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Biodiversity as a creator of productivity and interspecific competitiveness of winter cereal species in mixed cropping

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ABSTRACT

The study evaluated the productivity of three species of winter cereals – wheat, rye, and triticale – in sole cropping and in mixtures of two and three species. Asymmetrical interspecific competition was noted during generative growth stages. The greatest competitive strength was observed for triticale in the mixture with wheat during the heading stage. In the two-species mixtures with equal proportions (50:50), triticale produced greater biomass. In the three-species mixture, the productivity of rye and triticale depended mainly on their initial high share in the crop (50%). Wheat, despite having a high share in the mixture, did not display high productivity, because the yield per spike and harvest index decreased. Rye in the mixed cropping with wheat produced significantly higher spike weight and culm weight in comparison with sole cropping. Triticale, despite being strongly competitive in the canopy during the generative growth phase, attained high grain yield per spike. The low competition coefficients for triticale relative to rye suggest that these two species have a similar competitive pressure during the period of harvests.

1. Introduction

Cereals are the most important group of crops worldwide and are the main source of energy and protein in the diet of humans and animals (Sarwar et al., 2013). The increasing demand for food in developed and developing countries, as well as natural disasters such as drought, disease, and pests, pose a major challenge for agricultural production in the 21st century. Single-species crops are currently dominant in cereal cultivation. An alternative to sole cropping of cereal species may be mixtures of cereals, mainly interspecific, which according to estimates, currently account for 1% of sowing of cereals (Zając et al., 2014). In Poland, however, the percentage of mixtures in the total area on which cereals are grown is much higher (14%). These are primarily mixtures of spring cereals, mainly barley and oats, sown on poorer soil following cereal crops. In these circumstances, mixed cropping of different species or varieties of cereals exploits biodiversity in the canopy to ensure high productivity in crop plants (Altieri, 1999; Finckh et al., 2000; Newton et al., 2009). Few studies have been conducted on the possibility of growing winter cereals for grain (Zając et al., 2014); however, more extensive research has been carried out on cultivation of cereals in mixed cropping for silage (Baron et al., 1996; Juskiw et al., 2000). It seems that increasing the species biodiversity of the winter cereal canopy may lead to an increase in productivity through better utilization of the resources of the environment. In the conditions of the temperate zone of Europe, most of the grain produced is used for animal fodder. Therefore, it is important to increase the productivity of mixtures, which can be achieved by multi-species sowing of crop plants (Sobkowicz et al., 2016a,b). Winter cereal plants have varying winter hardiness, which is highest in rye, intermediate in triticale, and lowest in barley. The presence of rye in a mixture is a kind of biological insurance against excessively cold periods occurring in the temperate climate zone, and thus the importance of this species as a component of winter cereal mixtures will increase. Historically, rye was domesticated much later than wheat. As conditions for cultivation deteriorated, rye gradually displaced wheat. The rye that is currently cultivated is an example of a secondary crop that emerged from weeds as a result of natural selection and therefore retained strong competitive traits in a mixed canopy (Behre, 1992).

Another example among cereals is triticale, an intergeneric hybrid combining the best characteristics of rye (adapted to inferior soil conditions) and wheat (yield quality). Currently, triticale is a dynamically spreading cereal crop due to its broad potential for use as grain and fodder (Hinojosa et al., 2002). In mixed cropping, it exhibits greater competitiveness than wheat, which determines

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the high productivity of the species and predisposes it to cultivation in mixtures (Oleksy and Szmigiel, 2001).

Studies on multi-species cropping indicate that biodiverse mixtures lead to an overall increase in crop productivity (Tilman and Wedin, 1996). This phenomenon is reflected in two-species mixtures, because the different location and time of utilization of nutrients reduce the overlapping of crop demands observed in single-species cropping. Many studies have been conducted to evaluate the benefits of mixed cropping (Andersen et al., 2004). Potential benefits include the efficient utilization of habitat resources (Zając et al., 2014; Vandermeer, 1990) and improved productivity (Fukai and Trenbath, 1993).

The phenomenon of competition for nutrients in interspecies mixtures has been discussed extensively (Andersen et al., 2004), but few studies have been conducted on the productivity of more complex mixtures (Juskiw et al., 2001; Sobkowicz et al., 2016a,b; Andersen et al., 2007).

Brooker et al. (2008) showed that increasing the number of component species in mixed crops makes the results of intraspecific competition less predictable Sobkowicz et al. (2016a,b) demonstrated that the competitive hierarchy observed during the fully ripe stage in spring cereals in a four-component mixture reflects the hierarchy observed in three-component mixtures. The authors of the study found that mixtures did not differ in the yield. The spring cereal mixtures exhibited more stable yield than single-species crops. Since the current literature lacks information on the effect of interspecific competition in mixed cropping of winter cereals, the aim of the study was to evaluate the productivity of winter mixtures, as well as competition between species cultivated in two- and three-species mixtures of winter cereals and the dominance of the species.

1.1. Study site

The experiment was conducted at the experimental station in Prusy, Krakow, Poland (47°24′ N lat., 7°19′ E long., 300 m a.s.l.). The experiment was set up on very good complex, first class loess soil. The soil pH was 6.2 and total C and N in the topsoil (0–30 cm) was 1.18% and 0.169%, respectively. The plants were sown on the 30th of September and harvested on 3rd of August.

1.2. Experimental design

The experiment included three leading winter species with a similar rate of growth and development: rye (cv. Amber), triticale (cv. Borowik), and wheat (cv. Ozon).

The experiment was set up in a randomized block design in triplicate. Each plot had an area of 10 m^2. The species were sown in a sole cropping system as follows: rye at a density of 200 grains/m^2, triticale at 300 grains/m^2, and wheat at 400 grains/m^2. In the two-species mixture, each species had an equal share: rye with triticale (50:50), rye with wheat (50:50), and triticale with wheat (50:50). In the three-species mixture, three possibilities were tested, with the following proportions of rye, triticale, and wheat: a) 50:25:25, b) 25:50:25, and c) 25:25:50. Plants were sown in six 10 m rows at a distance of 12 cm, irrespective of the cropping system.

Mineral fertilizers were applied before sowing in the amount of 24 kg ha^{-1} of N, 60 kg ha^{-1} of P, and 99 kg ha^{-1} of K. At the elongation stage, nitrogen was applied at 50 kg ha^{-1} in all plots. Basfoliar 2.0 36 Extra was applied at 8 l/ha. Lintur 70 WG was applied at 0.18 kg ha^{-1} for weed management, and Amstaw 250 S.C. at 0.6 l/ha, and Artea 330 EC at 0.4 l/ha for disease control.

We assumed that crop productivity is determined by the generative growth phase. Therefore, the biometric plant measurements were made first in the heading stage – 234 days after sowing (DAS), and then during the anthesis stage – 254 DAS, the milk stage (development of fruit) – 270 DAS, ripening (soft dough) – 290 DAS, and senescence (over-ripe) – 304 DAS. In the characteristic growth stages from each of 3 replications, shoots were collected from the 1 m^2 plot area. The species shoots were separated based on inflorescence and percentage of each species was then calculated. The content of total dry biomass was obtained using oven-drying method by drying and heating chamber BINDER, FED 720 (105 °C for 3 h).

Plant density per m^2 was estimated during the anthesis stage and fully ripe stage (Table 1). In addition, during the fully ripe stage, prior to harvest, detailed biometric measurements of shoots were performed: culm weight (g) and length (cm), spike weight (g) and length (cm), the number of spikelets per spike, the number of grains per spikelet, the number of grains per spike, grain yield per spike (g), and harvest index (HI). After combine harvesting, the seeds from two- and three-species mixtures were separated manually to determine the shares of grain weight of each component, which was used to calculate the RY index.

To evaluate the response of a species to competition with respect to another species in the mixture, the relative yield (RY) was calculated on the basis of grain yield for each species in the two-species mixture (Weigel and Joliffe, 2003) and the three-species mixture (De Wit and Van den Bergh (1965) using the following formula:

$$\mathrm{RYa} = (\mathrm{Yma}/\mathrm{Ysa}) \times (1/\mathrm{p}) \quad (1)$$

where RYa is the relative yield of species **a** in the mixture, Yma is the yield of species **a** in the mixture, Ysa is the yield of species **a** in sole cropping, and p is the sowing proportion.

RYa < 1 means that species **a** is suppressed in the mixture by the collective pressure of other species in a multi-species mixture.

If RYa > 1, the competition from plants of neighbouring species in a multi-species mixture is weaker for species **a** than between plants of species **a** in a pure stand (Sobkowicz et al., 2016a,b).

1.3. Growth model in crops

A logistic growth function (Hunt, 1982) was used to fit the biomass yield data for each crop component of sole crops and of intercrops:

$$m(t) = \frac{a \cdot e^{b \cdot (t-k)}}{1 + e^{b \cdot (t-k)}}, \quad (2)$$

where m is the biomass of the crop species, a is a scale parameter which determines the maximum value of the biomass, b specifies the initial growth rate, and k determines the position of the curve.

To analyse the mutual competition of two plant species, a simple interspecific model (Andersen et al., 2007) was used:

$$m_{i(ij)}(t) = m_{i(i)} \frac{p_i \cdot c_i}{p_i \cdot c_i + p_j \cdot c_j} \quad (2)$$

The competition of three plant species was described by the following formula:

$$m_{i(ij)}(t) = m_{i(i)} \frac{p_i \cdot c_i}{p_i \cdot c_i + p_j \cdot c_j + p_k \cdot c_k}, \quad (3)$$

where m is the dry mass yield of crop components i, j, and k; p is the relative proportion of the crop component; and c is the competitive coefficient of a given crop.

The growth model assumes that the competitive coefficient of two crop components i and j in dual intercrops is the same as in triple intercrops of plants i, j and k ($c_{ij(ij)} = c_{ij(ijk)}$) (Andersen et al., 2007).

Relative competitive strength (CS) was estimated using the following relation:

$$m_{i(ij)}(t) = m_{i(i)} \frac{p_i}{p_i + p_j \cdot CS_{ij}}, \quad (4)$$