealed a significant impact of applied magnesium and sulfur on components of yield performance in the first branch (Table 4). This pattern of N economy was observed in 2008. The post -anthesis increase in dry matter production, mainly pods, was the prerequisite of high yield of seeds. This fact corroborates the hypothesis developed by Diepenbrock (2000), who indicated the length of pods as the key attribute of the high-yielding oil-seed plantation. Plants followed the strategy "fast biomass accumulation" could develop a reasonable number of pods, but in expense of seed density, especially for pods of secondary branches. It seems probably that the prolonged pre-anthesis growth due to oversupply of nitrogen resulted in overproduction of vegetative biomass, as occurred in 2009. This phenomenon can be explained by a shortage of carbohydrate production for developing pods since the onset flowering, finally leading to seed density reduction (Habekotte 1993).

CONCLUSION

The conducted study implicitly documented that yield of oilseed rape significantly depends on the dominant strategy of plant growth during the pre- and post-anthesis periods. The study showed that the yield of seeds depends on the seed capacity to accumulate nitrogen. Plants following the strategy "slow by permanent biomass accumulation," which revealed in 2008 could continue biomass production from the onset of flowering. The highest yield of seeds was related to the increasing seed density in the first inflorescence as affected by magnesium and sulfur supply. This strategy revealed also a positive impact of N content in leaves at flowering stage of growth on seed density in the principal inflorescence. The second pattern of canopy performance by oilseed rape, which took place in 2009, termed as "fast biomass accumulation" was not as productive as the first one. It resulted in the seed density reduction, as a prerequisite of the decrease of the N physiological sink size, leading to the seed yield decrease. There was found a negative impact of N content in leaves on seed density in secondary branches.

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