

Winter wheat: results of long-term fertilizer experiment in Prague-Ruzyně over the last 60 years

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ABSTRACT

The study evaluates how sixty years of application of organic manures and mineral fertilizers (ten fertilizer treatments altogether), planting of cultivars with different length of stem (long- and short-stem cultivars) and preceding crops (potatoes and alfalfa) affected grain and straw yields of winter wheat in the Prague-Ruzyně long-term fertilizer experiment (RFE). Fertilizer treatments did not affect grain yield during the first ten years of the RFE experiment (1959–1968), but influenced straw yield. The grain yield ranged from 5.08 (control) to 5.43 (farmyard manure) t/ha, straw yield varied from 6.02 t/ha (control) to 8.31 t/ha (poultry slurry (PS) + $N_4P_2K_2$). In the last ten years of the RFE experiment (2004–2013) grain yield ranged from 7.01 t/ha (control) to 8.88 t/ha (stale + $N_4P_2K_2$), while straw yield decreased and varied from 3.12 (control) to 6.21 t/ha (PS + $N_4P_2K_2$). Comparing the potatoes and alfalfa as preceding crops, the grain yield was 0.5 t/ha higher after alfalfa, but straw yield was 1.3 t/ha higher after potatoes. Introduction of short-stem cultivars increased average grain yield about 2 t/ha and decreased average straw yield about 0.85 t/ha.

Keywords: cereals; *Triticum aestivum*; fertilization; dry stalks; crop rotation

Among all cereals, wheat holds a unique place in Europe. It is by far the most popular cereal crop in the European Union, covering almost half of the EU arable land. It is also the fourth, most produced crop worldwide (FAO 2014). According to the International Grains Council, the estimated production was 713 million tons in 2014 (IGC 2015).

Wheat popularity started approximately during the 1950's. Wheat is capable to provide high yields under a wide range of conditions and, in comparison with other cereals, wheat gluten proteins are able to form a visco-elastic dough, an important property to bake leavened bread (Arendt and Zannini 2013).

Due to new knowledge and experiences from the fields such as plant protection and nutrition, crop technology, genetics and breeding and due to social and economic factors, the wheat yields rose by 250% over the last 40 to 50 years (Calderini and Slafer 1998). According to Dixon (2007), wheat

productivity rose from 1.49 t/ha in 1970 to 3 t/ha in 2010. Several factors played an important role in reaching such achievement. First factor was the fertilization. According to Jaggard et al. (2010) the dose of nitrogen applied to agriculture land increased from 50 to 180 kg/ha between 1950 and 1980 globally. The positive effect of higher rates of nitrogen on wheat yield and quality is supported by the results of many experiments (López-Bellido et al. 1998, Blandino and Reyneri 2009) and became a common knowledge nowadays. Second factor was the genetics. The important contribution of genetics consists in the development of short-stem cultivars, which are resistant to lodging and reaching anthesis earlier than old cultivars (Austin 1999). According to Hejman and Kunzová (2010), the yield differences between long and short-stem cultivars can be up to 0.8 t/ha. Also, recent progress allows providing cultivars with attributes, which are customized to particular

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soil-climate conditions, thus producing higher yields and better quality.

Yet, the application of high doses of mineral fertilizers can negatively affect the environment, causing contamination of ground water with nitrates and eutrophication of surface waters. Also, today's agriculture and fertilizer production depends heavily on the consumption of non-renewable fossil fuels, affecting the environment by releasing carbon dioxide and other combustion gases (Refsgaard et al. 1998). According to Swaminathan and Sukalac (2004) the fertilizer industry uses about 1.2% of the world energy consumption and is responsible for about the same share of global greenhouse gases emissions. More than 90% of this energy is used in the production of ammonia.

It is expected that human population will expand to 9 or even 11 million in 2050 (Cohen 2003). Also, the weather will fluctuate far more from the standard conditions. Extreme situations, such as drought and floods, will appear more frequently (Olesen et al. 2011). Under extreme weather, even high doses of mineral and organic manures applied to wheat cannot secure and provide satisfying yields and quality (Hliseníkovský et al. 2015). These facts create a huge pressure on farmers and food industry to provide sustainable production and on scientists to offer significant knowledge to support their endeavour. Long-term field experiments can provide significant information about the effects of different fertilizers, crop rotations and climate conditions on yield and quality of arable crops. In this paper, the effect of different fertilizer treatments, preceding crops and cultivars on winter

wheat grain and straw yields in the Prague-Ruzyně fertilizer experiment (RFE) over the last sixty years was evaluated.

MATERIAL AND METHODS

Site description. The RFE is located on the western edge of Prague (50°05'15"N; 14°17'28"E) and was established in 1954. The mean temperature during the experiment was 8.5°C, mean precipitation was 498.3 mm (1954–2014, Ruzyně weather station). The average temperature and precipitation annual growth were 0.04°C and 1.2 mm, respectively, from the establishment of the experiment. The altitude is 338 m a.s.l. According to the World Reference Base for Soil Resources (2015), the soil type was classified as Luvisol (LV). The ground water level is 20 m below the field surface. The soil pH (H₂O) was 6.5 in the top 20 cm before the establishment of the experiment.

Experimental design. The RFE consists of five fields (Figure 1). Each field consists of 96 individual plots, in which 24 fertilizer treatments are replicated four times and arranged in a completely randomized block design. The size of the individual plot is 12 m × 12 m, but only 5 m × 5 m central area was used for experimental purposes. In this study, field number II was analysed. The crop rotation of the field number II consisted of: cereals (45%), root crops (33%) and alfalfa (22%). For the purposes of this paper, 10 out of 24 fertilizer treatments were analysed: control (unfertilized); N₁P₁K₁; N₂P₁K₁; N₄P₂K₂; farmyard manure (FYM); farmyard ma-



Figure 1. An aerial photograph of Prague-Ruzyně fertilizer experiment, showing experimental strips I–V

Table 1. Field number II crop rotation and doses of applied mineral fertilizers (kg/ha) and organic manure (t/ha)

	Crops in the crop rotation								
	alfalfa	alfalfa	winter wheat	sugar beet	spring barley	potatoes	winter wheat	sugar beet	spring barley
Mineral fertilizer (kg/ha)									
N ₁	–	–	40	80	30	50	40	80	30
N ₂	–	–	60	120	50	90	80	120	50
N ₄	–	–	75	200	70	110	95	200	70
P ₁	50	70	48	64	48	50	48	64	48
P ₂	70	100	60	80	60	70	60	80	60
K ₁	160	220	96	150	80	144	96	150	80
K ₂	220	300	120	200	100	224	120	200	100
Organic manure (t/ha)									
Farmyard manure	–	–	–	21	–	15	–	21	–
Dung water	–	–	–	40	–	30	–	40	–
Pig slurry	–	–	–	60	–	43	–	60	–

nure + N₄P₂K₂ (FYM + N₄P₂K₂); dung water (DW); dung water + N₄P₂K₂ (DW + N₄P₂K₂); poultry slurry (PS) and poultry slurry + N₄P₂K₂ (PS + N₄P₂K₂). The detailed description of fertilizer treatments (with doses of applied nutrients) and complete crop rotation is provided in Table 1. The amount of N, P and K applied directly to winter wheat depended on the preceding crop and was lower after alfalfa and higher after potatoes. Alfalfa was the preceding crop for winter wheat in 1959, 1968, 1977, 1986, 1995, 2004 and 2013, potatoes served as the preceding crop in 1963, 1972, 1981, 1990, 1999 and 2008. Crop management practices (tillage, deep ploughing, seed bed preparation, depth of seeding) were constant during the experiment. Pesticides were used only if necessary, growth regulators have never been used. Nitrogen was applied as calcium ammonium nitrate (27% N), phosphorus as super phosphate (8.3% P) and potassium as potassium chloride (49.8% K). Three organic manures were also evaluated in this paper: farmyard manure; dung water and poultry slurry. All organic manures were applied in the autumn before planting of root crops. The average annual doses of nutrients applied in manure treatments and manure treatments combined with mineral fertilizers are shown in Table 2.

Nine winter wheat cultivars with different length of the stem were used during the experiment.

The long-stem cultivars were Pyšelka (1959), Hadmerslebener (1963), Mironovská 808 (1968 and 1972), Jubilar (1977 and 1981) and Sandra (1986); the short-stem cultivars were Zdar (1990), Samanta (1995 and 1999), Alka (2004), Barroko (2008) and Mulan (2013).

Data analysis. The RFE grain and straw yields were analysed by Statistica 12.0 (www.statsoft.com). The effect of fertilizer treatment, preceding crop and length of straw was analysed by one-way analysis of variance (ANOVA). In the case of significant ANOVA results the Tukey's *HSD* post hoc test was applied to determine differences among individual factors. Linear regression was used to analyse temporal trends in the grain and straw yields of individual treatments and for the

Table 2. The average annual doses of nutrients (N, P, K) (kg/ha) applied in selected fertilizer treatments

Fertilizer treatment	N	P	K
Farmyard manure (FYM)	31.6	8.7	37.3
FYM + N ₄ P ₂ K ₂	122.6	62.6	177.6
Dung water (DW)	30.6	1.2	53.8
DW + N ₄ P ₂ K ₂	121.6	61.6	176.6
Pig slurry (PS)	130	38	43.4
PS + N ₄ P ₂ K ₂	221	161	276

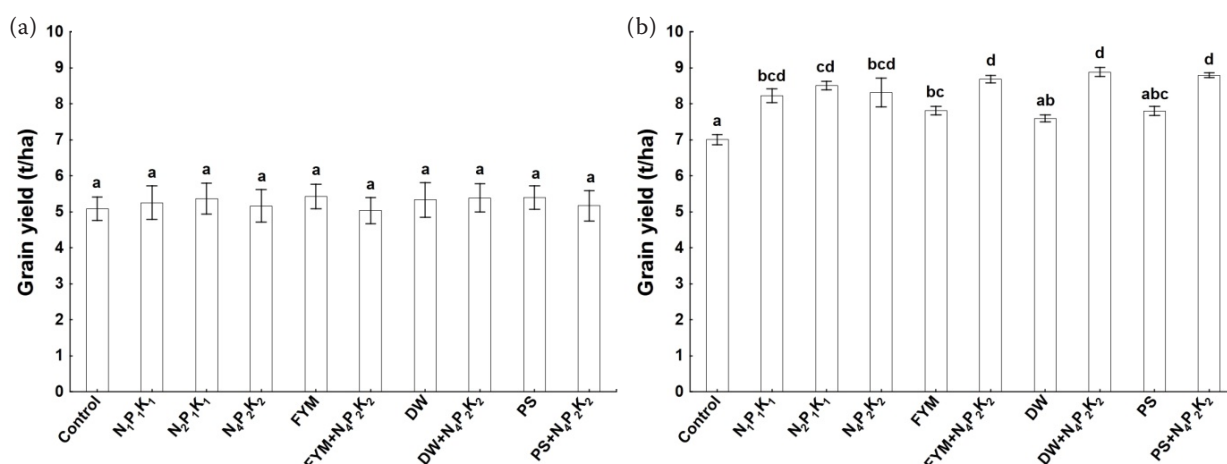


Figure 2. The average grain yield (t/ha) as affected by fertilizer treatment during the (a) first ten years (1959, 1963, 1968) and (b) last ten years (2004, 2008, 2013) of the Prague-Ruzyně fertilizer experiment; FYM – farmyard manure; DW – dung water; PS – pig slurry

calculation of annual yield growth (AYG) and annual straw yield decrease (ASD).

RESULTS

No significant effect of fertilizer treatment on grain yield was recorded during the first ten years (1959, 1963, 1968) of the RFE ($df = 9$; $F = 0.122$; $P = 0.999$). The average grain yield ranged from 5.08 t/ha (control) to 5.43 t/ha (FYM) (Figure 2a). On the other hand, the fertilizer treatment significantly influenced straw yield in the first decade of the RFE ($df = 9$; $F = 3.63$; $P < 0.001$), which varied from 6.02 t/ha (control) to 8.31 t/ha (PS + N₄P₂K₂) (Figure 3a).

In the last ten years of the RFE (2004, 2008, 2013), the differences between the fertilizer treatments increased significantly in the case of grain yield ($df = 9$; $F = 11.85$; $P < 0.0001$) and were significant in the case of straw yield ($df = 9$; $F = 9.76$; $P < 0.0001$), too. The grain yield increased, when compared with the RFE's first decade, and varied from 7.01 t/ha (control) to 8.88 t/ha (STA + N₄P₂K₂) (Figure 2b). Contrarily, the straw yield decreased, when compared with the same period, and varied from 3.12 (control) to 6.21 t/ha (PS + N₄P₂K₂) (Figure 3b).

Preceding crops considerably influenced the grain and straw yields (calculated over all fertilizer treatments and over the whole time of the experiment). The average grain yield following potatoes was 6.14 t/ha. After alfalfa, the av-

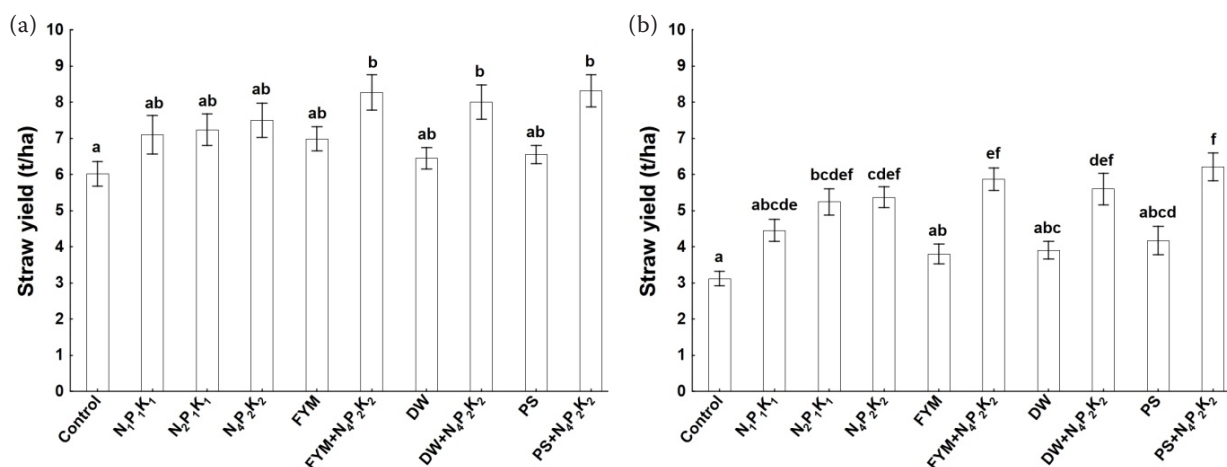


Figure 3. The average straw yield (t/ha) as affected by fertilizer treatment during the (a) first ten years (1959, 1963, 1968) and (b) last ten years (2004, 2008, 2013) of the Prague-Ruzyně fertilizer experiment; FYM – farmyard manure; DW – dung water; PS – pig slurry

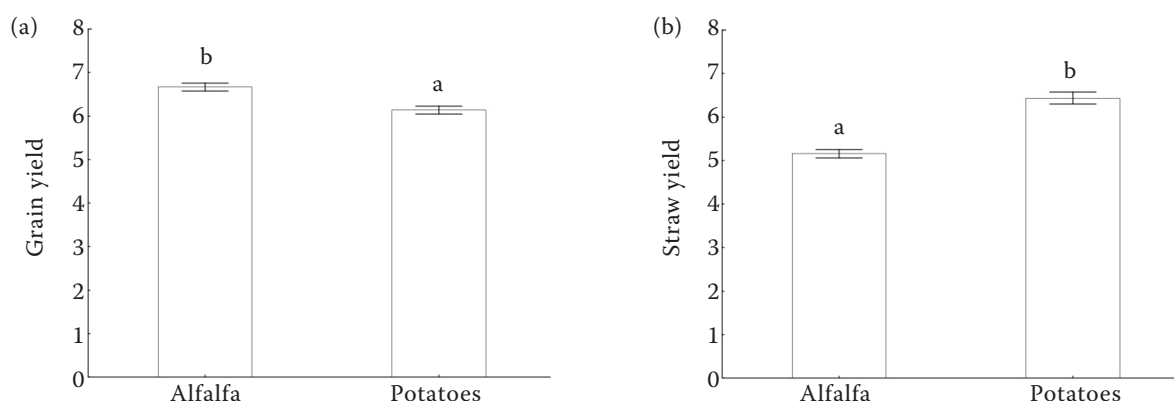


Figure 4. The average (a) grain yield (t/ha) and (b) straw yield (t/ha) as influenced by alfalfa and potatoes as preceding crops. The average values were calculated over all selected fertilizer treatments and over the whole time of the Prague-Ruzyně fertilizer experiment (1959–2013)

average grain yield increased to 6.67 t/ha ($df = 1$; $F = 16.2$; $P < 0.0001$) (Figure 4a). Preceding crop also significantly influenced the straw yield ($df = 1$; $F = 59.91$; $P < 0.001$) (Figure 4b). The average straw yield was 5.16 t/ha after alfalfa and 6.44 t/ha after potatoes.

Another factor, affecting the grain and straw yield considerably, was the cultivar's length of stem. The average grain yields of the long (1959–1986) and short (1990–2013) stem cultivars over the all fertilizer treatments were 5.49 t/ha and 7.52 t/ha, respectively ($df = 1$; $F = 414.5$; $P < 0.0001$) (Figure 5a). The average straw yields of the long and short-stem cultivars were 6.14 t/ha and 5.29 t/ha, respectively ($df = 1$; $F = 24.52$; $P < 0.0001$) (Figure 5b).

DISCUSSION

During the first ten years of the RFE (1959–1968) no significant differences in grain yield between selected fertilizer treatments were recorded (Figure 2a). This fact can be explained by soil conditions, the pre-experimental preparations and by crop rotation. According to Hejčman et al. (2012), luvisols are naturally highly fertile soils comparable to chernozems, and are capable to provide sufficient amount of nutrients, resulting in a sustainable production without any fertilizer inputs. This is supported by comparing our results with other long-term fertilizer experiments, in which the average grain yields in unfertilized control treat-

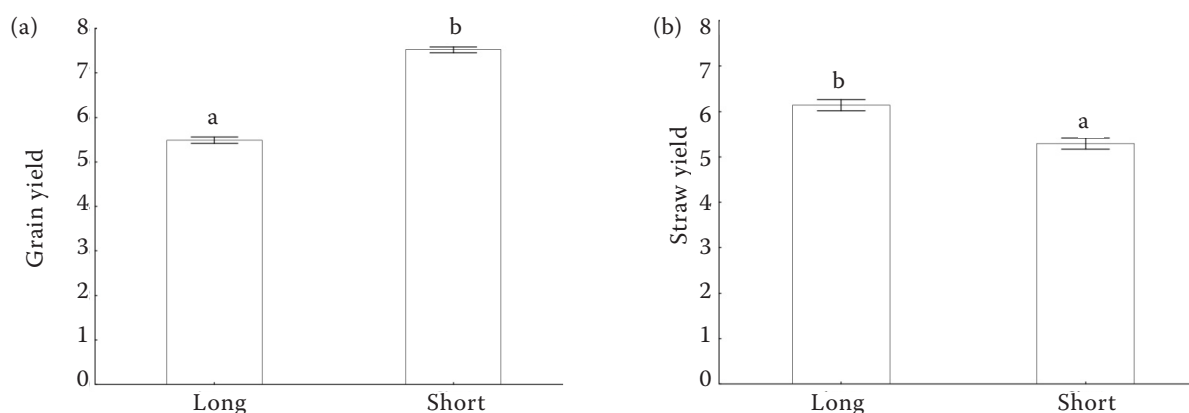


Figure 5. The average (a) grain yield and (b) straw yield (t/ha) as affected by stem's length of the wheat cultivar. The average values were calculated over all selected fertilizer treatments. The long-stem cultivars were planted from 1959 till 1986. The short-stem cultivars were planted from 1990–2013

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ments ranged from 0.8 to 2.7 t/ha (Hejzman et al. 2012). High grain yields in the first ten years of RFE are also a consequence of the pre-experimental preparations, including a unification of all experimental strips by planting alfalfa for two consecutive years. The alfalfa is a plant improving and enriching the soil nutrient reservoir. Our crop rotation included potatoes and alfalfa, crops positively affecting soil's condition. Finally, the old wheat cultivars were not so efficient as now a day's cultivars and their demand and ability to process added nutrients was lower in comparison with today's wheat cultivars.

The straw yield was significantly affected only by the treatments combining organic manures with mineral fertilizers (Figure 3a) during the first ten years of RFE (1959–1968). Those combinations encouraged vegetative growth of plants

more rapidly and thereby increased straw yields significantly when compared with control. Our records are in agreement with those of Hosseini et al. (2011).

During the second half of the 20th century the RFE's grain yield increased in all fertilizer treatments (Figures 6 and 7). The annual yield growth (AYG) ranged from 40.6 kg/ha and year (control) to 78.9 kg/ha and year (FYM + N₄P₂K₂), showing a positive effect of application of combinations of organic manure with mineral fertilizers.

During the last ten years of the RFE (2004–2013), a significant effect of fertilizer treatment on grain yield was recorded (Figure 2b). The highest yields were recorded in treatments combining organic manures and mineral fertilizers. If it is compared with the effect of application of mineral fertilizers only, which is a common practice nowadays,

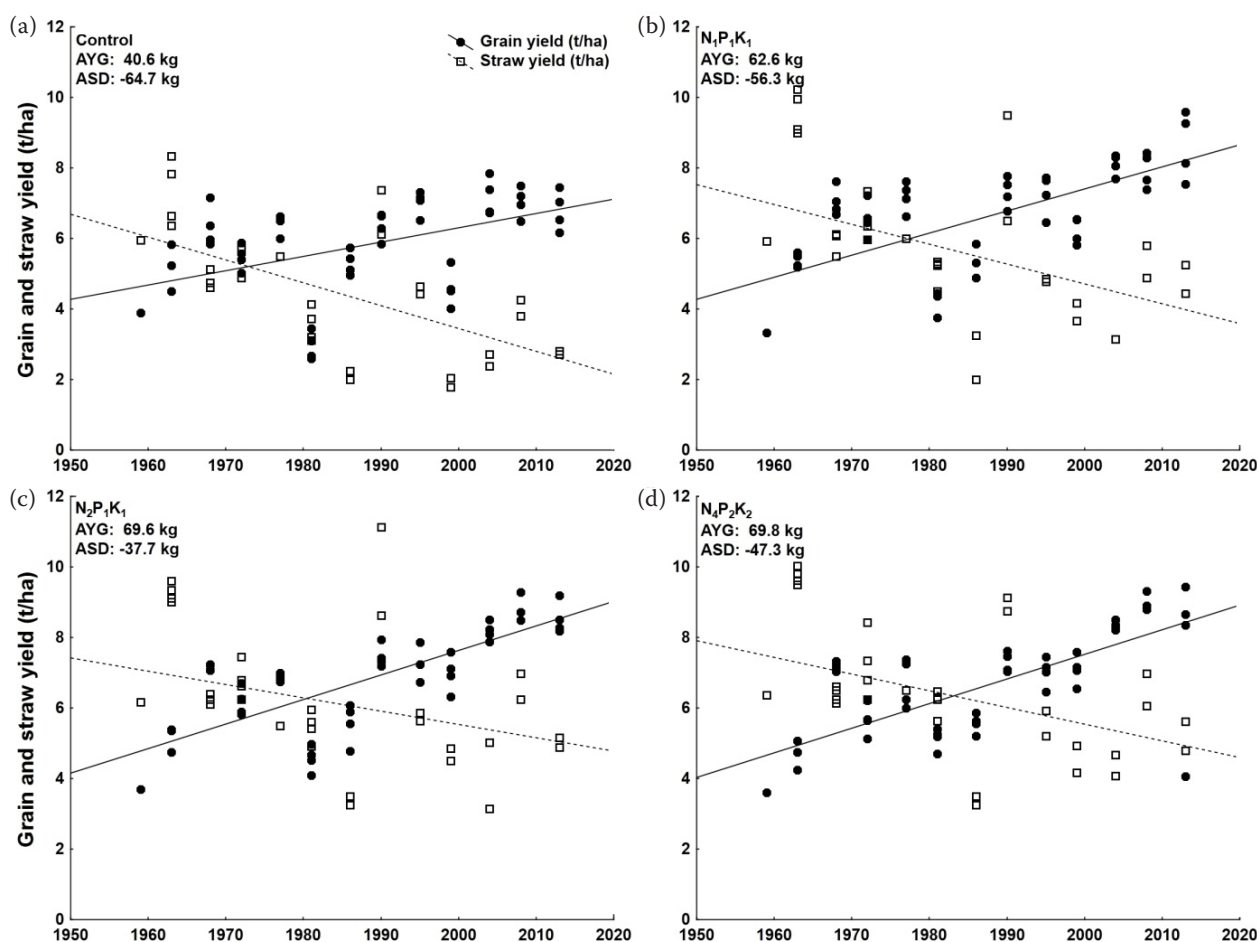


Figure 6. The winter wheat grain and straw yields and average yield growth (AYG) and average straw yield decrease (ASD) as affected by fertilizer treatment (a) control; (b) N₁P₁K₁; (c) N₂P₁K₁; (d) N₄P₂K₂) from 1959–2013. Black circles show grain yield (t/ha) from individual replicates, black squares shows straw yield (t/ha) from individual replicates

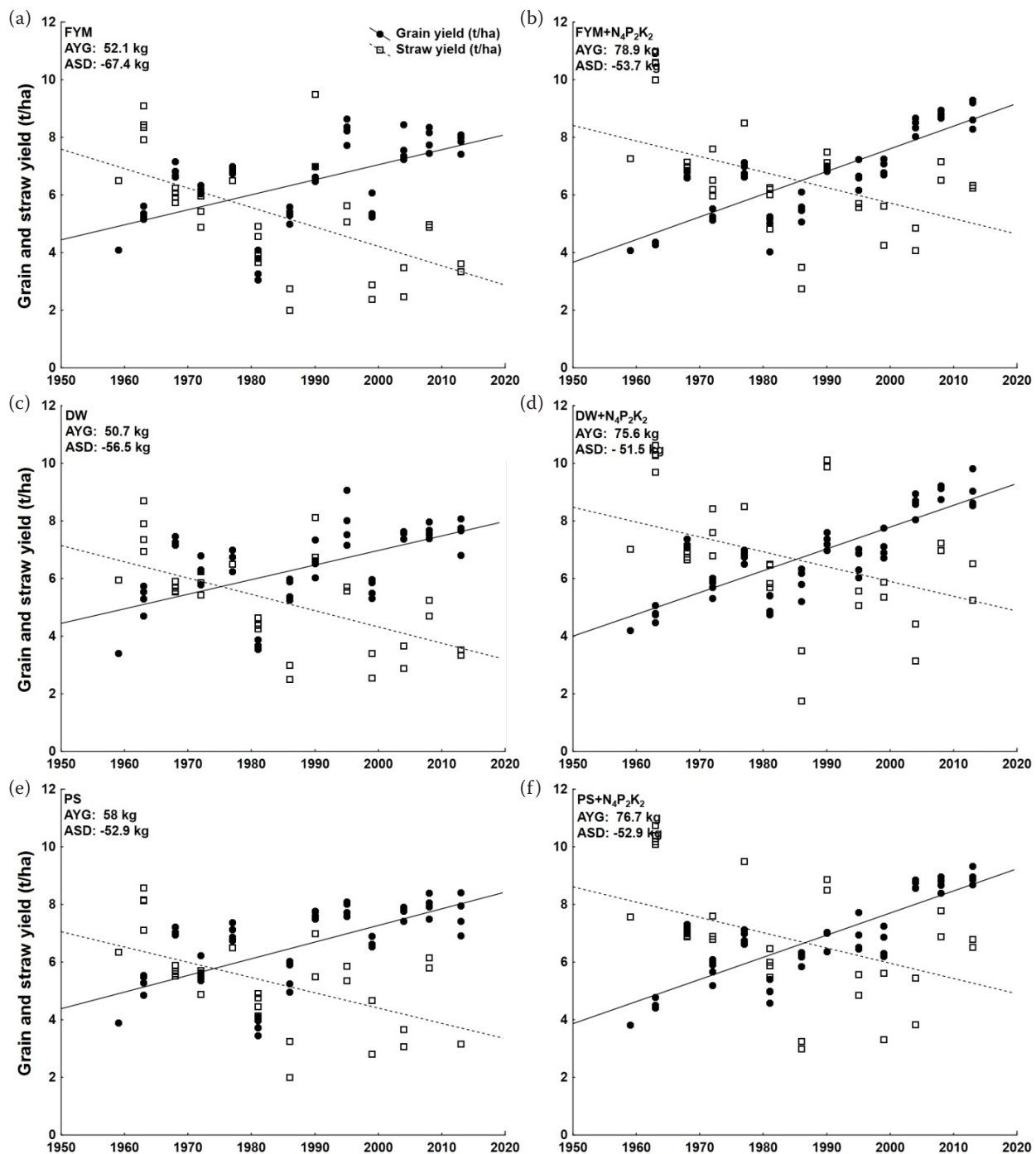


Figure 7. The wheat grain and straw yields and average yield growth (AYG) and average straw yield decrease (ASD) as affected by fertilizer treatment (a) farmyard manure (FYM); (b) FYM + $N_4P_2K_2$; (c) dung water (DW); (d) DW + $N_4P_2K_2$; (e) pig slurry (PS); (f) PS + $N_4P_2K_2$ from 1959–2013. Black circles show grain yield from individual replicates, black squares show straw yield from individual replicates

it was found that the application of high doses of nitrogen can be counter-productive. In our experiment, the application of the highest doses of nitrogen, phosphorus and potassium ($N_4P_2K_2$)

resulted in slightly lower yields when compared with lower rates of nutrients ($N_2P_1K_1$). This is in agreement with Ehlert et al. (2004), who found that in the variable rate N application, N fertilizer

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could be reduced by 8 kg without affecting wheat yield. Except of the mineral fertilizers, the introduction of short-straw cultivars also contributed to the yield increase significantly. In the present study, the difference between short- and long-stem cultivars was 37% on behalf of short-stem cultivars. According to Austin (1999), the greater yields of short-stem cultivars are consequence of their earlier anthesis and higher resistance to lodging. Higher yield fluctuation between fertilizer treatments in the last decade of the RFE was also recorded. From all of the fertilized treatments, the lowest yields were recorded in organic manure treatments. Surely the organic manure contains nutrients, but not so much as mineral fertilizers and manure releases them slowly. According to Pratt et al. (1973) 35, 10 and 5% of the total N in manure is available to crops during first, second and third year after application, respectively. Also, the mineralization of manure strongly depends on weather conditions. The ratio of farmyard manure mineralization decreases during dry seasons and increase during wet seasons, when the soil moisture is near the field capacity (Cassman and Munns 1980). Manures are known as soil improvers and in combination with mineral fertilizers can provide the best conditions for wheat to produce high grain and straw yields. The reason why significant differences between fertilizer treatments in the last decade of the RFE were recorded is that modern cultivars require higher nutrient incomes. According to Austin (1999), modern wheat cultivars require more nitrogen fertilizers, which influence the amount of chlorophyll in leaves (Blandino et al. 2009), root biomass formation (Rieger et al. 2008) and protein concentration (Kindred et al. 2008); if their greater yield potential shall be realized. On the other hand, our results show that even application of organic manures alone can provide sustainable production as the differences between organic manures and mineral fertilizers were minimal (Figure 2b). This is very useful information, especially for organic farmers.

The introduction of short-stem cultivars caused a decrease in straw yield (Figure 5b). The average straw yield decrease (ASD) varied from 67.4 (FYM) to 37.7 ($N_2P_1K_1$) kg/ha and year (Figures 6 and 7). Both, the grain and straw yields, were affected by preceding crops. The alfalfa had a better impact on grain yield (Figure 4a), while the potatoes positively affected the straw yield (Figure 4b). The alfalfa can serve as

a significant provider of nitrogen via biological N_2 fixation (Peoples et al. 1995) and supports the wheat with sufficient amount of nitrogen to produce high yields. With today's emphasis on environmentally sustainable agricultural development, the effects of the preceding crops are very useful not only for organic farmers, but also for conventional farmers as the correct crop rotation can reduce costs and environmental impacts.

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