

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

Edward Wilczewski

University of Technology and Life Sciences - UTP, 85-225 Bydgoszcz, Poland.

## ABSTRACT

**Aims:** The main objective was to determine the optimal rates of nitrogen fertilization on spring wheat grown after stubble catch crops 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<sup>-1</sup>]: 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<sup>-1</sup> in the year with a very good supply of rain water and 41-42 kg N·ha<sup>-1</sup>, 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<sup>-1</sup> 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<sup>-1</sup>.

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

## 1. INTRODUCTION

Nitrogen fertilization is a well recognized factor that determines both grain yield and its quality [1, 2, 3, 4]. A good supply of nitrogen to wheat determines the number of shoots formed, the length of spikes and grain filling [5]. However, owing to the increasing prices of the energy needed for the production of nitrogen fertilizers, their cost is increasing [6]. Moreover, a significant increase in yield often does not result in an improvement in crop

profitability. Therefore, the nitrogen application rate must be strictly adapted to the soil conditions and the availability of water for plants. It is also essential to determine the most profitable rate, which depending on the weather conditions may be 30%, while under conditions of an extreme rainfall deficit more than 90% less than the rate that would make it possible to obtain the maximum grain yield. To determine the rate which is economically optimal, it is necessary to know the environmental conditions and the current relationship between fertilization costs and the value of wheat grain.

The importance of the accurate determination of the nitrogen rate is particularly essential in wheat grown in light soils, where agronomic and economic effectiveness are more dependent on the availability of water in soil, which allows it to up the applied elements and to utilize them to produce a higher grain yield [2]. The most economical rate of nitrogen (MERN) may also be dependent on the availability of elements in the soil that are derived from the mineralization of plant residues left in the soil after the harvest of the previous crop of catch crops that are plowed in as green manure. In the study by Shah et al. [7], the agronomic effectiveness and nitrogen use efficiency were the highest when the organic to mineral nitrogen ratio in the fertilizers applied was 25:75.

The biomass of plants grown as a stubble catch crop is a valued organic fertilizer, which allows for the improvement of the biological properties of soil [8, 9] and an increase in the grain yield of cereals grown after them. This is of particular importance in the current system of agricultural production, which is characterized by a low proportion of legumes in the cropping system. Moreover, relatively low stocking rates results in a shortage of natural fertilizers.

The objective of the present research was to determine the influence of rainfall during the period from March to July on the optimal rates of the application of nitrogen fertilization for spring wheat grown after catch crops. Moreover, the influence of oilseed radish and field pea grown as catch crops on the spring wheat yield, depending on nitrogen rates, was also determined.

## 2. MATERIAL AND METHODS

### 2.1 Site and weather description

The effects of nitrogen fertilization and catch crops was evaluated on the basis of two factors, a field experiment 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. The split-plot experimental design with four replications was used.

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

Nitrogen fertilization was the first experimental factor. Fertilizers were applied before and during the spring wheat growing period: the control (without N fertilization); 40 kg of N (before sowing); 80 kg of N (40 kg before sowing and 40 kg at the BBCH 31-32 stage); 120

67 kg N (60 kg before sowing and 60 kg at the BBCH 31-32 stage); 160 kg N (60 kg before  
 68 sowing, 60 kg at the BBCH 31-32 stage and 40 kg at the BBCH 45-47 stage). The second  
 69 factor was the catch crops: field pea (*Pisum sativum* var. *arvense* L.); oilseed radish  
 70 (*Raphanus sativus* var. *oleiformis* L.) and the control without a catch crop. The area of the  
 71 plot was 30 m<sup>2</sup>.

72 **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              |

73 The field experiment was carried out on Alfisols that was formed of a sandy loam [10]. The  
 74 level of field water capacity at depths from 0 to 100 cm on this field range from 215 to 270  
 75 mm [11].

76 The soil was rich in available phosphorus and potassium and had an average magnesium  
 77 content. The concentration of organic carbon (C<sub>org</sub>) and total nitrogen (N<sub>tot</sub>) was 7.17 and  
 78 0.67 g in a kg of dry soil, respectively. Soil pH in 1M KCl was 6.47.

## 79 2.2 Plant measurement and analysis

80 After the spring barley was harvested, the soil was plowed and cultivated using a cultivator  
 81 with a roller. Catch crops were sown between August 3-11 in 2005-2007. After 70-77 days of  
 82 growth, the plants were harvested and the yield from each plot was weighed.

83 Spring wheat (*Triticum aestivum* L.), 'Tybalt' cultivar, was sown between March 30 and April  
 84 11 in 2006-2008 in the stands where the biomass of the catch crop had been plowed under  
 85 in order to evaluate its previous crop value. Each year, before the spring wheat was sown,  
 86 mineral fertilization was applied. Phosphorus and potassium were broadcast at doses of  
 87 28.4 kg P·ha<sup>-1</sup> and 74.7 kg K·ha<sup>-1</sup> and mixed with the soil using cultivator with a roller  
 88 aggregate.

89 Prior to harvest on each plot, the number of spikes and the number of grains in spike were  
 90 determined. Spring wheat was harvested during the period from August 1 to 8. ~~The grain~~  
 91 ~~yield was determined after the plants had been harvested.~~ Grain samples were taken from  
 92 each plot in order to determine its moisture and the 1000 grain weight. Grain yields were  
 93 calculated to 15% moisture.

94 The weather conditions were analyzed based on measurements made at the local  
 95 observations and measurement unit located at the Experimental Station in Mochelek.

## 96 2.3 Statistical analysis

97 Analysis of variance was done using the results obtained in individual years. The  
 98 significance of differences was determined using Tukey's test at a 95% level of confidence.  
 99 The analysis of regression was made using the Statistica for Windows program StatSoft.

100 The effectiveness of nitrogen fertilization ( $N_{\text{Eff}}$ ) was calculated separately for each interval  
101 rate (0-40; 40-80; 80-120 and 120-160 kg N·ha<sup>-1</sup>). Calculations were done according to the  
102 equation:

103 
$$N_{\text{Eff}} = (\text{yield at NX} - \text{yield at NX-40})/40$$
 (Eq. 1)

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

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

110 
$$p = -b/2a$$
 (Eq. 2)

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

113 The MERN was calculated by setting the first derivative of the regression equation of spring  
114 wheat grain yield in individual years for the price relation: the cost of 1 kg of nitrogen in the  
115 fertilizer applied to the value of 1 kg of wheat grain [4]. The cost of 1kg of nitrogen was  
116 assumed to be the market value of this element (4.30 PLN<sup>1</sup> per 1 kg) plus the cost of its  
117 application (0.50 PLN). The price of 1 kg of wheat grain (0.92 PLN) was adopted following  
118 the Agricultural Advisory Centre (ODR) at Minikowo of 02.11.2012 [12]. The price relation  
119 was  $4.80:0.92 = 5.22$ .

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

121 
$$f'(x) = 2ax + b$$
 (Eq. 3)

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

124 For  $f'(x) = 5.22$

125 
$$2ax + b = 5.22$$

126 
$$x = (5.22 - b)/2a$$

### 127 3. RESULTS

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

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

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**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 <sup>*</sup> (d.f.=4) | II - Catch crops <sup>^</sup> (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***                  |

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<sup>\*</sup> - rates of N [kg ha<sup>-1</sup>]: 0, 40, 80, 120 and 160;

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

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

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### 3.1 Yield of plants grown as stubble catch crop

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The yield of field pea and oilseed radish in the presented study was at an average level (Table 3). The highest yields of plant dry matter were obtained in 2006 and 2007 and the lowest in 2005. 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 mean post-harvest residue yield of field pea from 2005-2007 was significantly lower than that of oilseed radish.

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**Table 3. Dry matter yield of catch crops plowed in the autumn [Mg·ha<sup>-1</sup>]**

| Part of plant           | Plant species | Year                |        |        | Means for 2005-2007 |
|-------------------------|---------------|---------------------|--------|--------|---------------------|
|                         |               | 2005                | 2006   | 2007   |                     |
| Aboveground plant parts | FP*           | 1.07 a <sup>#</sup> | 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              |

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\*FP – field pea, OR – oilseed radish

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<sup>#</sup> – means marked with different letters in columns differ significantly at  $\alpha = 0.05$

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### 3.2 Spring wheat yield components

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

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166 **Table 4. The number of spring wheat spikes per m<sup>2</sup>**

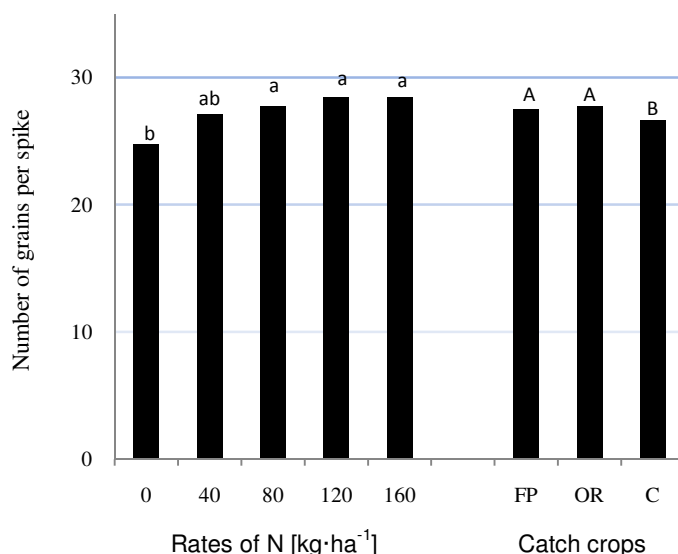
| Factors                                          |     | Year               |       |        |            |
|--------------------------------------------------|-----|--------------------|-------|--------|------------|
|                                                  |     | 2006               | 2007  | 2008   | 2006– 2008 |
| Nitrogen fertilization<br>[kg·ha <sup>-1</sup> ] | 0   | 520 b <sup>#</sup> | 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      |

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

168 <sup>#</sup> – means marked with different letters in columns differ significantly at  $\alpha = 0.05$

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

172 Fertilization with nitrogen had a significant effect on the number of grains in the spring  
173 wheat spikes (Fig. 1). This was the highest after the application of 80, 120 or 160 kg N·ha<sup>-1</sup>  
174 and significantly lower in wheat not fertilized with this element.

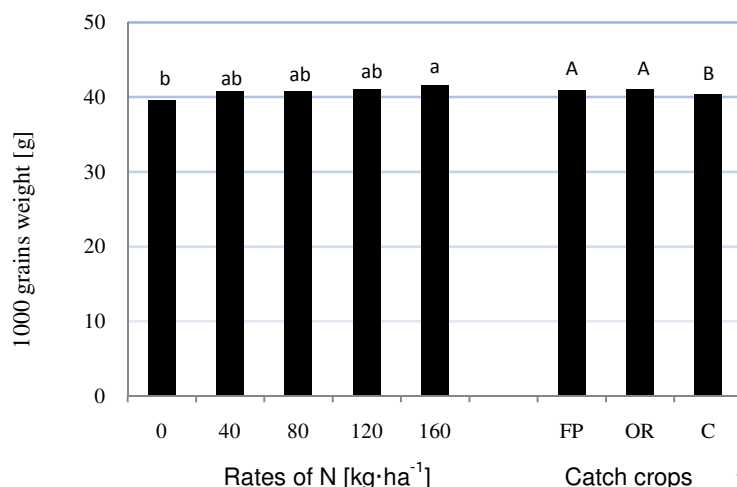


176 **Fig. 1. The number of grains per spike of spring wheat as affected by N-fertilization**  
177 **and catch crops plowed as a green manure in the autumn of previous year – means**  
178 **for 2006–2008**

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

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

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



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

FP – field pea, OR – oilseed radish, C – control (means marked with the same small or the same 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<sup>-1</sup>, after which a significantly higher weight of grain was harvested than after the application of 40 kg N·ha<sup>-1</sup>. The lowest wheat yield was obtained on treatments where nitrogen was not applied. Increasing the nitrogen rate to a level of 80 kg·ha<sup>-1</sup> 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<sup>-1</sup> gave the same yield as the control after the application of 80 kg N·ha<sup>-1</sup>. Increasing nitrogen fertilization from 80 to 120 kg·ha<sup>-1</sup> 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·ha<sup>-1</sup>], depending on nitrogen fertilization and biomass of catch crops plowed as a green manure – means for 2006–2008**

| Nitrogen fertilization<br>[kg·ha <sup>-1</sup> ] | Catch crop           |          |         | Mean    |
|--------------------------------------------------|----------------------|----------|---------|---------|
|                                                  | FP*                  | OR       | C       |         |
| 0                                                | 2.41 cA <sup>#</sup> | 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)

<sup>#</sup> – 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<sup>-1</sup>, the increase in yield amounted to 7.8 and 10.0%, respectively. Wheat fertilized with nitrogen at a rate of 80 kg·ha<sup>-1</sup> also had significantly increased grain yield under the influence of catch crops. After the application of 120 and 160 kg N·ha<sup>-1</sup> 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<sup>-1</sup> after catch crops and 174 kg·ha<sup>-1</sup> in control treatment (Table 6). In 2008 it was only 41-42 kg·ha<sup>-1</sup> and 51 kg·ha<sup>-1</sup> respectively.

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

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

<sup>#</sup> - regression equation calculated based on grain yields from plots expressed as kg per ha

<sup>&</sup> 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

The analysis of fertilization profitability determined based on the regression equations and relations of nitrogen prices to wheat grain value showed a poor economic effectiveness of this factor (Table 6). At the current price relation of nitrogen to wheat (5.22:1), the MERN for spring wheat were lower than the AORN by 24.1-35.2% in the year with a good or moderately favourable rainfall distribution. In the extremely dry year already nitrogen rates higher than 12 kg·ha<sup>-1</sup> in control treatment were unprofitable. The fertilization of spring wheat grown after field pea catch crop in this year was economically unjustified.

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

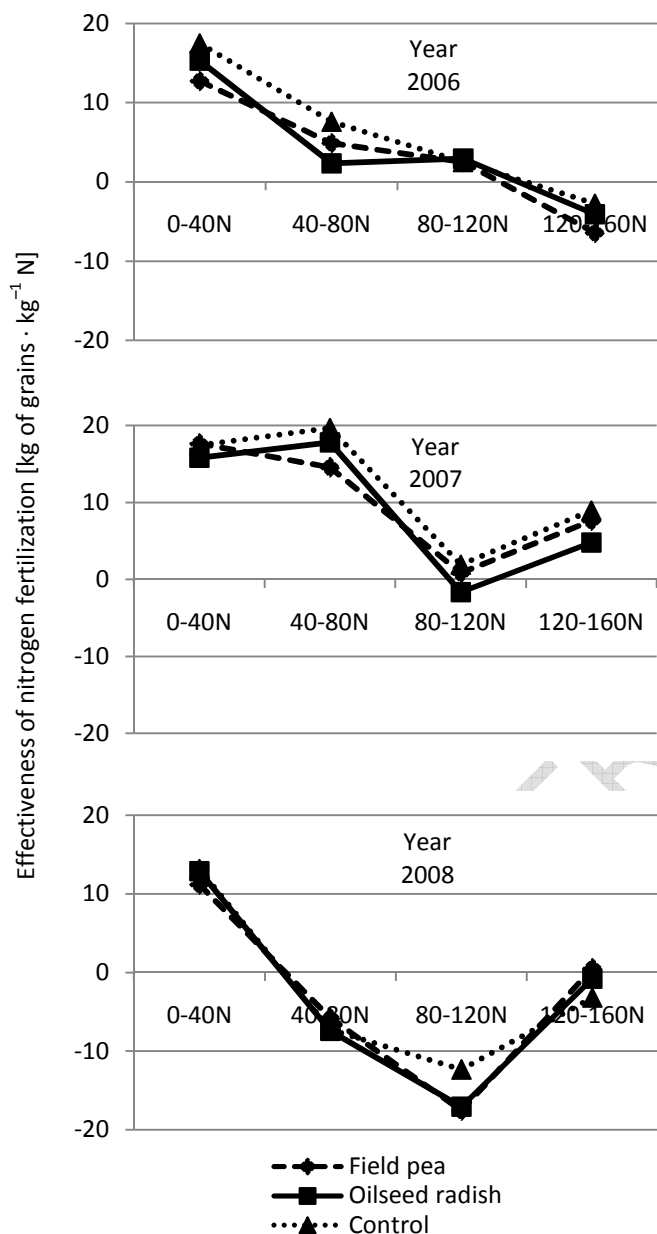


**Fig. 3. Effectiveness of nitrogen fertilization ( $N_{\text{Eff}}$ ) of spring wheat grown after catch crops (field pea, oilseed radish) or without them (control), measured separately in particular rate intervals (kg of grain yield increase  $\cdot$  kg<sup>-1</sup> N rate increase)**

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).

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

| Yield components                   | Yield of grain in years |       |       |
|------------------------------------|-------------------------|-------|-------|
|                                    | 2006                    | 2007  | 2008  |
| Number of spike per m <sup>2</sup> | 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  |

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

## 258 4. DISCUSSION

### 259 4.1 Yield of plants grown as stubble catch crop

260 The above-ground dry matter yield of plants grown as a stubble catch crop depends mainly  
 261 on the supply of water and fertilizer elements. Under conditions of a favourable distribution of  
 262 precipitation, good soil fertility and nitrogen fertilization applied at a rate of 60-90 kg·ha<sup>-1</sup> it  
 263 ranges from 3 to 6 Mg·ha<sup>-1</sup> [9, 13, 14]. In general, plants of the family Fabaceae give lower  
 264 yields than oilseed radish. In the present study, field pea formed a significantly higher yield  
 265 of above-ground dry matter and total biomass than oilseed radish. The reason for the poor  
 266 yield of radish could be the relatively low soil abundance of nitrogen. This element is taken  
 267 up by radish in very large amounts, often exceeding 160 kg·ha<sup>-1</sup> [14]. When grown in soil that  
 268 is not rich in nitrogen and under conditions where there is a lack of fertilizing catch crops  
 269 containing this element, radish cannot form as large a yield as pea.

### 270 4.2 Grain yield of spring wheat and its structure

271 The average grain yield of spring wheat from the 3 years of the study was very low (2.85  
 272 Mg·ha<sup>-1</sup>). This was a result of both the unfavourable weather conditions that prevailed in 2  
 273 out of the 3 years of the study and from the sandy-loamy soil that was not very fertile on  
 274 which the wheat was grown.

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

280 The results of research presented in the literature concerning the impact of catch crops on  
 281 the yield of succeeding crops are ambiguous. Many studies have shown negative effects  
 282 [15, 16, 17] or no impact of catch crops plowed into the biomass on the yield of cereals [18].  
 283 In order to obtain the desired effect, it is necessary to select the appropriate plant species for  
 284 growing as a stubble catch crop.

285 The results of current research indicate that legumes grown as catch crops and plowed in  
 286 autumn have a favorable effect on spring cereals. Their biomass in soil undergoes fast  
 287 mineralization and the nutrients that are released are taken up by cereals growing under  
 288 these conditions. The positive, successive impact of these catch crops is possible if they  
 289 produce a high yield of biomass. This is dependent mainly on the moisture conditions that  
 290 occur during July and August [19, 20]. Non-legume plants are less sensitive to the sowing  
 291 date and weather conditions during growth. However, their impact on the yield of cereals  
 292 grown after them is often much weaker. The results obtained confirm previous studies which

293 suggest that oilseed radish grown in stubble catch crops and used for green manure makes  
294 a significant improvement in the yield and grain quality of cereals [18].

#### 295 4.3 Effectiveness of spring wheat fertilization with nitrogen

296 The rainfall deficiencies that occurred during the present study had a very strong impact on  
297 the effectiveness of nitrogen fertilization and on the values of individual yield structure  
298 elements. The least favorable weather conditions that prevailed in 2008 at the stages of  
299 shooting, earing and flowering resulted in very weak spike formation. The maximal grain  
300 yield of spring wheat, amounting to only  $2.4 \text{ Mg} \cdot \text{ha}^{-1}$  under those conditions, could be  
301 obtained using  $41\text{-}51 \text{ kg N} \cdot \text{ha}^{-1}$ . Applying nitrogen in such conditions was unprofitable. In  
302 2007, when the water supply was very favourable throughout the growing period, the yield it  
303 ~~was possible to~~ obtained was almost two times higher and the AORN was 3.5 times higher.  
304 Those results confirm the well-known importance of nitrogen fertilization in yield formation,  
305 particularly under conditions where there is a good water supply [5, 21]. The obtained results  
306 confirm the necessity of flexible nitrogen fertilization. The rate of nitrogen applied pre-plant  
307 should not exceed  $40\text{-}50 \text{ kg} \cdot \text{ha}^{-1}$  particularly in lighter soils with poorer water retention. Such  
308 a rate is highly effective in respect of productivity, irrespective of the weather conditions  
309 during growth. The effectiveness of higher rates is determined by a good supply of water  
310 throughout the development period of spring wheat. The study by Boaretto et al., [22]  
311 indicates that the main part of nitrogen fertilization should be applied during the period of  
312 tillering. This ensures the maximal uptake of nitrogen by plants and minimal losses of this  
313 element from the soil. A negative aspect of top-dressing with nitrogen is the risk of its poor  
314 effectiveness under conditions of rainfall deficiency [3, 23]. Since the total precipitation and  
315 its distribution while carrying out the present study was usually unfavourable, the  
316 effectiveness of nitrogen fertilization in the present study was very low and was also different  
317 in individual years. Under those conditions, increasing the nitrogen rate from 80 to  $120 \text{ kg} \cdot \text{ha}^{-1}$   
318 did not result in an increase in the grain yield of spring wheat or even led to its  
319 decreasing. In a study conducted under more favourable soil and weather conditions [1], the  
320 optimal nitrogen rate for spring wheat was  $120 \text{ kg} \cdot \text{ha}^{-1}$ . In the present study, even in the year  
321 with a good water supply, no improvement of ~~spring yielding~~ was observed as a result of  
322 increasing the nitrogen rate from 80 to  $120 \text{ kg} \cdot \text{ha}^{-1}$ . This probably resulted from conducting  
323 the study on less favourable soil conditions.

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

#### 328 5. CONCLUSION

329 The optimal rate of nitrogen in spring wheat ~~cultivation~~ depended mainly on the total  
330 precipitation that prevailed during its growth. The MERN for spring wheat at the current price  
331 ~~relation~~ of nitrogen to wheat (5.22:1) was lower than the AORN by 24.1-35.2% in the year  
332 with a favourable rainfall distribution. In the extremely dry year, fertilization of spring wheat  
333 grown after field pea catch crop was economically unjustified and in the control was poorly  
334 profitable.

335 Field pea and oilseed radish grown for green manure resulted in a significant increase in the  
336 grain yield of spring wheat. The positive effect of catch crops decreased along with an  
337 increase in the nitrogen rate. This effect was very strong in spring wheat unfertilized with  
338 nitrogen or after the application of  $40 \text{ kg N} \cdot \text{ha}^{-1}$ , and significant after the application of  $80 \text{ kg}$   
339  $\text{N} \cdot \text{ha}^{-1}$ , whereas it did not occur under conditions of fertilization with higher rates of nitrogen.

340 **COMPETING INTERESTS**

341 Author have declared that no competing interests exist.

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