

The Efficiency of Nitrogen Fertilization of Spring Wheat Depending on Seasonal Rainfall

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ABSTRACT

Aims: The main objective was to determine the optimal rates influence of nitrogen fertilization on spring wheat grown after stubble catch crops or without them, in years with different total rainfalls during the period from March to July.

Study design: The split-plot experimental design with four replications was used.

Place and Duration of Study:

A field experiments were carried out in the years 2005-2008 at Mochelek (17° 13' E; 53° 13' N) – an Experimental Station of the University of Technology and Life Sciences in Bydgoszcz.

Methodology: A two-factor, field experiment was conducted on *Alfisols* formed of a sandy loam in the north-central Poland. The N rates were [kg·ha⁻¹]: 0, 40, 80, 120, 160. The second factor was the catch crops – that were investigated – field pea (*Pisum sativum* var. *arvense* L.), oilseed radish (*Raphanus sativus* var. *oleiformis* L.), and a control without a catch crop. The main studied features were spring wheat yield and its components, depending on nitrogen rates and total rainfall. Moreover the most economic rate of nitrogen for spring wheat in years with different amount of rainfall were calculated.

Results: The optimal rate of nitrogen in spring wheat cultivation depended mainly on the total precipitation that prevailed during its growth. The highest grain yield of this plant grown after catch crops could be obtained applying 140-160 kg N·ha⁻¹ in the year with a very good supply of rain water and 41-42 kg N·ha⁻¹, in the extremely dry year. The effect of catch crops on the yield of spring wheat depended on the rate of nitrogen. Very large increase in grain yield was obtained when no nitrogen was applied. After the application of 120 and 160 kg N·ha⁻¹ there was no effect of catch crops on spring wheat productivity.

Conclusion: The most economic rate of nitrogen for spring wheat was lower than the agronomically optimal rate by about 30% in the year with a favourable rainfall distribution. In the extremely dry year, the nitrogen fertilization of spring wheat grown after catch crops was economically unjustified. The effect of catch crops on grain yield was positive only in spring wheat fertilized with nitrogen at a rate of up to 80 kg·ha⁻¹.

Keywords: Efficiency; nitrogen fertilization; wheat; catch crop.

1. INTRODUCTION

Nitrogen fertilization is a well recognized factor that determines both grain yield. Nitrogen is a major factor in wheat development, affecting the shoot numbers, spike length, and grain filling which determine grain yield [1] and its quality [4, 2, 3, 4, 5]. A good supply of nitrogen to wheat determines the number of shoots formed, the length of spikes and grain filling [5].

21 However, owing to the increasing prices of the energy needed for the production of nitrogen
22 fertilizers, their cost is increasing [6]. Moreover, even a statistically significant increase in
23 yield often sometimes does not result in an improvement in crop profitability [7]. Therefore,
24 the nitrogen application rate must be strictly adapted to the soil conditions and the availability
25 of water for plants. It is also essential to determine the most profitable rate, which depending
26 on the weather conditions may be 30%, while under conditions of an extreme rainfall deficit
27 more than 90% less than the rate that would make it possible to obtain the maximum grain
28 yield. The optimum N fertilizer rate needed by a wheat crop to maximize profitability depends
29 on the economic ratios of fertilizer costs, wheat grain values and the environmental
30 conditions under which the crop is grown. Maximum profitability may be achieved at N rates
31 30% and even 90% less than those for maximum grain yields when growing conditions are
32 normal or extremely dry, respectively. To determine the rate which is economically optimal, it
33 is necessary to know the environmental conditions and the current relationship between
34 fertilization costs and the value of wheat grain. The most economical rate of nitrogen
35 (MERN) may also be dependent on the availability of elements in the soil that are derived
36 from the mineralization of plant residues left in the soil after the harvest of the previous crop.
37 The importance of the accurate determination of the nitrogen rate is particularly essential in
38 wheat grown in light soils, where agronomic and economic effectiveness are more
39 dependent on the availability of water in soil, which allows it to up the applied elements and
40 to utilize them to produce a higher grain yield [2]. It is particularly essential to precisely
41 determine the nitrogen rate for wheat grown on light soils, where agronomic and economic
42 effectiveness are determined by water content in soil. The available water allows the plants
43 to take up the applied nutrient elements and utilize them to produce a higher grain yield [3].
44 The most economical rate of nitrogen (MERN) may also be dependent on the availability of
45 elements in the soil that are derived from the mineralization of plant residues left in the soil
46 after the harvest of the previous crop, of catch crops that are plowed in as green manure. In
47 the study by Shah et al. [7], the agronomic effectiveness and nitrogen use efficiency were
48 the highest when the organic to mineral nitrogen ratio in the fertilizers applied was 25:75.

49 A valuable source of nitrogen and other nutrients for spring cereals can be the biomass of
50 plants grown as a stubble catch crop and plowed in the autumn of the previous year [8, 9]. is
51 a valued organic fertilizer, which it allows for the improvement of the biological properties of
52 soil [8, 9–10] and an increase in the grain yield of cereals grown after them. This is of
53 particular importance in the current system of agricultural production, which is characterized
54 by a low proportion of legumes, too high proportion of cereals in the cropping system. This
55 leads to decreasing the organic matter in the soil and deterioration of biological soil
56 condition. To prevent this unfavorable process, catch crops can be cultivated and produced
57 biomass can be used as a green manure. The plants which produce a high amount of
58 organic matter and may positively influence the yield of succeeding crops and its quality are
59 of particular value to achieve this aim. My previous research indicated that oilseed radish can
60 produce a high yield of biomass and has a high ability to accumulate nutrients remaining in
61 soil after the harvest of cereals [9]. Field pea is well known as a plant which has a positive
62 influence on soil condition and the yield of succeeding crops. When grown as a catch crop
63 and plowed in, it can significantly influence the yield of cereals [11].

64 Moreover, a relatively low stocking rates results in a shortage of natural fertilizers.

65 The objective of the present research was to determine the influence of rainfall during the
66 period from March to July on the optimal rates of the application of nitrogen fertilization for
67 spring wheat grown after catch crops or without them. Moreover, the influence of oilseed
68 radish and field pea grown as catch crops on the spring wheat yield, depending on nitrogen
69 rates, was also determined.

70 2. MATERIAL AND METHODS

71 2.1 Site and weather description

72 The effects of nitrogen fertilization and catch crops was evaluated on the basis of two factors
73 a Field experiments were conducted carried out in the years 2005-2008 at the Mochetek (17°
74 13' E; 53° 13' N) – an Experimental Station of the University of Technology and Life
75 Sciences in Bydgoszcz. The A split-plot experimental design with four replications was used,
76 where the whole plot treatments consisted of five N fertilizer rates and timings and the split-
77 plot treatments consisted of two catch crops and control, without catch crop.

78 The water supply during the growing period of spring wheat was highly varied in the years of
79 the study. In 2006 plants were well supplied with rain water during emergences, tillering and
80 shooting (Table 1). Further stages of development proceeded under conditions of a very
81 substantial rainfall deficit. In 2007 rainfall distribution was also well adapted to the needs of
82 spring wheat. Only a short-term deficiency of precipitation occurred in April. The water
83 supply in the period from May to July was 48-97% higher than the average for the area of
84 the study. In 2008 the weather conditions were extremely unfavourable for spring wheat. The
85 total precipitation in May and June accounted for only 28.4% of the mean total precipitation
86 for those months from that in the years 1949-2008.

87 Nitrogen fertilization was the first experimental factor. Fertilizers were applied before and
88 during the spring wheat growing period: the control (without N fertilization); 40 kg of N
89 (before sowing); 80 kg of N (40 kg before sowing and 40 kg at the BBCH 31-32 stage); 120
90 kg N (60 kg before sowing and 60 kg at the BBCH 31-32 stage); 160 kg N (60 kg before
91 sowing, 60 kg at the BBCH 31-32 stage and 40 kg at the BBCH 45-47 stage). The second
92 factor was the catch crops: field pea (*Pisum sativum* var. *arvense* L.); oilseed radish
93 (*Raphanus sativus* var. *oleiformis* L.) and the control without a catch crop. The area of the
94 plot was 30 m².

95 **Table 1. Total monthly precipitation on the research area [mm]**

Month	Year			Mean for 1949-2008
	2006	2007	2008	
March	27.4	47.9	61.2	24.3
April	77.0	17.6	38.7	28.0
May	59.9	73.1	11.5	41.7
June	21.8	105.5	15.5	53.5
July	24.2	104.7	58.7	70.8
Total III–VII	210.3	348.8	185.6	218.3

96 The field experiment was carried out on Alfisols that was formed of a sandy loam [10-12].
97 The level of field water capacity at depths from 0 to 100 cm on this field range from 215 to
98 270 mm [11-13].

99 The soil was rich abundant in available phosphorus (111 mg P per kg of dry soil) and
100 potassium (367 mg K per kg of dry soil) and had an average magnesium content (60.5 mg
101 Mg per kg of dry soil). The concentration of organic carbon (C_{org}) and total nitrogen (N_{tot}) was
102 7.17 and 0.67 g in a per kg of dry soil, respectively. Soil pH in 1M KCl was 6.47.

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106 2.2 Plant measurement and analysis

107 After the spring barley was harvested, the soil was plowed and cultivated using a cultivator
108 with a **crumbler** roller. Catch crops were sown between August 3-11 in 2005-2007. After 70-
109 77 days of growth, the plants were **harvested mowed at a height of about 5-7 cm** and the
110 **yield of green matter** from each plot was weighed. Subsequently samples of green matter
111 (about 1 kg per plot) were taken to determine the dry matter yield of this part of plants. The
112 rest of green matter was placed on plots and plowed in. The yield of post-harvest residue
113 was determined based on samples collected from soil monoliths of 25 × 25 × 25 cm, which
114 were screened and rinsed with water. Each sample consisted of stubble and roots.

115 Spring wheat (*Triticum aestivum* L.), 'Tybalt' cultivar, was sown between March 30 and April
116 11 in 2006-2008 in the stands where the biomass of the catch crop had been plowed under
117 in order to evaluate its previous crop value. Each year, before the spring wheat was sown,
118 mineral fertilization was applied. Phosphorus and potassium were broadcast at doses of
119 28.4 kg P·ha⁻¹ and 74.7 kg K·ha⁻¹ and mixed with the soil using cultivator with a **crumbler**
120 **roller aggregate**.

121 Prior to harvest on each plot, the number of spikes and the number of grains **in per spike**
122 **were determined**. The number of spikes was counted on 2 randomly chosen rows, each
123 4.55 m long, which is equivalent to 1 m². The number of grains per spike was determined
124 based on 20 randomly chosen spikes from each plot. Spring wheat was harvested using
125 Wintersteiger plot harvester, during the period from August 1 to 8. **The grain yield was**
126 **determined after the plants had been harvested**. Grain samples were taken from each plot in
127 order to determine its moisture and the 1000 grain weight. **The grains collected from each**
128 **plot were weighed and grain yield per ha was calculated**. Moreover, the grain moisture was
129 **determined and grain yields were calculated to 15% moisture**.

130 The weather conditions were analyzed based on measurements made at the local
131 **observations and measurement unit weather station** located at the Experimental Station in
132 Mochelek.

133 2.3 Statistical analysis

134 Analysis of variance was done using the results obtained in individual years. The
135 significance of differences was determined using Tukey's test at a 95% level of confidence.
136 **In the case of grain yield additionally, Student T test has been made to compare pairs of**
137 **independent samples i.e. yield obtained after field pea catch crop and 40 kg N per ha vs**
138 **yield obtained in control without catch crop and 80 kg of N per ha**.

139 The analysis of regression was made using the Statistica for Windows program StatSoft.
140 The effectiveness of nitrogen fertilization (N_{Eff}) was calculated separately for each interval
141 rate (0-40; 40-80; 80-120 and 120-160 kg N·ha⁻¹). Calculations were done according to the
142 equation:

$$143 N_{\text{Eff}} = (\text{yield at NX} - \text{yield at NX-40})/40 \quad (\text{Eq. 1})$$

144 where suitable values: 40, 80, 120 and 160 kg were set as NX (0, 40, 80 and 120 as NX-40)
145 in order to calculate the efficiency of nitrogen fertilization for rate intervals: 0-40, 40-80, 80-
146 120 and 120-160, respectively. The yield of spring wheat grain is expressed in kg per ha and
147 the calculated N_{Eff} is expressed in kg of grain per 1 kg of N applied at this interval.

148 Yields were fitted to a quadratic model: $Y = aN^2 + bN + c$, where Y is wheat grain yield (kg ha⁻¹),
149 N is the fertilizer N application rate (kg ha⁻¹), a is the intercept, b and c are regression

150 coefficients. The agronomically optimal rate of nitrogen (AORN) was determined by
151 calculation extremum of regression functions (p) of spring wheat grain yield in individual
152 years.

153
$$p \text{ AORN} = -b/2a \quad (\text{Eq. 2})$$

154 where a and b are suitable values from the regression equation ($f(x) = ax^2 + bx + c$)
155 calculated based on grain yield expressed as kg per ha.

156 Taking the first derivative of the quadratic model allows for the calculation of the slope (i.e.
157 dY/dN) at any selected value of N.

158 Setting the slope to equal the price ratio (PR) of 1 kg of N in the fertilizer applied to the
159 value of 1 kg of wheat grain allows for the calculation of most economic rate of nitrogen
160 (MERN) [5].

161 i.e. $PR = 2a(\text{MERN}) + b$, solving for MERN gives

162
$$\text{MERN} = (PR - b)/2a \quad (\text{Eq. 3})$$

163 The MERN was calculated by setting the first derivative of the regression equation of spring
164 wheat grain yield in individual years for the price relation: the cost of 1 kg of nitrogen in the
165 fertilizer applied to the value of 1 kg of wheat grain [4]. The cost of 1kg of nitrogen was
166 assumed to be the market value of this element (4.30 PLN¹ per 1 kg) plus the cost of its
167 application (0.50 PLN). The price of 1 kg of wheat grain (0.92 PLN) was adopted following
168 the Agricultural Advisory Centre (ODR) at Minikowo of 02.11.2012 [12-14]. The price relation
169 was $4.80:0.92 = 5.22$.

170 The first derivative of the regression equation of spring wheat grain yield has the form:

171
$$f'(x) = 2ax + b \quad (\text{Eq. 3})$$

172 where x is the searched MERN, a and b are suitable values from the regression equation
173 ($f(x) = ax^2 + bx + c$) calculated based on grain yield expressed as kg per ha.

174 For $f'(x) = 5.22$

175
$$2ax + b = 5.22$$

176
$$x = (5.22 - b)/2a$$

177 3. RESULTS

178 The water supply during the growing period of spring wheat was highly varied in the years of
179 the study. In 2006 plants were well supplied with rain water during emergences, tillering and
180 shooting (Table 1). In 2006, timely precipitation occurred during the critical plant growth
181 stages of tillering and shooting, although the remainder of the growing season had
182 significant moisture deficits (table 1). Further stages of development proceeded under
183 conditions of a very substantial rainfall deficit. In 2007 rainfall distribution was also well
184 adapted to the needs of spring wheat. Only a short-term deficiency of precipitation occurred
185 in April. The water supply in the period from May to July was 48-97% higher than the
186 average for the area of the study. In 2008 the weather conditions were extremely
187 unfavourable for spring wheat. The total precipitation in May and June accounted for only
188 28.4% of the mean total precipitation for those months from that in the years 1949-2008.

189

¹ Polish Zloty; 1 PLN = 0.31 USD (<http://www.money.pl/> 02.11.2012)

Table 1. Total monthly precipitation on the research area [mm]

Month	Year			Mean for 1949-2008
	2006	2007	2008	
March	27.4	47.9	61.2	24.3
April	77.0	17.6	38.7	28.0
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July	24.2	104.7	58.7	70.8
Total III–VII	210.3	348.8	185.6	218.3

Nitrogen fertilization as well as stubble catch crops had a significant effect on grain yield and on the yield structure elements components of spring wheat (Table 2). The effect of the nitrogen rate on the number of spikes and grain yield differed in the years of the study. In relation to the number of grains per spike and the 1000 grain weight, there was no interaction of the experimental factors with the years. Therefore, these features are presented in this paper in the form of means from the years for individual fertilization levels and catch crops. Due to the significant interaction between the experimental factors and the years in relation to grain yield, the results concerning this variable are presented both as the means from 2006-2008 and for individual years.

Table 2. F-values and significance levels from an analysis of the variance of main spring wheat traits

Traits of spring wheat	Factors			Interactions		
	I - Rate of N & (d.f.=4)	II - Catch crops^ (d.f. = 2)	I x II (d.f.=8)	I x Years (d.f.=8)	II x Years (d.f.=4)	I x II x Years (d.f.=16)
Number of spikes	8.068***	6.46**	0.42 ns	8.17***	0.32 ns	0.31 ns
Number of grains per spike	6.01***	11.66***	1.51 ns	0.90 ns	0.67 ns	0.71 ns
1000 grain weight	3.31*	7.64***	0.50 ns	1.57 ns	2.47 ns	1.10 ns
Grain yield	59.31***	93.68***	10.53***	48.31***	15.27***	2.23***

& - rates of N [kg ha⁻¹]: 0, 40, 80, 120 and 160;

^ - catch crops plowed in the autumn of previous year: field pea, oilseed radish and control without a catch crop

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$; d.f. - degree of freedom; ns – no significant;

3.1 Yield of plants grown as stubble catch crop

The yield of field pea and oilseed radish in the presented study was at an average level for the experimental region (Table 3). The highest yields of plant dry matter were obtained in 2006 and 2007 and the lowest in 2005. The Although the dry matter yield of field pea was significantly higher than that of oilseed radish, The difference resulted from a more than two times higher yield of pea aboveground biomass in comparison with oilseed radish. The the mean post-harvest residue yield of field pea from 2005-2007 was significantly lower than that of oilseed radish.

220

Table 3. Dry matter yield of catch crops plowed in the autumn [Mg·ha⁻¹]

Part of plant	Plant species	Year			Means for 2005-2007
		2005	2006	2007	
Green matter	FP*	1.07 a [#]	3.07 a	2.90 a	2.35 a
	OR	0.64 b	0.92 b	1.48 b	1.01 b
Post-harvest residue	FP	1.27	0.80 b	1.10	1.06 b
	OR	1.10	1.89 a	1.04	1.34 a
Total dry matter	FP	2.34 a	3.87 a	4.00 a	3.41 a
	OR	1.74 b	2.81 b	2.52 b	2.35 b

221 *FP – field pea, OR – oilseed radish

222 [#] – means marked with different letters in columns differ significantly at $\alpha = 0.05$ 223 **3.2 Spring wheat yield components**

224 Experimental factors had an effect on the features determining wheat yielding yield (Table 4,
 225 Figures 1 and 2). The nitrogen rate significantly modified the number of spikes of spring
 226 wheat in the years 2006-2008, which was the largest after the application of 40 kg·ha⁻¹, and
 227 significantly smaller for treatments that were not fertilized with nitrogen or that were fertilized
 228 with a very high rate of this element (160 kg·ha⁻¹). The effect of nitrogen on the number of
 229 spikes differed in individual years. In 2006 the number of spikes was the highest after the
 230 application of 120 or 160 kg N·ha⁻¹, and significantly smaller in wheat not fertilized with this
 231 element. In 2007 it was enough to apply 40 kg N·ha⁻¹ to obtain the maximal number of
 232 spikes. In 2008 spring wheat fertilized with nitrogen at a rate of 40 kg·ha⁻¹ also formed
 233 significantly more spikes than the wheat that was not fertilized and increasing the rate of this
 234 element to 120 and 160 kg·ha⁻¹ led to a significant decrease in the number of spikes.

235 **Table 4. The number of spring wheat spikes per m²**

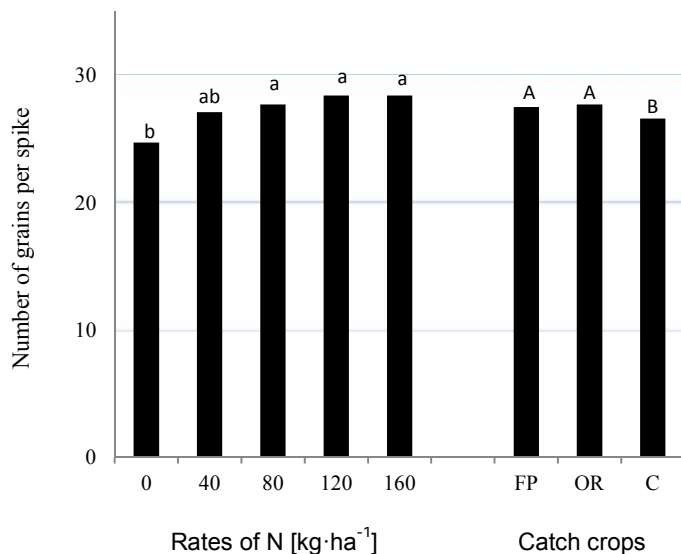
Factors		Year			
		2006	2007	2008	2006– 2008
Nitrogen fertilization [kg·ha ⁻¹]	0	520 b [#]	431 b	280 b	410 c
	40	556 ab	512 a	363 a	477 a
	80	572 ab	521 a	291 ab	461 ab
	120	588 a	523 a	250 bc	454 ab
	160	591 a	514 a	198 c	434 bc
Catch crop	FP*	574	507	283	455 a
	OR	571	505	276	451 a
	C	551	489	270	436 b

236 *FP – field pea, OR – oilseed radish, C – control (without a catch crop)

237 [#] – means marked with different letters in columns differ significantly at $\alpha = 0.05$

238 Both plants grown as a stubble catch crop for green manure exerted a significant, positive
 239 effect on the number of spikes of spring wheat from the years 2006-2008. The impact of this
 240 factor was not significant in individual years.

241 Fertilization with nitrogen had a significant effect on the number of grains in the spring
 242 wheat spikes (Fig. 1). This was the highest after the application of 80, 120 or 160 kg N·ha⁻¹
 243 and significantly lower in wheat not fertilized with this element.



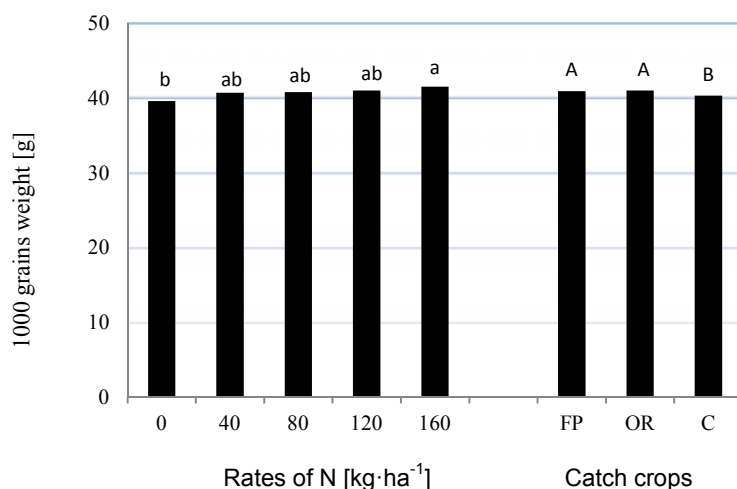
244

245 **Fig. 1. The number of grains per spike of spring wheat as affected by N-fertilization**
 246 **and catch crops plowed as a green manure in the autumn of previous year – means**
 247 **for 2006–2008**

248 *FP – field pea, OR – oilseed radish, C – control (means marked with the same small or the same*
 249 *capital letters do not differ significantly at $\alpha = 0.05$)*

250 Field pea and oilseed radish grown as stubble catch crop resulted in a significant increase in
 251 the number of grains per spike. No interaction was found between the experimental factors
 252 and years in relation to this feature.

253 The factors of the experiment significantly affected the 1000 grain weight (Fig. 2). On the
 254 treatments where 160 kg N·ha⁻¹ was applied, it was significantly larger than in the control
 255 without nitrogen fertilization. The stubble catch crops plowed in the autumn also contributed
 256 to a significant increase in the 1000 grain weight of spring wheat relative to the control.



257

258 **Fig. 2. The weight of 1000 grains of spring wheat [g] as affected by N-fertilization and**
 259 **catch crops plowed as a green manure – means for 2006–2008**

260 *FP – field pea, OR – oilseed radish, C – control (means marked with the same small or the same*
 261 *capital letters do not differ significantly at $\alpha = 0.05$)*

3.3 Spring wheat grain yield

The spring wheat grain yield was significantly dependent on both experimental factors (Table 5). On average in the three-year period of the study, the most favourable rate was 80 kg N·ha⁻¹, after which had a significantly higher weight of grain was harvested yield than after the application of 40 kg N·ha⁻¹. The lowest wheat yield was obtained on treatments where nitrogen was not applied. Increasing the nitrogen rate to a level of 80 kg·ha⁻¹ resulted in a significant increase in grain yield both on treatments where wheat was grown after catch crops and in the control without catch crops. Wheat grown after catch crops and fertilized with a rate of 40 kg N·ha⁻¹ gave the same yield as the control after the application of 80 kg N·ha⁻¹. Increasing nitrogen fertilization from 80 to 120 kg·ha⁻¹ resulted in a significant decrease in the grain yield of spring wheat grown after stubble catch crops.

Table 5. Grain yield of spring wheat [t Mg·ha⁻¹], depending on nitrogen fertilization and biomass of catch crops plowed as a green manure – means for 2006– 2008

Nitrogen fertilization [kg·ha ⁻¹]	Catch crop			Mean
	FP*	OR	C	
0	2.41 cA [#]	2.44 cA	2.11 cB	2.32 c
40	2.96 bA	3.02 abA	2.75 bB	2.91 b
80	3.14 aA	3.19 aA	3.01 aB	3.12 a
120	2.95 b	2.98 b	2.91 ab	2.95 ab
160	2.97 ab	2.98 b	2.95 a	2.97 ab
Mean	2.89 A	2.92 A	2.74 B	2.85

*FP – field pea, OR – oilseed radish, C – control (without a catch crop)

[#] – means marked with different small letters in columns or different capital letters in rows differ significantly at $\alpha = 0.05$

Field pea and oilseed radish grown as stubble catch crops for green manure caused a significant increase in the grain yield of spring wheat. The effect of catch crops on the yield of spring wheat depended on the rate of nitrogen. Wheat not fertilized with nitrogen responded with very large increases in grain yield (14.3% after pea and 15.5% after radish). After the application of 40 kg N·ha⁻¹, the increase in yield amounted to 7.8 and 10.0%, respectively. Wheat fertilized with nitrogen at a rate of 80 kg·ha⁻¹ also had significantly increased grain yield under the influence of catch crops. After the application of 120 and 160 kg N·ha⁻¹ there was no effect of catch crops on spring wheat productivity. The response of spring wheat to fertilization with nitrogen differed in individual years of the study. The second degree polynomial regression analysis indicates that the agronomically optimal rate of nitrogen (AORN) in 2007 amounted to 139-161 kg·ha⁻¹ after catch crops and 174 kg·ha⁻¹ in control treatment (Table 6). In 2008 it was only 41-42 kg·ha⁻¹ and 51 kg·ha⁻¹ respectively.

303
304

Table 6. Regression equations and yield of spring wheat at agronomically optimal rates of nitrogen (AORN) and the most economical rates of nitrogen (MERN)

Year	Catch crop	Regression equation [#]	Regression coefficient	AORN [kg·ha ⁻¹]	Yield at AORN [Mg·ha ⁻¹]	MERN & [kg·ha ⁻¹]	Yield at MERN [Mg·ha ⁻¹]
2006	FP*	$y = -0,073N^2 + 15,2N + 2043$	0.905	104	2.84	68	2.74
	OR	$y = -0,068N^2 + 14,7N + 2018$	0.895	108	2.81	70	2.71
	C	$y = -0,081N^2 + 19,0N + 1670$	0.952	117	2.78	85	2.70
2007	FP*	$y = -0,060N^2 + 19,3N + 3066$	0.920	161	4.62	117	4.50
	OR	$y = -0,076N^2 + 21,2N + 3112$	0.892	139	4.61	105	4.50
	C	$y = -0,062N^2 + 21,6N + 2636$	0.941	174	4.52	132	4.41
2008	FP*	$y = -0,059N^2 + 4,8N + 2261$	0.738	41	2.36	0	2.26
	OR	$y = -0,066N^2 + 5,6N + 2331$	0.780	42	2.45	3	2.36
	C	$y = -0,068N^2 + 6,9N + 2142$	0.795	51	2.32	12	2.22

305 *FP – field pea, OR – oilseed radish, C – control

306 [#] - regression equation calculated based on grain yields from plots expressed as kg per ha

307 & the values were calculated for the ratio of cost of 1 kg of N to price of 1 kg of grain: 5.22:1.00

308 The analysis of fertilization profitability determined based on the regression equations and
 309 relations of nitrogen prices to wheat grain value price ratio showed a poor economic
 310 effectiveness of this factor different effectiveness of this factor in individual years (Table 6).
 311 At the current price relation of nitrogen to wheat (5.22:1), the MERN for spring wheat were
 312 lower than the AORN by 24.1-35.2% in the year with a good or moderately favourable
 313 rainfall distribution. In the extremely dry year already nitrogen rates higher than 12 kg·ha⁻¹ in
 314 control treatment were unprofitable. In the extremely dry year an increase in nitrogen rates
 315 above 12 kg·ha⁻¹ in control treatment caused a decrease in profitability. The fertilization of
 316 spring wheat grown after field pea catch crop in this year was economically unjustified.

317 The effectiveness of nitrogen fertilization (N_{Eff}) within the range of 0 to 40 kg·ha⁻¹ was very
 318 high in all of the years of the study (Fig. 3). The average increase in grain yield per 1 kg of
 319 nitrogen applied ranged from 12.4 kg in 2008 to 17.0 kg in 2007. The effectiveness of higher
 320 nitrogen rates was much different in the years of the study. In 2006 a small positive effect
 321 was found in the range of 40 to 80 and of 80 to 120 kg·ha⁻¹. Increasing the rate from 120 to
 322 160 kg·ha⁻¹ resulted in a decrease in grain yield by 4.4 kg on average per each kg of the
 323 applied nitrogen. In 2007 a relatively high effectiveness of nitrogen was obtained within the
 324 range of 40 to 80 kg·ha⁻¹. The effectiveness of nitrogen fertilization in the range of 80 to 120
 325 kg·ha⁻¹ was from -1.63 for wheat grown after radish to 1.93 for wheat grown in the control
 326 without a catch crop. In 2008 the effectiveness in all of the studied ranges of rates above 40
 327 kg·ha⁻¹ was less than zero.

328

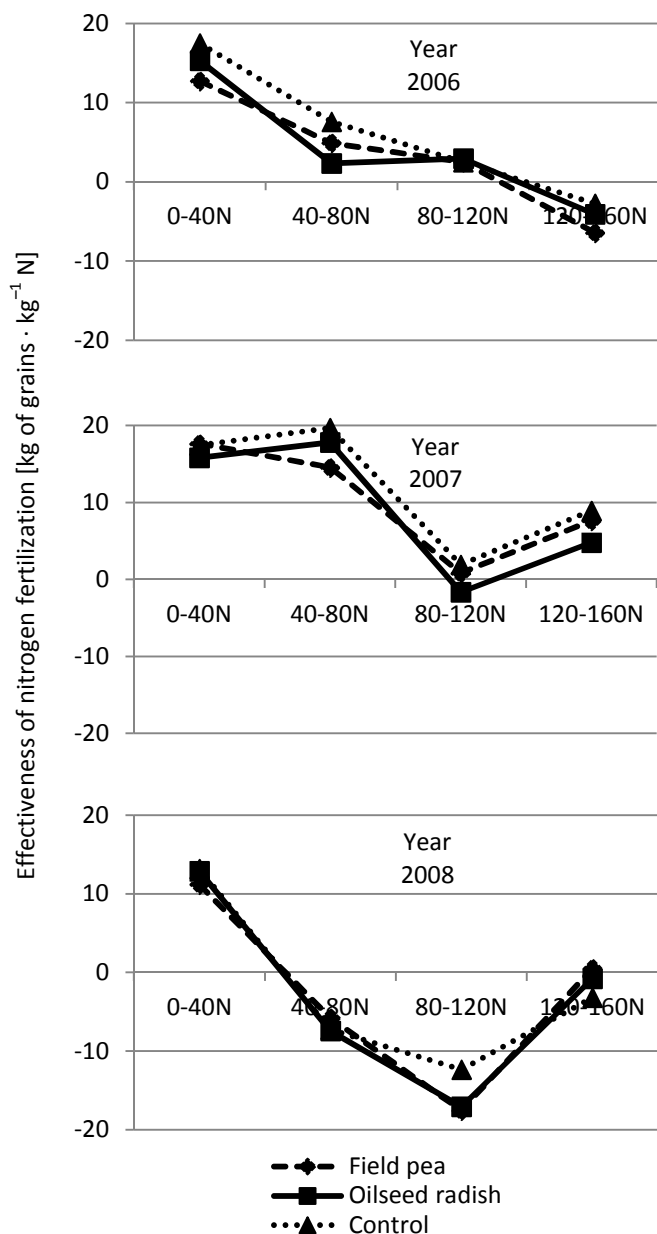


Fig. 3. Effectiveness of nitrogen fertilization (N_{Eff}) of spring wheat grown after catch crops (field pea, oilseed radish) or without them (control), measured separately in particular rate intervals (kg of grain yield increase · kg⁻¹ N rate increase)

In all of the years of the study, there was a correlation between grain yield and the number of spikes of spring wheat (Table 7). The number of grains per spike and the 1000 grain weight were positively correlated with grain yield only in the years with a good or moderate water supply (2007 and 2006).

340 **Table 7. Correlation coefficients between grain yield and the yield components of**
 341 **spring wheat ($n=15$)**

Yield components	Yield of grain in years Grain yield		
	2006	2007	2008
Number of spike per m ²	0.92*	0.85*	0.92*
Number of grains per spike	0.92*	0.88*	0.34
Weight of 1000 grains	0.65*	0.78*	0.09

342 * – significant at $\alpha = 0.05$;

343 4. DISCUSSION

344 4.1 Yield of plants grown as stubble catch crop

345 The above-ground dry green matter yield of plants grown as a stubble catch crop depends
 346 mainly on the supply of water and fertilizer elements. Under conditions of a favourable
 347 distribution of precipitation, good soil fertility and nitrogen fertilization applied at a rate of 60-
 348 90 kg·ha⁻¹ it ranges from 3 to 6 Mg·ha⁻¹ [9, 13, 14 8, 15, 16]. In general, plants of the family
 349 Fabaceae give lower yields than oilseed radish. In the present study, field pea formed a
 350 significantly higher yield of above-ground dry green matter and total biomass than oilseed
 351 radish. The reason for the poor yield of radish could be the relatively low soil abundance of
 352 nitrogen. This element is taken up by radish in very large amounts, often exceeding 160
 353 kg·ha⁻¹ [16]. When grown in soil that is not rich abundant in nitrogen and under conditions
 354 where there is a lack of fertilizing catch crops containing this element, radish cannot form as
 355 large a yield as pea.

356 4.2 Grain yield of spring wheat and its structure

357 The average grain yield of spring wheat from the 3 years of the study was very low (2.85
 358 Mg·ha⁻¹). This was a result of both the unfavourable weather conditions that prevailed in 2
 359 out of the 3 years of the study and from the sandy-loamy soil that was not very fertile on
 360 which the wheat was grown.

361 A positive effect of nitrogen fertilization on all the wheat yield components confirms the need
 362 for splitting its application into three rates. This is indicated by the effect of nitrogen
 363 fertilization on the 1000 grain weight of wheat. Increasing the N rate by as much as 120
 364 kg·ha⁻¹ did not affect this feature. Only after the application of 160 kg it was significantly
 365 higher than in the control. This effect results from the way of division of the highest nitrogen
 366 rate. The third part of this rate (40 kg·ha⁻¹) applied directly before wheat earing caused
 367 formation of better filled grain. Splitting into two equal parts spread before sowing and at the
 368 beginning of shooting stage, applied for rates 80 and 120 kg·ha⁻¹, had no effect on 1000
 369 grain weight. A positive effect of nitrogen applied before earing on the 1000 grain weight was
 370 obtained in 2007, characterized by a favourable rainfall distribution during spring wheat
 371 growing period. This effect was not observed in the other years. Thus in years that are
 372 characterized by rainfall deficit in this period the application of this rate is ineffective.
 373 According to Engel et al., [1] and Boaretto et al., [17] also the air temperature is of utmost
 374 importance for yield-forming influence of nitrogen applied at later development stages. Under
 375 conditions of very high temperatures the period of grain filling is shortened, leading to a
 376 decrease in 1000 grain weight and the yield. A negative effect of high temperatures on
 377 wheat yielding was observed even under conditions of high amount of precipitation. In the
 378 present study, in 2 of 3 years air temperatures in the period of grain filling were considerably
 379 higher than the long-term averages, which combined with rainfall deficit led to formation of
 380 poorly filled grain.

381 Field pea and oilseed radish grown as a stubble catch crop for green manure exerted a
382 positive effect on the grain yield of spring wheat. This positive effect resulted mainly from an
383 increase in the number of spikes and the number of grains per spike. The 1000 grain weight
384 was also dependent on catch crops, but an increase in the value of this feature under the
385 influence of plowed biomass was only 1.5-1.7%.

386 The results of research presented in the literature concerning the impact of catch crops on
387 the yield of succeeding crops are ambiguous. Many studies have shown negative effects
388 [15, 16, 17 18, 19, 20] or no impact of catch crops plowed into the biomass on the yield of
389 cereals [18 21]. In order to obtain the desired effect, it is necessary to select the appropriate
390 plant species for growing as a stubble catch crop.

391 The results of current research indicate that legumes grown as catch crops and plowed in
392 autumn have a favorable effect on spring cereals. Their biomass in soil undergoes fast
393 mineralization and the nutrients that are released are taken up by cereals growing under
394 these conditions. The positive, successive impact of these catch crops is possible if they
395 produce a high yield of biomass. This is dependent mainly on the moisture conditions that
396 occur during July and August [19, 20 22, 23]. Non-legume plants are less sensitive to the
397 sowing date and weather conditions during growth. However, their impact on the yield of
398 cereals grown after them is often much weaker. The results obtained confirm previous
399 studies which suggest that oilseed radish grown in stubble catch crops and used for green
400 manure makes a significant improvement in the yield and grain quality of cereals [18 21].

401 4.3 Effectiveness of spring wheat fertilization with nitrogen

402 The rainfall deficiencies that occurred during the present study had a very strong impact on
403 the effectiveness of nitrogen fertilization and on the values of individual yield structure
404 elements. The least favorable weather conditions that prevailed in 2008 at the stages of
405 shooting, earing and flowering resulted in very weak spike formation. The maximal grain
406 yield of spring wheat, amounting to only 2.4 Mg·ha⁻¹ under those conditions, could be
407 obtained using 41-51 kg N·ha⁻¹. Applying nitrogen in such conditions was unprofitable less
408 profitable. In 2007, when the water supply was very favourable throughout the growing
409 period, the yield it was possible to obtained was almost two times higher and the AORN was
410 3.5 times higher. Those results confirm the well-known importance of nitrogen fertilization in
411 yield formation, particularly under conditions where there is a good water supply [5, 21 1,
412 24]. The obtained results confirm the necessity of flexible nitrogen fertilization. The rate of
413 nitrogen applied pre-plant should not exceed 40-50 kg·ha⁻¹ particularly in lighter soils with
414 poorer water retention. Such a rate is highly effective in respect of productivity, irrespective
415 of the weather conditions during growth. The effectiveness of higher rates is determined by a
416 good supply of water throughout the development period of spring wheat. The study by
417 Boaretto et al., [22 17] indicates that the main part of nitrogen fertilization should be applied
418 during the period of tillering. This ensures the maximal uptake of nitrogen by plants and
419 minimal losses of this element from the soil. A negative aspect of top-dressing with nitrogen
420 is the risk of its poor effectiveness under conditions of rainfall deficiency [3, 23 4, 25]. Since
421 the total precipitation and its distribution while carrying out the present study was usually
422 unfavourable, the effectiveness of nitrogen fertilization in the present study was very low and
423 was also different in individual years. Under those conditions, increasing the nitrogen rate
424 from 80 to 120 kg·ha⁻¹ did not result in an increase in the grain yield of spring wheat or even
425 led to its decreasing. In a study conducted under more favourable soil and weather
426 conditions [1 2], the optimal nitrogen rate for spring wheat was 120 kg·ha⁻¹. In the present
427 study, even in the year with a good water supply, no improvement of spring yielding wheat
428 yield was observed as a result of increasing the nitrogen rate from 80 to 120 kg·ha⁻¹. This
429 probably resulted from conducting the study on less favourable soil conditions.

430 The large differences in the economic effectiveness in the years of the study, which resulted
431 from extremely different supplies of rain water to plants, are typical for light soils. Under such
432 conditions, a growth in yield that can compensate for the incurred costs of fertilizers is
433 possible only in years with an optimal rainfall distribution or by applying irrigation [5-1].

434 5. CONCLUSION

435 The optimal rate of nitrogen in spring wheat cultivation production depended mainly on the
436 total precipitation that prevailed during its growth. The MERN for spring wheat at the current
437 price relation ratio of nitrogen to wheat (5.22:1) was lower than the AORN by 24.1-35.2% in
438 the year with a favourable rainfall distribution. In the extremely dry year, N fertilization of in
439 spring wheat grown after field pea catch crop was economically unjustified and in the control
440 (without catch crops) it was poorly hardly profitable.

441 Field pea and oilseed radish grown as a catch crop and plowed in for green manure resulted
442 in a significant increase in the grain yield of spring wheat. The positive effect of catch crops
443 decreased along with an increase in the nitrogen rate. This effect was very strong in spring
444 wheat unfertilized with nitrogen or after the application of 40 kg N·ha⁻¹, and significant after
445 the application of 80 kg N·ha⁻¹, whereas it did not occur under conditions of fertilization with
446 higher rates of nitrogen.

447 COMPETING INTERESTS

448 Author have declared that no competing interests exist.

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