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Contributed Paper

Can Photosynthetic Performance of Oat (*Avena sativa* L.) Plants be Used as Bioindicator for Their Proper Growth Conditions?

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ABSTRACT

Recently, oat (*Avena sativa* L.) plants are cultivated as worldwide functional food. The aim of this study was to analyse the response of photosynthetic apparatus of naked and hulled oat cultivars grown under different nitrogen fertilization dosage as well as different weather and soil conditions (different locations). Our analysis showed a significant influence of all studied experimental factors i.e. location, year, nitrogen dosage, cultivar/strain, leaf position on some selected chlorophyll fluorescence (ChlF) parameters and grain yield. Soil and climatic conditions/environments had the largest and statistically significant contribution to the variability of the analysed ChlF parameters, while the genotype (cultivar/strain) effect was the highest for grain yield. For other effects, the values were much smaller. Our results suggest that chlorophyll fluorescence measurements should be used in oat field experiments as a trustable and useful tool to study the reactions of plants photosynthetic apparatus under natural environments and to predict its yielding. Moreover, it can help to establish the optimal growth conditions for individual cultivars, including fertilizers' dosing.

Keywords: naked oat, hulled oat, chlorophyll fluorescence, photosynthesis

1. INTRODUCTION

Oat (*Avena sativa* L.) is a widely-grown crop both for human and animal nutrition. Chemical composition as well as therapeutic, dietary and protection against heart disease properties of its grain arouse a growing interest as functional food. The oat grain has a good nutritional value, because of its higher protein and fat content, as well as more preferred unsaturated fatty acid content as compared to other cereals [1]. However, high share of hull (husk) of oat grain (approx. 25-30%) limits the usefulness of this species in the feeding of monogastric animals. Introduced to the practice the cultivars of naked oats increase the possibility of using oats in feeding purposes because of the surpassing protein and fat content as well as a favourable fiber composition among the cereals [2].

Climatic conditions play an important role in shaping the grain yield of oats. They can cause lodging of plants and affects the grain quality. Oat has low soil and heat requirements, but high demand for moisture, therefore it could be cultivated in more humid and cool temperate zones. Besides, due to the short vegetation period, it can be sown quite high in the mountains [3]. Proper selection of oat cultivars to the soil and climate conditions, with adequate agricultural techniques is a basis for obtaining high yields of good quality grain. Due to the different genotype, the naked oats in relation to the husk ones, may have other requirements for certain factors associated with the agronomical practices. Optimum application of fertilizers is very important for both increasing the profit of agricultural production [4] and sustainable nature resources management [5]. Oat is one of the cereals that are less responsive to increase yields with high fertilization thus, determination of the optimal dosage of fertilizers, including nitrogen, must be taken into the account. . Nitrogen deficiency slows the growth of plants, shortens their vegetative development, accelerates ageing and reduces the photosynthetic efficiency of plants [6, 7].

Plants growing under natural conditions, experience many unfavourable factors, that interfere with the photosynthesis process leading to decrease in growth and yielding as well. Chlorophyll *a* fluorescence (ChlF) measurement is reliable approach to monitor the efficiency of the photosynthetic apparatus and evaluating of physiological condition of photosynthesizing organisms [8-9]. Measurements of chlorophyll fluorescence are a very sensitive, quick and non-invasive technique reflecting the bioenergetics state of the plant. Analysis of induction curve supports understanding the relationships between the photochemical processes of the light phase of photosynthesis and the biochemical reactions of the dark phase [9]. The analysis of fluorescence signals provides detailed information on the status and functions of photosystem II (PSII) reaction centers, light-harvesting antenna complexes, and both the donor and acceptor sides of PSII [10]. Measurements of ChlF could be applied to study, directly or indirectly, all phases of light photosynthesis: water photolysis, electron transport, creation of pH gradient across thylakoid membranes and ATP synthesis [9]. Recording and analysis of ChlF parameters is a precise tool for studying the reaction and functioning of photosynthetic apparatus under stress conditions [10-16].

Chlorophyll fluorescence research deals with the plant reactions to various nutrients deficiency [9]. The latter strongly influences the structure and function of key photosynthetic machinery components, including PSII. For example, the shortage of nitrogen, sulphur and iron strongly affects the synthesis of protein complexes, furthermore low level of nitrogen, magnesium and iron decreases the chlorophyll synthesis [6, 17]. Therefore, the changes in nutrients contents can be directly or indirectly inferred from measured and calculated ChlF parameters. Although the specific effect of nitrogen in several crop species was observed [6, 18], the data on the influence of plant nutrition on chlorophyll fluorescence of oat foliage are still not available. Moreover, most of the studies were experiments, performed in controlled conditions, which in most cases not correspond to environment plants experience in nature.

The aim of this study was to check if some measured and calculated chlorophyll fluorescence parameters can be used as bioindicators for oat plants (naked and hulled oat cultivars and strains) performance under different nitrogen fertilization dosages, weather and soil conditions.

2. MATERIALS AND METHODS

2.1 Plant Cultivation and Treatment

Field experiments were conducted during 2008–2010 in four localities: Przecław, Lubliniec N., Dukla and Krasne (located in south-eastern Poland in the Subcarpathian Region). They are characterized by different soil conditions and similar nutrients content (Table 1). The studies were carried out on soils, which are commonly used for oat in that region. The meteorological data were recorded by local weather stations (Table 2). Subcarpathian Region is one of the warmest regions in Poland, with average rainfall of approx. 470 mm during April-August. Total of precipitation in the studied locations was more variables compared to the average of air temperature. Analysis of variance (ANOVA) and post-hoc analysis, revealed a significant difference in average air temperature and total precipitation between locations, years and months. The mean air temperature in both the years and in the location, was medium varied (CV = 25.0), as opposed to the sum of precipitation which was highly variable (CV = 61.7). During the three-years study period Dukla significantly differed from the others locations and had the lowest mean temperature (15.0°C) and the highest average precipitation totals (117.9 mm). In all locations, the highest rainfall was recorded in 2010 (significant difference). The average air temperature from April to August ranged between 15 °C (Dukla) and 16 °C (Przecław, Lubliniec N. and Krasne). In each year (and month) the temperature varied significantly: in 2008 it was the lowest (15.4°C), while in 2010 the highest (16.1°C). Temperature in April was more varied than in August (CV 8.2 and 2.9, respectively). Mean air temperature in May, June and July was similar. In April and August both mean temperature and sum of precipitations were significantly different between themselves and others.

Table 1. Soil physical and chemical properties of locations

Locations	GPS positions	Soil groups	pH (KCl)	C_{org} (g/kg)	N (g/kg)	Available P (mg/kg)	Available K (mg/kg)	Available Mg (mg/kg)	Soil textural class
Przecław	50°19’N, 21°48’E	Gleicfluvisol	5.02	5.97	0.60	85	120	57	clay loam
Lubliniec N.	50°29’N, 23°09’E	Haplic luvisol	5.17	7.57	0.57	106	158	52	loamy sand
Dukla	49°55’N, 21°68’E	Haplic cambisol	6.37	12.59	1.51	77	202	82	silty clay
Krasne	50°03’N, 22°06’E	Eutriccambisol	5.30	13.9	0.82	50	154	38	sandy silt

Naked (cv. Polar, strain STH 7505) and hulled (cv. Krezus, strain STH 7105) cultivars and strains of oat were cultivated. Cultivars Polar and Krezus are medium-height, while strains STH 7505 and STH 7105 are dwarf. Seeds of oat originated from Plant Breeding Strzelce Ltd., Co. Plant Breeding and Acclimatization Institute Group in Poland. They were sown on the first decade of April at sowing density of 550 seeds/m^2.

Treatments included four levels of nitrogen (N) fertilization (kg N/ha): 0 (control), 40 (before

Table 2. Basic statistical parameters of the variability of the meteorological conditions during the oat growing season.

		Sum of rainfall (mm)					Mean air temperature (°C)				
		Mean	**Min.**	**Max.**	**SD**	**CV**	**Mean**	**Min.**	**Max.**	**SD**	**CV**
Location	Przeclaw	85.7	1.0	174.0	55.1	64.3	16.0	8.9	20.8	4.0	24.9
	Lubliniec N.	82.4	7.6	195.0	52.2	63.3	16.0	9.1	22.4	4.2	26.1
	Dukla	117.9	17.9	246.5	69.4	58.9	15.0	8.2	19.6	3.9	26.0
	Krasne	93.2	3.7	200.2	54.9	58.9	16.0	8.9	20.8	4.0	25.2
Year	2008	83.6	35.6	230.0	43.7	52.3	15.4	8.4	18.9	3.9	25.4
	2009	68.1	1.0	174.0	51.2	75.1	15.7	10.0	20.2	3.5	22.7
	2010	132.7	27.2	246.5	60.8	45.8	16.1	8.2	22.4	4.5	27.7
Month	April	37.7	1.0	85.3	27.1	71.9	9.4	8.2	10.7	0.8	8.7
	May	129.6	71.4	246.5	55.1	42.5	13.5	12.6	14.7	0.6	4.7
	June	112.2	35.6	235.0	57.9	51.6	17.3	15.6	18.4	0.9	5.1
	July	119.4	38.0	230.0	64.0	53.6	19.7	17.5	22.4	1.3	6.5
	August	75.1	34.0	117.0	28.9	38.5	18.8	18.0	19.7	0.5	2.9
Total		94.8	1.0	246.5	58.5	61.7	15.7	8.2	22.4	3.9	25.0

sowing), 80 (40 kg before sowing + 40 kg at the stage of tillering BBCH 25) and 120 (40 kg before sowing + 40 kg at the stage of tillering BBCH 25 + 40 kg at the beginning of heading stage BBCH 53). Phosphorus fertilization (P–35 kg/ha) as triple superphosphate, and potassium (K–85 kg/ha) as potassium chloride were applied before sowing.

Before sowing, seeds were dressed with Baytan Universal 094 FS (400 mL/100kg of seeds). Plants were sprayed with the herbicide Chwastox Turbo 340 SL (2L/ha), fungicide Falcon 465 EC (0.6L/ha) and insecticide Bi 58 Nowy EC 400 (0.5L/ha) at the stage of tillering. Pesticides were applied according to the procedure instructions. Grain harvest took place on the first (Przecław) and second (Lubliniec N., Dukla, Krasne) decade of August of the study years.

2.2 Methods and Measurement

Photosynthetic activity of plants was measured twice during heading stage (BBCH 59) by measuring chlorophyll fluorescence (ChlF) parameters. It includes: the maximum efficiency and primary yield of photochemistry of photosystem II (PSII) (F_v/F_m and F_v/F_o, respectively); time at which the maximum fluorescence (F_m) value was reached (T_{fm}); area above the fluorescence curve between F_o and F_m proportional to the pool size of the primary plastoquinone electron acceptors on the reducing side of PSII (A); photosynthetic performance index (PI_{ABS}); its individual partial components – the efficiency of light absorption (RC/ABS; where: RC - Active Reaction Centers, ABS - Absorption Energy Flux) and the measurement of forward electron transport (1-Vj)/Vj). Parameters were recorded by a portable Plant Efficiency Analyzer (Pocket PEA, Hansatech Instruments Ltd., Norfolk, UK). The intensity of the light pulse was 3500 μmol/ m^2/s at wave length 650 nm. Measurements were performed on each plot, on randomly selected 20 plants, on the adaxial surface of the first (flag) and second (penultimate) fully expanded leaf from the top, after adapting to darkness for 30 min. Chlorophyll fluorescence parameters are shown as relative units. In order to determine grain yield, oat grain samples were collected at harvest. The grain was then dried to approx. 15% and cleaned from dust and tailings.

2.3 Statistical Analysis

The experimental design was a split-plot with 3 replications. The area of a single plot was 16.5 m^2. The experimental factors were the genotype (G; cultivar/strain), the level of nitrogen fertilization (N) and the leaf position (LP). Combination of location and year was treated as various environments (E). In order to evaluation the variability of the features analysed, the means, minimum, maximum, standard deviations (SD) and coefficients of variation (CV) were calculated. Multifactor analysis of variance (ANOVA) was conducted to evaluate the effects of the analysed factors and their interactions on the ChlF parameters and grain yield. Significance of treatment effects and their interactions were analysed by the Tukey's test at P-value<0.05. The mutual interdependence between variables was defined by correlation analysis.

The variance components were calculated to estimate the contribution of the factors and their interactions in the total variability of analysed variable. For this purpose, the variance components were presented as percentage of the sum of all variance components and were obtained using procedure VARCOMP with method REML in SAS. A Principal Component Analysis (PCA) was performed to evaluate the relationships between the ChlF parameters and to characterize the multivariate differences between them and (i) examined environments (combination of locations and years), (ii) level of nitrogen fertilization, and also (iii) genotype (cultivar/strain). The analyses were performed using software STATISTICA 13.1 (StatSoft, Tulsa, USA), SAS 9.3 (SAS Institute Inc., Cary, NC, USA) and R (version 2.15.2; http://cran.r-project.org/).

3. RESULTS AND DISCUSSION

The variance analyses showed a significant influence of investigated factors (environment, N dosage, genotype, leaf position) and their interactions (N×E, G×E and E×LP) on selected ChlF parameters and grain yield. Location and climatic conditions in the years (environments) had the highest and statistically significant contribution to the variability of the all analysed ChlF parameters, while the genotype (cultivar/strain) effect was the highest for the grain yield. For other effects, the values were much smaller (Table 3).

Maximum efficiency of PSII (F_v/F_m) provides a very useful relative measure of photochemical activity of photosynthetic apparatus [19, 20]. According to the available literature, F_v/F_m values for non-stressed leaves in full development phase are remarkably consistent at approx. 0.83 [8, 21]. In our study environment (location and meteorological conditions) had high contribution to the variability of F_v/F_m parameter (30%) (Table 3) and differed significantly (Table 4). Lower values of F_v/F_m were found for oat growing on soil of haplic luvisol in Lubliniec N., than other studied locations. High rainfall, also modified this parameter. The highest values of F_v/F_m in all studied cultivar/strains, were found during wet year (2010), while the lowest in the dry one (2009, Figure 1). Moreover, the obtained results indicate, that N deficiency conditions (control) have been inhibitory effect on the plants F_v/F_m values. The highest values were recorded for objects fertilized with 120 kg N/ha. Difference between the control and the highest dosage of N was small (3%), but statistically significant. Our results are consistent with the literature which shows, that F_v/F_m parameter of ChlF achieved lower values in plants exposed to N deficiency [6, 22, 23]. High level of N fertilization could increase the efficiency of the excitation energy captured by open PSII centers in leaves [10]. In our study oat cultivars under high dosage

Table 3. Effects (P-values) of the factors and their interactions on the analysed chlorophyll fluorescence parameters and grain yield based on an analysis of variance and the share of the factors and their interaction in the total variability of the analysed feature (share is presented as percentages in brackets). See the results text to learn about the enclosed abbreviation.

Factors	F_v/F_m	F_v/F_o	$PI_{(ABS)}$	RC/ABS	T_{fm}	A	(1-Vj)/Vj	Grain yield
Environment (E)	0.00*(30)	0.00*(37)	0.00*(37)	0.00*(38)	0.00*(68)	0.00*(21)	0.00*(39)	0.00*(12)
N dosage (N)	0.00*(6)	0.00*(5)	0.00*(9)	0.00*(10)	0.00*(3)	0.00*(2)	0.00*(6)	0.00*(8)
Cultivar/Strain (G)	0.00*(3)	0.00*(3)	0.00*(1)	0.00*(2)	0.00*(3)	0.00*(2)	0.00*(1)	0.00*(61)
Leaf position (LP)	0.00*(2)	0.00*(3)	0.14(0)	0.00*(2)	0.03*(0)	0.00*(12)	0.00*(8)	1.00(0)
N×E	0.00*(2)	0.01*(2)	0.01*(2)	0.00*(4)	0.01*(1)	0.06(2)	0.00*(3)	0.00*(3)
N×LP	0.24(0)	0.17(0)	0.73(0)	0.67(0)	0.66(0)	0.73(0)	0.71(0)	1.00(0)
G×N	0.49(0)	0.45(0)	0.08(1)	0.03*(1)	0.80(0)	0.93(0)	0.21(0)	0.00*(1)
G×E	0.25(0)	0.36(0)	0.02*(2)	0.00*(3)	0.03*(1)	0.69(0)	0.00*(3)	0.00*(13)
G×LP	0.24(0)	0.17(0)	0.55(0)	0.29(0)	0.81(0)	0.72(0)	0.30(0)	1.00(0)
E×LP	0.00*(3)	0.00*(2)	0.00*(4)	0.00*(5)	0.00*(2)	0.04*(2)	0.00*(6)	1.00(0)

* – significant effect at the 0.05 probability level.

Table 4. Mean values of chlorophyll fluorescence parameters and grain yield of oat plants.

Factors		F_v/F_m	F_v/F_o	$PI_{(ABS)}$	RC/ABS	T_{fm}(ms)	A(bms)	(1-Vj)/Vj	Grain yield t/ha
Location	Przecław	0.785^{b}	3.826^{b}	4.065^{c}	1.523^{c}	347.7^{b}	786888^{bc}	0.650^{c}	5.521^{c}
	Lubliniec N.	0.759^{a}	3.334^{a}	2.290^{a}	1.059^{a}	295.8^{a}	594825^{a}	0.581^{a}	4.428^{a}
	Dukla	0.793^{c}	3.955^{b}	3.826^{b}	1.466^{bc}	369.1^{b}	843435^{c}	0.635^{bc}	4.632^{b}
	Krasne	0.790^{bc}	3.953^{b}	3.746^{b}	1.421^{b}	410.3^{c}	711223^{b}	0.621^{b}	4.574^{a}
Year	2008	0.779^{a}	3.704^{a}	3.369^{a}	1.332^{a}	317.2^{a}	743418^{b}	0.625^{b}	4.503^{a}
	2009	0.777^{a}	3.684^{a}	3.310^{a}	1.316^{a}	341.7^{b}	783815^{b}	0.634^{b}	5.068^{c}
	2010	0.788^{b}	3.872^{b}	3.714^{b}	1.445^{b}	394.7^{c}	674476^{a}	0.606^{a}	4.795^{b}
N dosage	0	0.769^{a}	3.530^{a}	2.878^{a}	1.210^{a}	322.9^{a}	695185^{a}	0.606^{a}	4.193^{a}
	40	0.779^{b}	3.708^{b}	3.195^{b}	1.286^{a}	333.9^{a}	693884^{a}	0.608^{a}	4.683^{b}
	80	0.786^{bc}	3.837^{bc}	3.726^{c}	1.438^{b}	367.5^{b}	748206^{ab}	0.630^{b}	5.016^{c}
	120	0.791^{c}	3.925^{c}	4.031^{d}	1.514^{b}	378.7^{b}	807413^{b}	0.644^{b}	5.262^{d}
Cultivar/Strain	Polar*	0.778^{ab}	3.675^{ab}	3.639^{b}	1.430^{b}	385.0^{b}	810100^{b}	0.633^{b}	3.681^{a}
	Krezus	0.788^{c}	3.886^{c}	3.330^{a}	1.300^{a}	347.9^{a}	698585^{a}	0.612^{a}	6.405^{d}
	STH 7505*	0.785^{bc}	3.823^{bc}	3.600^{b}	1.400^{b}	344.3^{a}	730719 a	0.623^{ab}	3.905^{b}
	STH 7105	0.773^{a}	3.616^{a}	3.261^{a}	1.318^{ab}	325.8^{a}	705284 a	0.620^{ab}	5.164^{c}
Leaf position	1st	0.777^{a}	3.659^{a}	3.553^{a}	1.414^{b}	359.3^{b}	815936 b	0.637^{b}	
	2nd	0.785^{b}	3.841^{b}	3.362^{a}	1.310^{a}	342.2^{a}	656408 a	0.607^{a}	

Mean values followed by the same letters (a, b, c) are not significantly different at the 0.05 level according to the Tukey's test; * Naked oats.

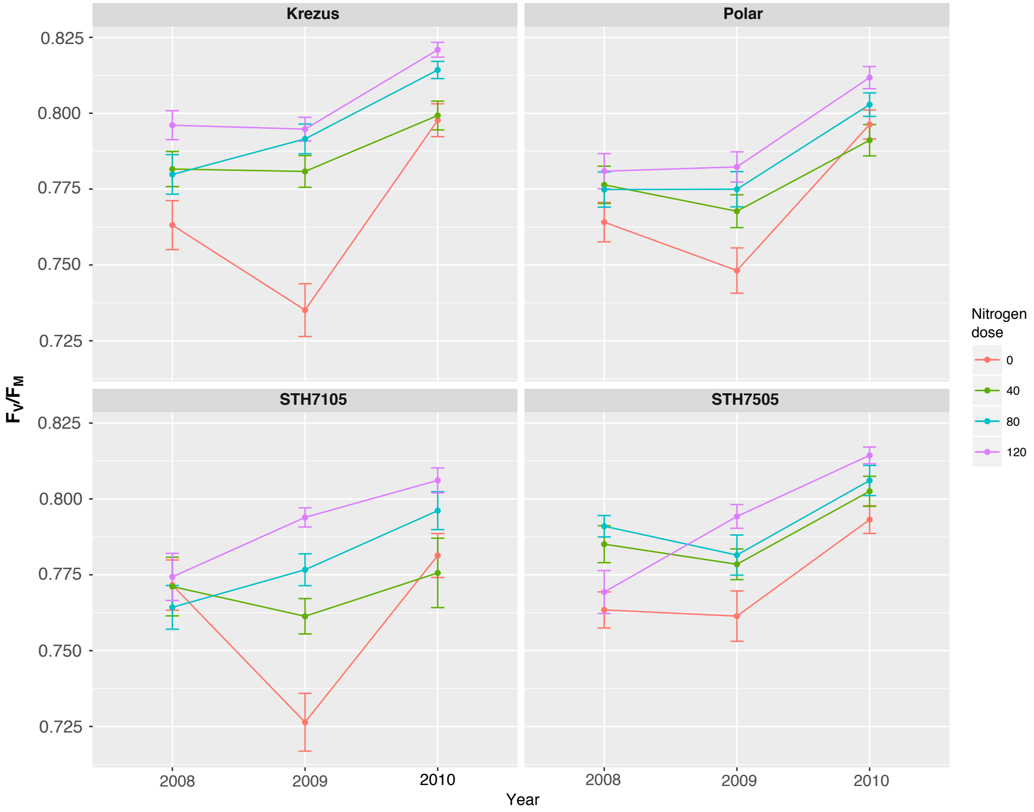

Figure 1. Year to year changes in maximum efficiency of Photosystem II (F_v/F_m) in different oat (*Avena sativa* L.) cultivars/strains under different nitrogen treatment.

of N contained more chlorophyll, and thus the PSII apparatus remained functional, the crops had lots of green leaves, and there was a continued use of the light captured by the remaining PSII apparatus, leading to a higher F_v/F_m and PSII efficiency. Whereas under low N dosage, many of the green leaves became yellow, and the PSII apparatus captured less light, causing lower and F_v/F_m values.

According to literature an increase in F_v/F_m is associated with the increase in Rubisco content, and the activity of RuBPcase in the Calvin cycle and phosphoenolpyruvate carboxylase (PEP carboxylase) in the C_4 photosynthetic path can be used to improve the photosynthetic electron transport in chloroplasts, yielding oxygen, nicotinamide adenine dinucleotide phosphate hydrate (NADPH), and ATP, thereby increasing photosynthesis, chlorophyll concentration, and thus elevating the leaf weight of plants [24], In our study, slight but significant lower values of F_v/F_m parameter in the flag leaf were observed as well. These results are in disagreement with those of Živčák *et al.* [13-14] who showed that there is no decrease in F_v/F_m value in the youngest fully developed leaf of wheat due to N deficit. In our experiment, F_v/F_m values of the STH 7105 strain were the lowest in comparison with any other studied genotype. Simultaneously, we did not find any difference in the F_v/F_m values between naked and hulled and also between dwarf and medium-height oats. The latter finding could be treated as novel fact since it is reported for first time.

In this report, impairment of the PSII photochemistry was also visible by decrease in the maximum primary yield of photochemistry of PSII (F_v/F_o), which showed a similar amplitude as F_v/F_m ratio and hence similar sensitively reflected changes in plant photosynthetic efficiency (Table 4). This was particularly evident in terms of the impact of climatic conditions, nitrogen dosage and the response of the tested cultivars/strains (Figure 1, 2). According to Zhao *et al.* [25] decreases of the activity of PSII reaction centers (F_v/F_o) of cells in nitrogen-deficiency conditions, indicate that the photosynthetic apparatus was damaged and that light energy conversion efficiency decreased. The alteration of PSII photochemical reactions also suggest that the ability of the photosynthetic apparatus to maintain plastoquinone molecule tightly bound to PSII (Q_A) in an oxidative state weakened.

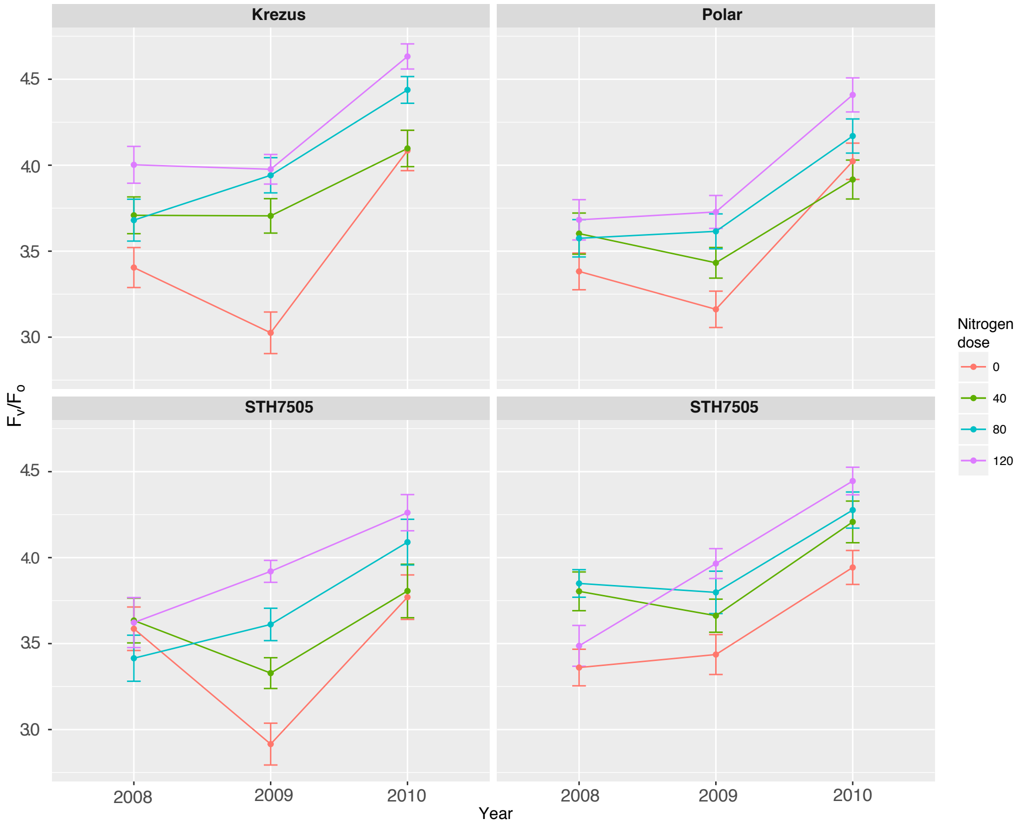

Figure 2. Year to year changes in maximum primary yield of photochemistry of PSII (F_v/F_o) in different oat (*Avena sativa* L.) cultivars/strains under different nitrogen treatment.

The photosynthetic performance index (PI_{ABS}) is the product of an antenna reaction center and electron transport dependent parameter [9, 26]. It is the most widely used parameter from the ChlF parameters, which provides quantitative information about the general state of plants and their vitality [10, 27, 28]. In our study photosynthetic performance index (PI_{ABS}) reached the highest values in plants cultivated on fluvisol in Przecław, whereas it's the lowest values were in Lubliniec N., where drought during heading stage caused disturbance of photochemical reactions in thylakoids and rates of enzymatic reactions in chloroplasts. The obtained results also show, that different dosages of N fertilizers led to alterations in PI_{ABS} values in oat. Lower values were found in plants poorly nourished with N. Positive effects of higher N treatments on PI_{ABS} values have been documented e.g. in soybean [29] maize [30] and wheat [14]. In our report impairment of the PSII photochemistry under N deficiency could be better envisaged by variation in the PI_{ABS} parameter which showed a much greater amplitude than F_v/F_m ratio and hence more sensitively reflected changes in photosynthetic activity [9]. Naked oats (cv. Polar and strain STH 7505) had significantly higher PI_{ABS} values compared to the hulled (cv. Krezus and strain STH 7105), and differences observed was 9%. The efficiency of light absorption by oat photosynthetic apparatus (RC/ABS) decreased significantly on loamy sand in Lubliniec N. as compared with other studied locations (Table 4). Simultaneously, higher rainfall in 2010 resulted in an increase in RC/ABS values. It was also noted that this parameter had significantly lower values in the absence of the N and when a dosage of 40 kg N/ha was applied. The use of 80 kg N/ha increased the values approx. by 20%, while 120 kg N/ha dosage by 25%. The reduction of RC/ABS values under the influence of nitrogen deficiency was also recorded by Zhao *et al.* [25]. The authors found that due to nitrogen starvation, the photochemical efficiency of PSII and the activity of PSII reaction centers (RCs) decreased, and photoinhibition of PSII occurred. It was stated inactivation of the oxygen-evolving complex (OEC) and decreased light energy conversion efficiency. In our study a greater RC/ABS, was characteristic for the tested naked cultivar Polar and strain STH 7505. The values of the efficiency of absorption of light also changed depending on the leaf position on the oat plant and were the highest at the flag leaf.

T_{fm} is referred to non-reduced plastoquinone pool (PQ), which increases under operation of stress factors [31]. This was confirmed in the current research. The time at which the maximal fluorescence (F_m) intensity was reached (T_{fm}) in oat plants, differed in localities under study and depended on soil and meteorological conditions during vegetation period (Table 4). Shortening of time to reach F_m was found in Lubliniec N on sandy soil. Significant time delays in achieving F_m was associated with higher values of this parameter and occurred in other localities on heavy soils. It was also found, that nitrogen deficiency (0 and 40 kg/ha) induced a reduction in T_{fm} value, while nitrogen fertilization (80 and 120 kg/ha) increased the time to obtain F_m (Table 4, Figure 3). Among the tested cultivars of oat, naked cv. Polar, with higher values of leaf area, was characterized by significantly higher values of T_{fm} than the others. Our results indicate that there is significantly increase of T_{fm} value for the youngest (1^{st}), fully developed leaves, which were most likely to be exposed to the stress factors.

The area (A) above the fluorescence curve between F_o and F_m is proportional to the pool size of the electron acceptors on the reducing side of Photosystem II. According to Kalaji and Guo [26] if electron transfer from the reaction centres to the quinone pool is blocked, this area is reduced. Our studies showed, that the area above the fluorescence curve as well as forward electron transport (1-Vj)/Vj), like other chlorophyll fluorescence parameters, had significantly lower values in Lubliniec N. (Table 4). The increase in both parameters was observed under increasing nitrogen dosages (Figure 4). Simultaneously, higher values of A above chlorophyll induction curve was achieved at naked cultivar Polar. This parameter was higher for flag leaves in comparison to penultimate ones. This could be result of electron transport from reaction centers to plastoquinone is blocked in penultimate leaves and plants with higher vegetative biomass (as in the case of hulled oat). Similarly, the lowest values of A in 2010 year in comparison to 2008 and 2009, seems to confirm the PSII disorder as a result of water stress, caused by excessive rainfall during the vegetation period.

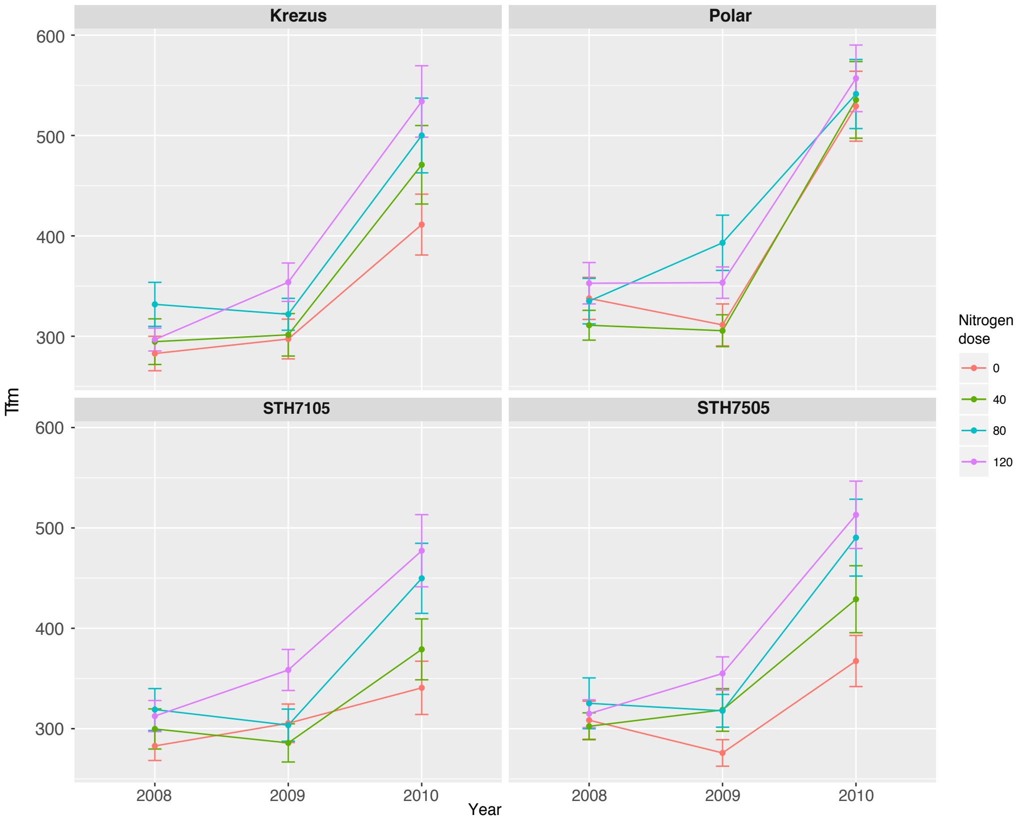

Figure 3. Year to year changes in time at which the maximum fluorescence (F_m) value was reached (T_{fm}) in different oat (*Avena sativa* L.) cultivars/strains under different nitrogen treatment.

Temporal changes of ChlF parameters in oat cultivars and strains were observed in study period. The highest decline of F_v/F_m in dry year 2009 was noted in naked cultivar Polar and STH 7505 strain (Figure 1). I was also found, that in STH 7105 strain fertilized with N dosage above 40 kg N/ha, showed continuous increase of F_v/F_m during the whole study period. A similar trend was observed in maximum primary yield of photochemistry of PSII (F_v/F_o; Figure 2). The time at which the maximal fluorescence intensity was reached is prolonged significantly in all cultivars and strains, especially in the period of 2009-2010. There were a significant difference in T_{fm} between control (non-fertilized) and fertilized plants in all studied cultivars and strains except cv. Polar (Figure 3). In all cultivars/strains, we found higher values of A and forward electron transport (1-Vj)/Vj) in fertilized plants as compared to control. However, a strong decline of these parameters was observed in 2010 (which was characterized by high rainfall) and was found in STH 7505 strain (Figures 4, 5).

In order to summarise relationships among ChlF parameters and environmental conditions, the Principal Component Analysis was performed. The first two axes, explained 76.6 % of variance in the data set. The first one, which explained 50.1% of variance, is related to inter-locality differences and separated the plants grown in Dukla and Krasne with higher values of RC/ABS, F_m, T_{fm} and PI_{ABS} from those from Lubliniec (Figure 6). The second axis, which explained 26.6% of variance, could be related to changes in time. When we compared

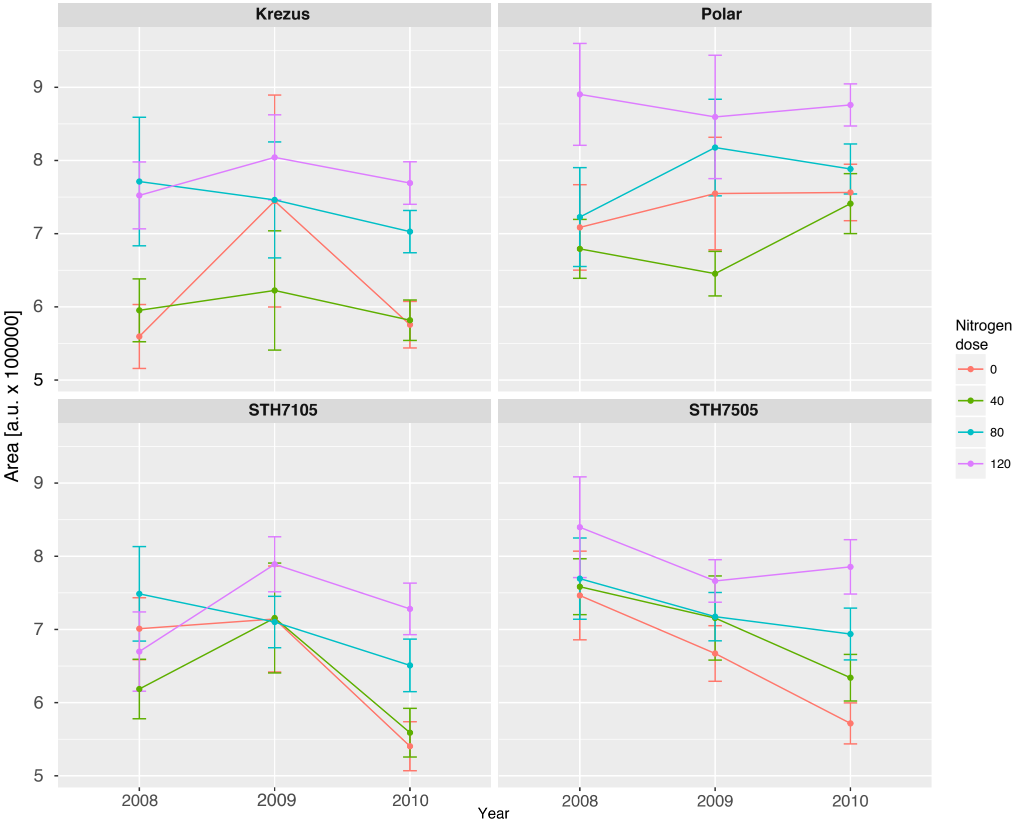

Figure 4. Year to year changes in Area – a pool size of the electron acceptors Q_A on the reducing side of Photosystem II in different oat (*Avena sativa* L.) cultivars/strains under different nitrogen treatment.

the changes in photosynthetic apparatus response to nitrogen application, a difference between the naked and hulled cultivars and strains were denoted. The fertilization of cv. Polar and strain STH 7505 plants with 120 kg N/ha resulted in increased values of A, RC/ABS and forward electron transport (1-Vj)/Vj) parameters. Increasing the N dosage for cv. Kresus and STH 7105 plants enhanced F_v/F_m, F_v/F_o, F_v and F_m parameters (Figure 7).

The quantity of oat grain yield was significantly dependent on the location of crop, meteorological conditions in the year, N dosage and cultivar/strain. The genotype had the highest share in the variability of the grain yield (61%) (Table 3). Significant share was also observed for the environment, interaction effect G×E (cultivar/strain ×environment) and N dosage. The highest grain yield was found for growing oats on soil of gleic fluvisol in Przecław compare to other studied locations (Table 4). Moderate rainfall in 2009 and favourable their distribution for plants during vegetation period also increased them. In 2008 and 2010 the grain yields were lower by 11.2% and 5.4%, respectively. This was due to the drought in a critical stage of shooting in 2008 and lodging of plants as a result of heavy rainfall in 2010. This is in agreement with the results of Doehlert *et al.* [32] who suggested that warm spring weather, and cooler summer temperature, without excessive rains during grain filling, generated not only the best yields of oat but also high quality grain. The applied

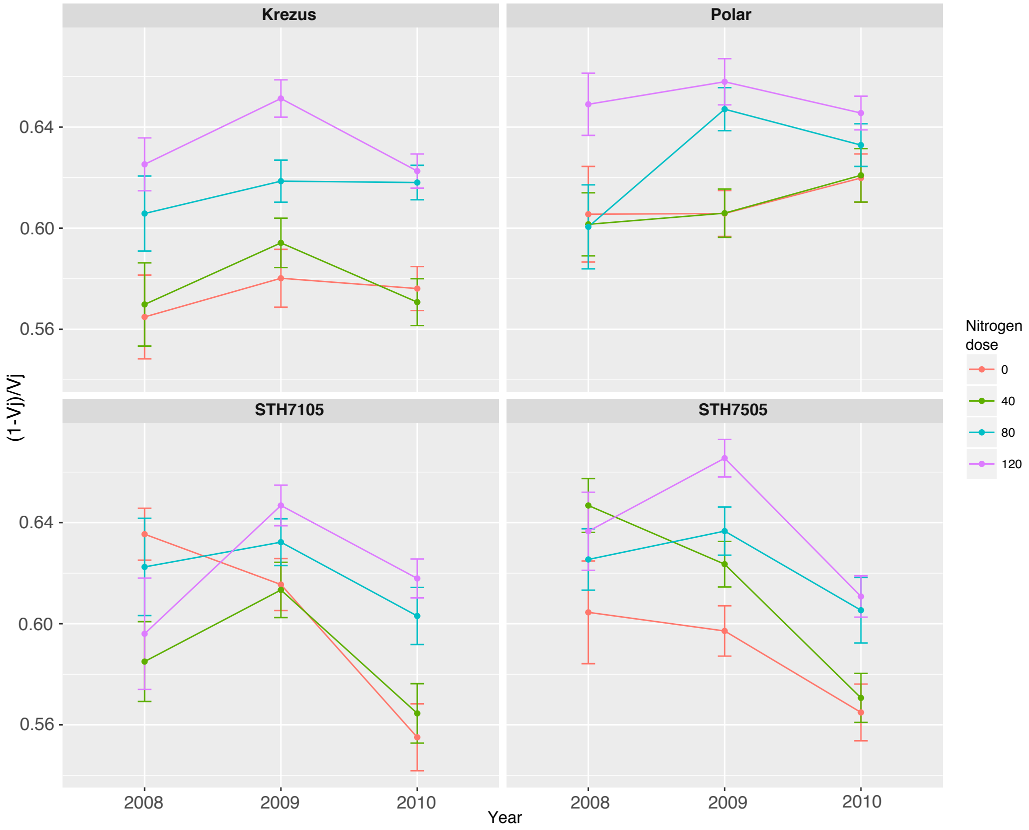

Figure 5. Year to year changes in (1-Vj)/Vj) referred to forward electron transport in different oat (*Avena sativa* L.) cultivars/strains under different nitrogen treatment.

dosages of N significantly increased grain yield of oats. The highest yields were obtained with the application of 120 kg N/ha, both in naked and hulled oats. Increased grain yield between dosage of N 40 and 80 kg/ha was similar for naked and hulled of oats and amounted to approx. 7.1%. Whereas, increased grain yield between 80 and 120 kg N/ha was lower and amounted to 3.8% in naked and 5.6% in hulled cultivars. In the Walens [33] study the increase in oat yields was only observed at a dosage of 60 kg N/ha compared to control. Application higher dosage of N did not result in a significant increase in yields of grain and yield of the naked oat was 33% lower than that of hulled. In our study hulled cv. Krezus characterized by the highest grain yield in response to nitrogen fertilization than other cultivars. This is in agreement with the results of Andruszczak *et al.* [34] who found that cv. Krezus was characterized by higher weight of grain per panicle and weight of 1000 grains. As a result, the obtained grain yield was twice higher in relation to the naked oat.

A comparison of the correlation coefficients related to ChlF parameters (F_v/F_m, F_v/F_o, PI_{ABS}, RC/ABS) showed a significant relationship between them (Table 5). In our study, **independently of tested cultivar or strain**, the grain yield of oat was positively correlated with the F_v/F_m, F_v/F_o, $PI_{(ABS)}$, RC/ABS parameters (weak but significant correlation). However, **there were no clear correlations at the level of tested cultivars and strains**. Cultivar Polar and STH

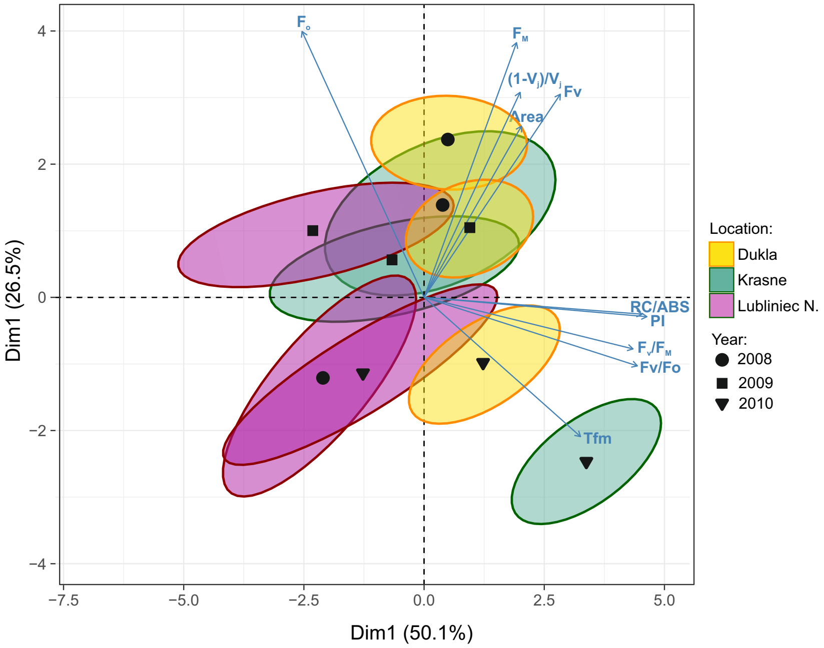

Figure 6. Principal Component Analysis (PCA) performed in order to evaluate the relationships between the chlorophyll fluorescence (ChlF) parameters and to characterize the multivariate differences between ChlF parameters in oat plants grown in examined environments (combination of locations and years).

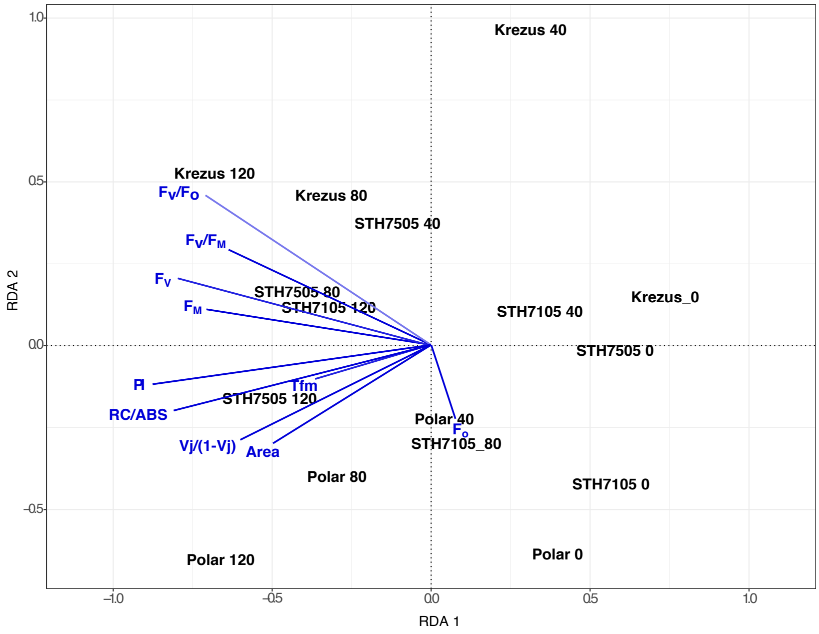

Figure 7. Principal Component Analysis (PCA) performed in order to study the relationships between the chlorophyll fluorescence (ChlF) parameters and to characterize the multivariate differences between ChlF parameters and level of nitrogen fertilization and cultivars/strains.

Table 5. Correlation coefficients (r) between the analysed chlorophyll fluorescence parameters and grain yield.

	$\mathbf{F_v/F_m}$	$\mathbf{F_v/F_o}$	$PI_{(ABS)}$	RC/ABS	T_{fm}	A	(1-Vj)/Vj
$\mathbf{F_v/F_o}$	0.97*						
$PI_{(ABS)}$	0.72*	0.78*					
RC/ABS	0.70*	0.74*	0.97*				
T_{fm}	0.41*	0.46*	0.51*	0.53*			
A	0.11*	0.15*	0.51*	0.47*	0.37*		
(1-Vj)/Vj	0.15*	0.15*	0.55*	0.62*	0.14*	0.67*	
Grain yield	0.19*	0.20*	0.14*	0.11*	n.s.	n.s.	n.s.

* – significant correlation at the 0.05 probability level; n.s. – indicates factor non-significant.

7505 strain showed the highest photosynthetic performance (PI_{ABS}) and pool size of the primary plastoquinone electron acceptors on the reducing side of PSII (Area parameter) but the lowest grain yield. On contrary, cv. Kruzus and STH 7105 strain showed low values of the above mentioned parameters but highest grain yield. The latter result is in agreement with Janušauskaite and Feiziene [22] work who did not find a close correlation of ChlF parameters (F_o, F_m, F_v/F_m) with spring triticale grain yield.

4. CONCLUSIONS

Summarizing, our results conducted on various oat genotypes revealed that, on the base of the use of plants photosynthetic efficiency measurements, the growth environments (soil and climatic conditions in individual localities) were the strongest factors that affects plant photosynthetic performance, while the genotype (cultivar/strain) had the highest share in the variability of the grain yield. Our results also suggest that the fast and non-invasive measurements of some chlorophyll fluorescence parameters can help to choose the best localization and nitrogen dosage for oat plant cultivation. However, to assure reliable filed results, these measurements should be conducted on more than 2 leaves at different growth stage per plant.

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