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Effect of chemical weed control on crop yields in different crop rotations in a long-term field trial

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ABSTRACT

The study is based on data from a long-term field experiment of extent and duration seldom found in weed science. Yield losses from weed infestation of individual crops and crop rotations were studied in a field trial conducted since 1972 at two sites in the Czech Republic. The ongoing trial comprises multi-crop and simple crop rotations with 50 and 75% cereals, respectively. Three herbicide treatments were used: (1) untreated; (2) synthetic auxins (MCPA; 2,4-D; only in simple crop rotation) and (3) targeted herbicide combinations, including sulfonylureas, triazines, ureas, and synthetic auxins. Crop yields and weather data were recorded during the trial period and the effects of herbicide application on yield were determined for crop rotation. Yield losses in untreated controls increased in the following order: spring barley < winter wheat < pea < oilseed rape < potato. Because of the limited weed control spectrum, the use of synthetic auxins had lower yield effect than targeted herbicide combinations. Yields tended to increase over time in treated plots for almost all crops at the more productive Hněvčeves site, while stagnation or even decrease were observed in untreated plots. The mean treatment effect steadily increased as the experiment progressed, raising from 4.9% in 1972–1985 to 76.9% in 2006–2016. Dependent on individual crops and crop rotation, herbicide treatment ensured 13–50% higher crop yields than untreated plots. Treatment with targeted herbicide combinations reduced the negative impact of simple crop rotation on weed infestation and ensured sufficient crop yields.

1. Introduction

Weed infestation in crop production systems reduces both yield and quality (Hance and Holly, 1990) by competition between the crop and weeds for water, nutrients, light and carbon dioxide, and also by allelopathy (Monaco et al., 2002). Overall, weeds reduce major crop potential yields up to 34%; a greater reduction than from diseases and pests (Oerke, 2006). German studies also indicated that weeds cause the highest yield losses of all noxious organisms in conventional farming (Zwerger et al., 2004). However, crop yield loss varies greatly in different situations. Bridges (1992) compared crop losses caused by weeds in United States production systems with and without herbicides. Yield reductions were similar across different grain crops and the geographic locations in herbicide treated systems, while they varied substantially in the absence of herbicides. In temperate climates such as Northwest Europe and parts of North America, the loss is markedly lower because losses are minimised due to the common use of pesticides and good agricultural practice of the farmers. The overall loss potential is especially great in high productivity regions and in tropical and subtropical areas where weather conditions favour pest development (Oerke, 2006).

Yield losses also vary because crops have different competitive ability against weeds (van Heemst, 1985). Crop competitiveness is a genetic trait influenced by genotype, crop management, and environment (Asif et al., 2014). Barley (*Hordeum vulgare* L.) and rye (*Secale cereale* L.) are generally more competitive than wheat (*Triticum aestivum* L.) (Mason et al., 2007) while grain legumes such as pea (*Pisum sativum* L.) compete poorly with weeds in early growth stages (Corre-Hellou et al., 2011). Harker (2001) reported crop yield losses in the order of spring barley < canola (*Brassica* L. spp.) < pea in central Alberta in weedy plots compared with weed-free plots. Moreover, competitive ability and yield losses vary among cultivars and years due to both crop and weed species response to environmental conditions (Andrew et al., 2015), and it is therefore appropriate to evaluate the long-term impact

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of the main influencing factors.

Asif et al. (2014) reported that species composition and weed density were the major determining factors in crop competitiveness. Some authors found a linear negative correlation between crop yield and densities of weed species or the total weed infestations (Stasinskis, 2009; Vanaga and Lapins, 2000), but non-linear models are also appropriate to predict yield losses (Ali et al., 2013).

Stasinskis (2009) presented the highest impact of herbicide use (64.1%) on winter wheat yield compared to soil tillage (9.5%) and the preceding crop (2.0%). The importance of chemical weed control increases with simplification of crop rotations and reduced soil tillage. Herbicides were identified as the main factor on increasing wheat yield in Canada and corn and soybean yields in United States (Gianessi, 2013). Similarly according to Keller et al. (2014, 2015) long-term yield increase in winter wheat and maize was possibly due to chemical weed control. Neither the progress in agrotechnology nor the introduction of high-yielding cultivars would have had significant impact on yield without effective weed control. Although reduced herbicide application may not cause short-term increase in weed infestation and yield loss (Boström and Fogelfors, 2002; Kudsk and Streibig, 2003; Kudsk, 2008; Salonen, 1993), it leads to long-term higher densities in less sensitive species and significant consequent yield losses (Hossard et al., 2014; Pallut and Moll, 2008).

Crop yield is influenced not only by agrotechnology and the use of fertilizers and pesticides, but also by site and climate conditions (Chloupek at al., 2004). Long-term field trials have enabled monitoring of temporal yield trends and assessment of factors that change slowly and depend strongly on the weather in particular years (Moss, 2004). Most Czech Republic long-term field trials have been conducted by the Crop Research Institute in Prague and have provided important information for agriculture and environmental science (Madaras and Lipavský, 2009). Widespread use of herbicides in agriculture in the second half of the last century initiated foundation of the Herbicide Field Experiment at two sites in 1972. This trial enabled evaluation of the effect of long-term herbicides use on changes in weed populations and provided unique data on crop yields and other valuable information. Although trial data was continuously evaluated, current statistical methods and modern software now enable more complete assessment. The aim of this study was to determine yield losses caused by weeds for various crops and rotations under more than 40-year influence of different herbicide treatments. We focussed on two hypotheses while analysing the dataset from the field experiment: (1) yield is positively affected by herbicide treatment and (2) the effect of herbicides on yield is uneven across different crops.

2. Materials and methods

2.1. Experimental site

The long-term field trial has been conducted since 1972 at two experimental stations of the Crop Research Institute in the Czech Republic; Hněvčeves (50.31487 N, 15.71612 E, sugar beet growing region) and Pernolec (49.77053 N, 12.68099 E, potato growing region). The long-term climatic and soil characteristics are listed in Table 1. The determined available nutrients of 20 cm soil samples taken after crop harvest with approximately five-year intervals from each site are listed in Table S2. Based on soil analyses, mineral fertilisers were applied to ensure adequate plant-available nutrient contents.

The trial was established in two different crop rotation systems (CR) with specific cereal percentages: (1) multi-crop CR (MCR) with 50% cereals and 50% broadleaf crops (winter wheat - oilseed rape - winter wheat - root or tuberous crops - spring barley - pea) and (2) simple CR (SCR) with 75% cereals and 25% legumes (winter wheat - spring barley-spring barley - pea). Three herbicide treatments were used: (1) untreated control; (2) synthetic auxins in simple crop rotation (MCPA; 2,4-D in cereals and bentazone in pea) and (3) targeted herbicide combinations according to observed weed infestation. At the start of the field experiment and during the 1980s photosystem II inhibitors (especially triazines) were mostly used. Afterwards ALS inhibitors (especially sulfonylureas) prevailed in cereals and microtubule inhibitors or ACCase inhibitors in pea. Photosystem II inhibitors were mostly used for potato and synthetic auxins together with mitosis inhibitors (metazachlor) for oilseed rape. Herbicides were always applied at the 2 to 6-leaf crop stage. No other weed management was applied. The experiment was carried out as a split-plot design with five combinations of crop rotation (main plots) and herbicide treatments (sub-plots): MCR*untreated, MCR*targeted, SCR*untreated, SCR*auxins and SCR*targeted; with four replications of each combination. The 100 m^2 (10 m by 10 m) plots were established 10 m from field boundaries and separated from each other by 1–2 m stripes in order to avoid interactions between treatments. Field trial complied with good experimental practice (GEP) standards. Standard (optimal) crop-specific cropping practice recommended for experimental sites was conducted in all plots throughout the trial: conventional tillage up to 20–25 cm depth; N, P, K, Mg, Ca crop fertilisation according to soil analyses; fungicide and insecticide treatment when needed.

The crop cultivars were chosen for suitability to local temporal climate and soil conditions. This was based on the recommendations of the Central Institute for Supervising and Testing in Agriculture (http://eagri.cz/public/web/en/ukzuz/portal/) and their wide use in practice at certain period of time. Improved high-yielding cultivars were introduced throughout the experiment. Long-straw wheat varieties (Mironovská, Jubilar) were used at trial commencement, high-yielding short-straw varieties (Regina, Hana) were introduced after the 1980's. Varieties with powdery mildew resistance and higher grain weight per spike (Bohemia, Sakura, Sulamit) were planted from 2000. The parameters of Czech wheat varieties are described in Dvořáček et al. (2014). The original Czech Diamant spring barley variety was used at trial commencement. Following planted varieties have had better malting quality (Jersey, Sebastian, Bojos). Semi-leafless pea varieties (Eso, Zekon, Gotik) were introduced after the 1990's. These had reduced lodging and lower yield losses from diseases. Potato varieties were not changed as often. Radka, the most widely cultivated local variety was used until the 1990's. Subsequent Ditta and Adéla varieties had higher yields and higher resistance to blight and viral diseases. Hybrid varieties of oilseed rape (Artus, NK Octans) were used after 1995.

Table 1
Experimental climatic and soil characteristics, with available nutrients measured by Mehlich III extraction followed Carter (1993) (average values over the experimental period).

Experimental site	Altitude	Average annual temperature	Average annual rainfall	Soil Classification	pH (KCl)	pH (H_2O)	$Ca_{avail.}$	$P_{avail.}$	$K_{avail.}$	$Mg_{avail.}$
	m	°C	mm				mg kg^{-1}	mg kg^{-1}	mg kg^{-1}	mg kg^{-1}
Hněvčeves	265	8.2	573	Haplic Luvisol on loess, clay-loam	6.06	6.81	2339	99.9	272.3	241.3
Pernolec	530	7.1	559	Cambisol on orthogneiss, sandy loam	5.09	6.14	1300	60.0	91.6	79.5