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The biodiversity of weed communities of dent maize, narrow-leaved lupin and oat in relation to cropping system and weed control

Bioróżnorodność zbiorowiska chwastów w kukurydzy, łubinie wąskolistnym i owsie w zależności od systemu uprawy i regulacji zachwaszczenia

Summary: The aim of the experiment was to assess the effect of cropping system and as well as various methods of weed control on the biodiversity of the weed community of dent maize, narrow-leaved lupine and spring oat. The data used in the study came from a three year field experiment carried out at the Experimental Station in south-eastern Poland (50°42'N, 23°16'E). The following factors were studied: 1. Cropping system – sole cropping and strip intercropping; 2. Weed control – mechanical and chemical. Changes in the diversity of the segetal flora are analysed using the species richness index (*S*), the Shannon-Wiener diversity index (*H*'), the Margalef index (*R*), the Simpson dominance index (*D*) and Pielou's evenness index (*J*'). The use of chemical weed control increased the diversity of the weed community in all species tested compared to mechanical weed regulation. Chemical weed regulation significantly decreased the value of Simpson dominance index due to the limitation of the occurrence of dominant weed species. Strip intercropping increased weed biodiversity, however, the influence of cropping systems depended on the crop species and the weed control method used.

Key words: biodiversity, intercropping, Shannon-Wiener diversity index, Margalef index, Simpson dominance index, Pielou's evenness index

INTRODUCTION

Biodiversity plays a very important role in ensuring the proper functioning of eco-systems, including agroecosystems [Zhang et al. 2007]. The progressive intensification of agriculture has led to a reduction in the genetic diversity of crops. The spatial and temporal diversity of land use has decreased as well [Chateil et al. 2013]. In integrated agricultural production programs, it is recommended to return to traditional crop rotation while maintaining the proper crop sequence and to increase the species diversity of fields by means of intercropping [Lithourgidis et al. 2011]. The diversity in intercropping systems is greater than in monocultures. The better utilization of light, water and nutrients in mixed crops results in greater yield stability, reduces the risk of disease, pests and weeds and increases the natural enemy fauna abundance and diversity [Amala and Shivalingaswamy 2018]. From ecological theory [Brooker 2006], any yield benefits could come at the expense of the weed community. The basis of such reasoning is, that by increasing diversity in the crop, the crop can use resources more efficiently due to differential traits between crop genotypes. This more efficient use of environmental resources by the crop mixture may decreased the resources availability to the accompanied segetal flora. This in turn can reduce the biodiversity of weeds by limiting their functionality or by changing the traits of the weeds to avoid competition between them [Pakeman et al. 2020]. Baumann et al. [2000] reported that intercropping increases light interception by the weakly competitive component and can, therefore, shorten the critical period for weed control and reduce growth and fecundity of late-emerging weeds. Strip inter-cropping is a form of intercropping that involves growing two or more plant species in the same field and at the same time [Jurik and Van 2004, Głowacka 2014]. Placing plants in separate strips allows for independent mechanical cultivation and harvesting. It also minimizes competition between neighbouring plants and increases productivity, especially in the border rows of the strips. Due to reduced threats from pests and diseases, less pesticides can be applying. Research shows that strip intercropping can also reduce weed infestation [Liebman and Dyck 1993].

According to Oerke [2006] weeds are a particularly interesting pest model case as they are responsible for the highest potential yield losses, as well as an important component of vegetal biodiversity in agricultural landscapes [Mézière et al. 2015]. The presence of weeds in crop fields is a natural phenomenon. However, cultivated plants and weeds growing side by side compete for the factors necessary for growth and development, and weeds are very often more competitive than crop plants. Therefore, weeds must be adequately controlled to maintain good plant development and crop yields [Haliniarz et al. 2018]. On the other hand, weeds are also an important component of agroecosystems. According to Chen et al. [2000] and Marshall et al. [2003], a bio-diverse weed population maintains the proper balance and function of the agroecosystem by protecting against natural enemies, controlling pests, preventing soil erosion, improving nutrient circulation, and reducing environmental pollution. However, human activity eliminates or severely reduces the occurrence of many living organisms, including weeds, leading to a reduction in biodiversity. This is disadvantageous because greater biodiversity largely translates to increased plant productivity [Leps et al. 2001, Benton et al. 2003]. The factors that modify the biodiversity of segetal flora in agricultural crops are the environmental conditions and soil maintenance method [Lisek and Sas-Paszt 2015]. The number of weeds and their relative proportions vary depending on the forecrop, the species being cultivated, crop rotation, the time and number of cultivation treatments, and the type of herbicides used [Derksen et al. 1993, Jastrzębska et al. 2013, Haliniarz et al. 2018]. According to Zuo et al. [2008], an ideal crop management system is one that controls weed populations while maintaining biodiversity of weed flora.

The weed biodiversity can be estimated by the different indices of biodiversity, taking into account the number of species and their proportional abundance, their frequency, or the amount of biomass produced. According to Nkoa et al. [2015] three indices are often used to estimate diversity within plant communities: the Margalef index, the Shannon–

Wiener diversity index, and the Simpson's dominance index. In the last decade, many papers on weeds diversity have appeared in the world literature [Feledyn-Szewczyk 2008, Jastrzębska et al. 2012, Mézière et al. 2015, Pawlonka et al. 2015] also including those relating to the influence of intercropping system on the diversity indices of weed communities [Baumann et al. 2000, Takim 2012]. However, in literature are comparatively few articles that deal with the weed diversity in strip intercropping, in particular using other indicators than the number or mass of weeds. In our other study the effect of strip intercropping as well as various methods of weed control on the number, aboveground biomass and species composition of weed communities was assessed [Głowacka 2013]. Cited manuscript presents a detailed analysis of the species composition of communities, their number and the biomass produced by weeds in dent maize, narrow-leaved lupine and oat. However, in the study of weed infestation in crops, the diversity of weeds and the dominance of individual species are also very important [Sobiech et al. 2018]. The unfavorable impact of the community of several dominant species of weeds may be greater than in the case of their greater biodiversity [Booth and Swanton 2002]. Taking into account the above statement, it appears question about the importance of weed number and biomass regulation for shaping their biodiversity.

The purpose of this investigation is to evaluate the biodiversity of the weed flora and how it is affected by the crop system and the weed control.

MATERIALS AND METHODS

The data used in the study came from a field experiment carried out in 2008–2010 at the Experimental Station in south-eastern Poland (50°42'N, 23°16'E). The experiment was established on brown soil, slightly acidic (pH_{KCl} – 6.0), with medium organic matter content (18 g kg^{-1}), high content of P – 175 mg P_2O_5 kg^{-1} and K – 206 mg K_2O kg^{-1} and average Mg content – 57 mg Mg kg^{-1}. The subject of the study was the Celio cultivar of dent maize, the Sonnet cultivar of narrow-leaved lupine, and the Kasztan cultivar of oat. The experimental design included the following factors:

1. Cropping system – sole cropping and strip intercropping (three species grown side by side in strips 3.3 m wide);

2. Weed control method – mechanical and chemical. The experiment was carried out in a split-plot design with four repetition. In sole cropping the size of the plots was 26.0 m^2 for sowing (4 × 6 m) and 22.0 m^2 for harvest. In intercropping plot size was 13.2 m^2 for sowing and 11 m^2 for harvesting. The most important information on cultivation technology and agrotechnical treatments in individual species grown in the experiment are shown in Table 1. Tillage was carried out according to the agrotechnical recommendations for maize, narrow-leaved lupin and oats. A detailed information of the conditions of the study and agrotechnical procedures is given in an earlier paper [Głowacka 2014].

Weed infestation was assessed two weeks before harvest by determining the species composition as well as the number and dry weight of weeds [Malicki et al. 1986]. At the time of weed infestation assessment, the cultivated plants were in the following development stages: oat – BBCH 85, dent maize – BBCH 83, narrow-leaved lupin – BBCH 87/89. On each plot, two random sample areas were set off with a 1 m × 0.5 m frame. Within each frame, individual weed plants were counted and weed flora was determined. When the weeds had been extracted and their roots cut off, the plants were dried and weighed to determine the air-dry weight of individual species and the total above ground weight of weeds. Weeds were pre-dried for four days at room temperature. Then the samples were dried in a laboratory dryer for 6 h at 105°C.

Table 1. Agrotechnical treatments in individual species grown in the experiment

Procedures	Maize	Narrow-leaved lupin	Spring oat
Date of sowing	28.04.2008 02.05.2009 05.05.2010	11.04.2008 12.04.2009 15.04.2010	11.04.2008 12.04.2009 15.04.2010
Seeding rate	110,000 seeds per hectare	180 kg ha^{-1}	180 kg ha^{-1}
Row spacing	65 cm	20 cm	15 cm
mineral fertilization* (kg ha^{-1})			
N P K	140 35 100	20 26 99	60 22 110
weed control			
Mechanical	weeding of interrows twice (first at the 5–6 leaf stage: BBCH 15–16, and again 2 weeks later)	harrowing twice (first after sowing, pre-emergence: BBCH 00–01, then after emergence, before the plant reached a height of 5 cm: BBCH 13–15)	harrowing twice (first at the 1-leaf stage: BBCH 10, then at the 5-leaf stage: BBCH 15)
Chemical – herbicides	a.i. bromoxynil + terbuthylazine at 144 g ha^{-1} + 400 g ha^{-1} at the 4–6 leaf stage (BBCH 14/16)	a.i. linuron directly after sowing at 675 g ha^{-1} + a.i. metamitron at 2,800 g ha^{-1} after emergence at the 2–3 leaf stage (BBCH 12/13)	a.i. 4-chloro-2-methylphenoxyacetic acid at 550 g ha^{-1} at the full tillering stage (BBCH 22/23)
Harvest	30.08.2008 05.08.2009 09.09.2010	16.08.2008 21.08.2009 26.08.2010	02.08.2008 06.08.2010 10.08.2010

* P and K was applied before sowing, N – in oats and lupines before sowing, in maize 1/2 before sowing and 1/2 in the 4–5 leaf stage – BBCH 14/15.

On the basis of samples collected from particular plots the differences in the diversity of the weed community were analysed using: the species richness index (*S*), the Shannon–Wiener diversity index (*H’*) [Simpson 1949, Nkoa et al. 2008], the Margalef index (*R*) [Nkoa et al. 2008], the Simpson dominance index (*D*) and Pielou’s evenness index (*J’*) [Sienkiewicz 2010]. Since the harmfulness of weeds depends not only on their number but also on the weight they produce, and even numerous but small plants are less harmful than those occurring in low density but with high biomass the Shannon–Wiener diversity index and the Simpson dominance index were calculated for both the number and the biomass of weeds. Estimating biodiversity indicators for weed weight was used in other studies [Jastrzębska et al. 2010, 2019].

The following equations were used to calculate the analyzed indexes:

– Species richness index (*S*) – number of species in the community [Nkoa et al. 2008].

– The Margalef index (*R*): $R = (S - 1) / lnN$, where *N* – total number of individuals on the sample [Nkoa et al. 2008, Sienkiewicz 2010].

– The Shannon–Wiener diversity index (*H'*): $H' = \Sigma\ (p_i \times lnp_i)$, where p_i – proportion of the number of *i*-species individuals in the community (or biomass generated by species *i*) to the number (or biomass) of all individuals in the community [Simpson 1949].

– The higher the value of the Shannon–Wiener index, the greater the diversity of a community.

– The Simpson dominance index (*D*): $D = \Sigma\ p_i^2$; where p_i as defined above.

– The Simpson dominance index (*D*) characterizes the species dominance of the community. It expresses the probability of two individuals of the same species being present in a random sample. For this index, 0 means infinite diversity and 1 indicates no diversity; hence the higher the *D* value, the lower the diversity [Sienkiewicz 2010].

– Pielou's evenness index (*J'*): $J' = H' / lnS$

– The evenness index expresses the ratio of actual diversity to maximum diversity. Evenness can take values from 0 to 1, with 1 indicating completely even distribution of species [Tang et al. 2014].

Biodiversity indices were calculated for each plant species in sole cropping and in strip intercropping. Additionally, biodiversity indices for strip intercropping were calculated by treating the three strips with different plant species (dent maize, narrow-leaved lupin, spring oat) as one field.

The results were analysed statistically using variance analysis with Statistica 13 PL software (Tulsa, USA). A three-way analysis of variance (ANOVA) was carried out to determine the effect of year, cropping system and weed control methods on the variability of the biodiversity of weed communities in dent maize, narrow-leafed lupin and spring oat. Year, cropping system and weed control methods were considered fixed effects. Replication was considered a random effect. The effect of year, cropping system, weed control methods, and their interactions were analysed using a split–split-plot design with the year being designated as whole plots, strip cropping as subplots, and weed control methods as sub–sub-plots. There was no significant interaction between years and treatments. Prior to analysis of variance, the normality of variable distribution was checked using the Shapiro-Wilk W-test and the homogeneity of variance using Levene's test. The differences between means were evaluated with Tukey's test. The results were tested at a probability of 95%. The tables and the figures present average values from three years and four replications.

RESULTS

Irrespective of the cropping system and weed control methods, maize had the lowest species richness index (*S*) among all species analysed in the experiment. The weed control methods significantly affected the species richness index. In maize and narrow-leaved lupin, the number of weed species in the plots with herbicides was greater than in the mechanically weeded plots. In spring oat, the use of herbicides decreased *S* index. The influence of the cropping method and the interaction between analyzed factors were not significant (Tab. 2).

The interaction between cropping system and weed control significantly influenced the Margalef index only in maize. Strip intercropping increased the value of this index in the mechanically weeded plots, while on the plots where herbicides were applied the Margalef index was higher for sole cropping. On average for the cropping systems, strip intercropping increased the value of this index for narrow-leaved lupin but decreased it for spring oat. In maize, the differences between sole cropping and strip intercropping were not significant. The use of herbicides increased the Margalef index for maize and narrow-leaved lupin and decreased it for oat. But is worth noting, that the value of this index for the chemical and mechanical weed control differed most in the maize crop.

The interaction between cropping system and weed control method did not significantly affect the Pielou's evenness index in any of the species tested. The values of the Pielou's evennes index for maize, lupin and oat were higher when chemical weed control was used. Strip intercropping increased species evenness in the weed flora of lupin and oat, irrespective of the weed control method (Tab. 2).

Table 2. Biodiversity indices: species richness index (*S*), the Margalef index (*R*) and Pielou's evenness index (*J'*) calculated for the number of weeds (mean for 3 years)

Cropping system	Weed control	Maize			Narrow-leaved lupin			Spring oat		
		S	*R*	*J'*	*S*	*R*	*J'*	*S*	*R*	*J'*
Sole cropping	M*	11	2.75^{a}	0.62	20	4.26	0.68	21	4.73	0.63
	C	16	5.73^{d}	0.76	20	4.89	0.81	15	4.04	0.76
Strip cropping	M	13	3.45^{b}	0.61	20	4.41	0.74	19	4.33	0.67
	C	15	5.20^{c}	0.88	21	5.16	0.85	14	3.83	0.82
p		n.s.	*	n.s	n.s.	n.s	n.s.	n.s.	n.s.	n.s
average for factor										
Sole cropping		17	4.24	0.57	23	4.58^{A}	0.72	23	4.39^{B}	0.63
Strip cropping		17	4.33	0.70	23	4.79^{B}	0.77	21	4.08^{A}	0.68
p		n.s.	n.s	n.s	n.s.	*	n.s.	n.s.	**	n.s.
M		15^{A}	3.10^{A}	0.57^{A}	21^{A}	4.34^{A}	0.70^{A}	23^{B}	4.53^{B}	0.62^{A}
C		17^{B}	5.47^{B}	0.79^{B}	26^{B}	5.03^{B}	0.78^{B}	18^{A}	3.94^{A}	0.73^{B}
p		*	**	**	**	**	*	*	*	*

* Weed control: M – mechanical, C – chemical. *p* * 0.05, ** <0.01; n.s. – not significant. Means in column followed by the same letter are not statistically different at the α = 0.05 level. Small letters for cropping system × weed control, capital letters for cropping system, letters in italics for weed control.

In the present study, the values of the Simpson dominance index confirm that the use of a herbicide for weed control decreased the species dominance of the weed in all species tested. Strip intercropping also decreased the species dominance of the weed community as expressed by the Simpson index, but only in narrow-leaved lupin. In maize and spring oat, the differences between sole cropping and strip intercropping were not significant. The interaction between cropping system and weed control methods did not significantly affect the Simpson dominance index for maize, narrow-leaved lupin or oat (Tab. 3).

Table 3. Biodiversity indices – the Shannon–Wiener diversity index (*H'*) and the Simpson dominance index (*D*) calculated for the number of weeds (mean for 3 years)

Cropping system	Weed control	Maize		Narrow-leaved lupin		Spring oat	
		H'	*D*	*H'*	*D*	*H'*	*D*
Sole cropping	M*	1.48	0.30	2.03	0.23	1.92	0.24
	C	2.12	0.18	2.46	0.12	2.05	0.18
Strip cropping	M	1.57	0.27	2.21	0.20	1.96	0.24
	C	2.37	0.12	2.60	0.10	2.17	0.15
p		n.s	n.s.	n.s	n.s.	n.s	n.s.
average for factor							
Sole cropping		1.63^{A}	0.24	2.25^{B}	0.18^{B}	1.99	0.21
Strip cropping		1.97^{B}	0.20	2.41^{A}	0.15^{A}	2.07	0.20
p		**	n.s	*	*	n.s.	n.s
M		1.53^{A}	0.29^{B}	2.12^{A}	0.22^{B}	1.94	0.24^{B}
C		2.25^{B}	0.15^{A}	2.53^{B}	0.11^{A}	2.11	0.17^{A}
p		**	*	*	**	n.s.	**

* Weed control: M – mechanical, C – chemical. *p* * 0.05, ** <0.01; n.s. – not significant. Means in column followed by the same letter are not statistically different at the $\alpha = 0.05$ level. Small letters for cropping system × weed control, capital letters for cropping system, letters in italics for weed control.

For maize, the Simpson dominance index (*D*) calculated on the basis of weed weight was similar to that calculated for the number of weeds. In sole cropping it was 0.26 and 0.17 for mechanical and chemical weed control, respectively. In strip intercropping, the Simpson index was 0.31 and 0.13 for mechanical and chemical regulation of weed infestation. For narrow-leaved lupin and oat, the *D* index for weed biomass was higher than for the number of weeds, but only under the conditions of mechanical weed control. Strip intercropping significantly reduced the Simpson dominance index for mechanically weeded narrow-leaved lupin, from 0.42 (for sole cropping) to 0.28. Where chemical weed control was used, the differences between sole cropping and strip intercropping were not significant (Fig. 1). In each crop species, the use of herbicides significantly reduced the value of the Simpson index compared to the mechanical regulation of weed infestation.

In the described experiment, the values of the Shannon–Wiener index indicated that the diversity of the weed community was highest in the chemically weeded lupin in strip intercropping (*H'* = 2.60) and lowest in the mechanically weeded maize in sole cropping (*H'* = 1.48). This index showed that strip intercropping significantly increased weed biodiversity in the maize and narrow-leaved lupin crops (Tab. 3). The Shannon–Wiener index for chemically weeded maize and lupin was higher than in the case of mechanical weeding. For oat, the differences between the weed control methods were not significant.

Values of the Shannon–Wiener index based on the biomass of weeds for maize, narrow-leaved lupin and oat were lower than for the number of weeds, but the differences were not big. For the each plant species tested in the study, this index was higher when chemical weed control was used. On the other hand, the beneficial effect of strip intercropping on the diversity of the weed community could be seen in the mechanically weeded lupin crop. Under the conditions of mechanical weed control, the *H'* index was 1.44 in sole cropping and 1.96 in strip intercropping (Fig. 1).

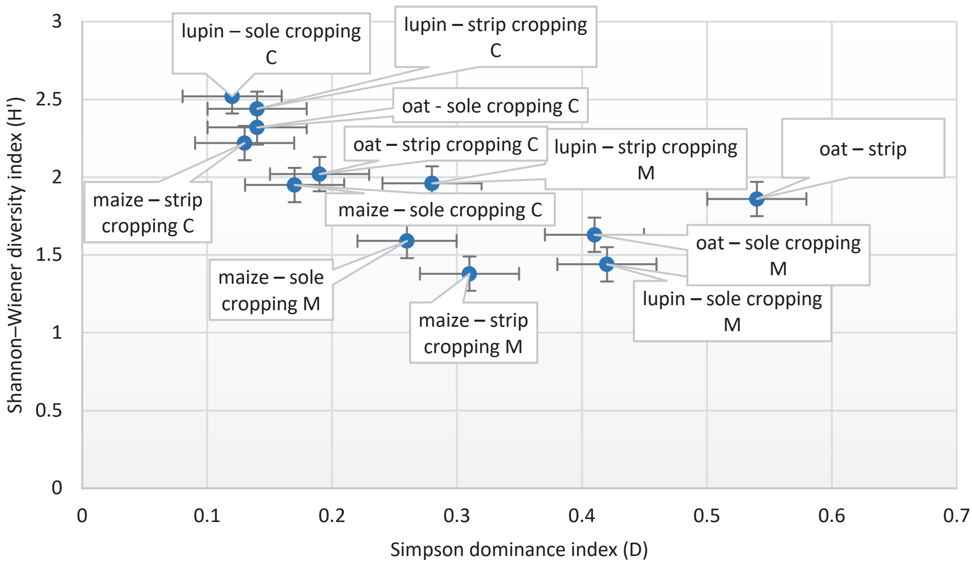

Fig. 1. Biodiversity indices computed on the base of weeds biomass. Weed control: M – mechanical, C – chemical

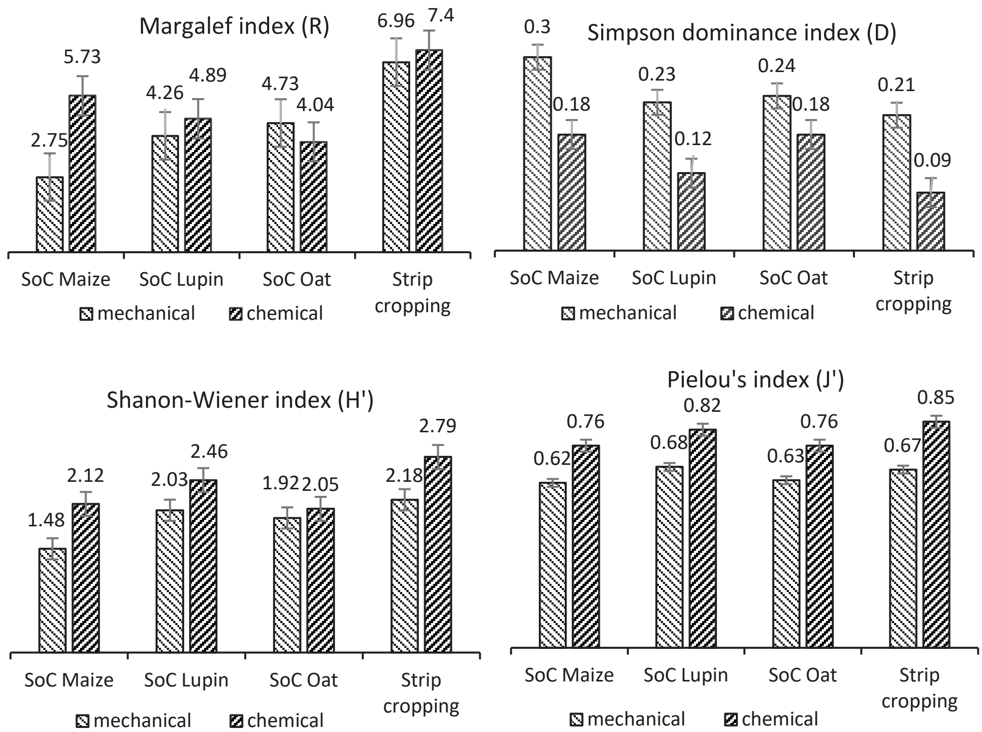

Fig. 2. Biodiversity indices for plant in sole cropping in comparison to the indexes calculated for strip intercropping of dent maize/narrowed-leaved lupin/spring oat in treated as one field. SoC – sole cropping

In strip intercropping, dent maize, narrow-leaved lupin and common oat were grown at the same time and in the same field, side-by-side in strips 3.3 m wide. Therefore, the strips of these three species can be treated as one field. In this approach, the biodiversity indices taking into account species composition and numbers of weeds in each of the three crop plants have slightly different values. As shown in Figure 2, the biodiversity of weed flora in the strip intercropping of maize, narrow-leaved lupin and oat was much higher than in each of the three species grown in sole cropping. The greatest differences were found for maize.

DISCUSSION

In our other paper we stated that strip intercropping increased the yield of maize biomass and the seed yield of narrow-leaved lupin and oat in comparison to sole cropping. In addition the land equivalent ratio value confirms that the maize/narrow-leaved lupin/oat strip intercropping was more efficient than the sole cropping [Głowacka 2014]. Apart from yield benefits intercropping strategies reduced segetal flora density and aboveground biomass and differentiated weed species composition [Liebman and Davis 2000]. A detailed analysis of the impact of strip intercropping on the abundance and aboveground biomass of species occurring in the weed community in maize, lupine and oats was presented in the previous article. It was stated that the most abundant segetal species in the maize, narrow-leaved lupin and oat were *Echinochloa crus-galli* (L.) P. Beauv., *Chenopodium album* L. and *Galinsoga parviflora* Cav. [Głowacka 2013].

Based on changes in the number and weight of weeds presented and discussed in detail in an earlier work [Głowacka 2013], strip intercropping generally reduces the weed infestation of crops. This is beneficial from the farmer's point of view. However, more and more attention is paid to maintaining or increasing the biodiversity of ecosystems, including agro-ecosystems. The biodiversity of a given community is determined both by the richness of species and their mutual quantitative proportions within the community. Therefore, to estimate biodiversity, appropriate indices are used, taking into account the diversity and dominance of species. In presented study the differences in the biodiversity of the weed community were analysed using the species richness index, the Shannon–Wiener diversity index, the Margalef index, the Simpson dominance index and Pielou's evenness index.

Species richness is measured as the number of species in a given area, without taking into account differences in the shares of these species [Jastrzębska et al. 2019]. In the present study, irrespective of the experimental factors, the weed flora of narrow-leaved lupin and spring oat had higher species richness than that of maize. The cropping system did not affect the species richness of the weed community in the crops. Poggio [2005] similarly concluded that species diversity in intercropped field pea and barley was not lower than in the monoculture, particularly in terms of species richness. Other studies show that the overall species richness of a weed phytocoenosis sometimes depends less on the experimental factor and more on the crop plant, weather conditions, and other less recognized factors [Rzymowska et al. 2019]. Jastrzębska et al. [2013] also found that the species composition of the weed community, particularly its quantitative structure, was primarily influenced by the crop species, and not the agricultural production system used.

Application of herbicides is believed to be a factor causing floristic impoverishment of agrophytocoenoses [Pawlonka et al. 2015]. In the present study, the use of herbicides significantly increased the species richness index in maize and narrow-leaved lupin as compared to mechanical weed control. As it was stated in our previous work [Głowacka 2013] herbicides reduced the number of weeds compared to the mechanical regulation of weed infestation – from 35 to 14 pcs per m^2 in maize, from 78 to 49 pcs per m^2 in lupine and from 66 to 31 pcs per m^2 in oats. In addition, the application of herbicides significantly reduced the abundance of the most competitive species, i.e. *Echinochloa crus-galli*, *Chenopodium album* and *Galinsoga parviflora*, in maize and narrow-leaved lupin, which enabled the growth and development of other less competitive weed species. This is beneficial because the harmfulness of the weed community is determined not only by the number of weeds but also by their species composition. The greater the species diversity of weeds, the less harmful they are [Stupnicka-Rodzynkiewicz et al. 2004].

The biodiversity of a given community is determined not only by the richness of species, but also by their mutual quantitative proportions within the community. Indices commonly used to estimate within-community diversity include the Margalef index, the Shannon–Wiener diversity index, the Simpson dominance index and Pielou's evenness index [Simpson 1949, Jastrzębska et al. 2013, 2019, Nkoa et al. 2015]. Intercropping may enhance not only planned biodiversity, as more crop species are grown in the agroecosystem, but also the biodiversity associated with spontaneously occurring fauna and flora [Malézieux et al. 2009]. Sharma and Banik [2013] reported that weed diversity and evenness was higher in baby corn/legume intercrops than in sole cropping. This might be due not only to the synergistic effect of the mixture, but also to the total higher crop density in the intercropping system as compared to the sole crops. Strip intercropping is a form of intercropping [Jurik and Van 2004, Głowacka 2014]. In these system, species are grown in adjacent strips, and the plant density is the same as in sole cropping. Few studies confirm the influence of strip intercropping in reducing the number and biomass of weeds [Liebman and Dyck 1993, Głowacka 2013]. In the present study, strip intercropping significantly increased the value of the Shannon–Wiener diversity index in maize and narrow-leaved lupin in comparison to sole cropping. Strip intercropping also increased the value of the Margalef index in narrow-leaved lupin, while decreasing it in spring oat. Our research shows that the interaction between the cropping system and weed control influences the Margalef index only in maize. Strip intercropping increased the value of this index in the mechanically weeded plots, while in the plots where herbicides were applied it was higher for sole cropping. The differences between the cropping systems were even greater when the strips of three species in strip intercropping were treated as one field to calculate the diversity indices of the weed community. This confirms that this cropping system can be a practical application of ecological principles based on biodiversity, biotic interactions and other natural regulation mechanisms [Spellerberg and Fedor 2003, de la Fuente et al. 2012]. The Shannon–Wiener diversity index is one of the most reliable and commonly used measures of the biodiversity of a community of organisms [Spellerberg and Fedor 2003, Tang et al. 2014]. According to the 5-point scale devised by Jurko [1986] for the Shannon–Wiener diversity index (*H'*), the biological diversity of the maize and oat samples was low (*H'* from 1.48 to 2.37), irrespective of the cropping system and weed control method. In the narrow-leaved lupin, on the other hand, the biodiversity of the weed community according to Jurko's scale was intermediate (*H'* 2.46 for sole cropping and 2.60 for strip intercropping), but only where chemical weed control was used.

Other studies have shown a decrease in species diversity as a result of the use of herbicides [Edesi et al. 2012, Jastrzębska et al. 2019]. Our research did not confirm such a relationship. The use of herbicides increased the value of the Margalef index, the Shannon–Wiener diversity index, and Pielou's evenness index in maize and narrowed-leaved lupin in comparison to mechanical weed regulation. It also decreased the Simpson dominance index. It is worth noting, however, that the differences between chemical and mechanical weed control were highest in the maize crop. This is probably because in the maize, as it was stated in other paper [Głowacka 2013], the three dominant weed species *Chenopodium album*, *Echinochloa crus-galli* and *Galinsoga parviflora* accounted for 82–99% of their total number in conditions of mechanical weed control, while herbicides application reduced their share to 47–69%. According to Squire et al. [2000], highly competitive and potentially dominant weeds are specially targeted by herbicides, and that may alter the distribution of species abundances. On the other hand, Mayerová et al. [2018] found that herbicide treatments, depending on their active substances or their combination, can reduce weed species diversity expressed by *H'*, but also may have no effect on it. High species richness can be expected to be positively correlated with high diversity and low dominance in a community of organisms. However, research by Otto et al. [2012] and Jastrzębska et al. [2013] has shown that comparison of the number of species and species diversity in weed communities does not always give consistent results, which was also the case in our research.

In experimental studies of the biodiversity of phytocoenoses, the most commonly used measures are the number of species, their proportional density, their frequency, and the amount of biomass produced [Kwiatkowska and Symonides 1985, Sienkiewicz 2010]. Given that weed competitiveness with crops is a function of their biomass rather than their density, since even quite numerous but small weed seedlings cause little harm, using biomass as the basis for indices seems more reasonable [Jastrzębska et al. 2010, 2019]. In the present study, the values of the Shannon–Wiener diversity index based on the biomass of weeds for maize, narrow-leaved lupin and oat were lower than for the number of weeds, but the differences were not big. In the studies conducted by Jastrzębska et al. [2010], the Shannon–Wiener indices calculated on different bases (density and biomass) showed high convergence. According to cited authors this is justified by the fact that *Chenopodium album*, which was the most numerously represented weed species, also dominated in the community in terms of the biomass produced. For the three crop species tested in our experiment, this index was higher when chemical weed control was used. On the other hand, the beneficial effect of strip intercropping on the diversity of the weed community estimated on the basis of weed biomass could be seen in the chemically weeded maize crop and the mechanically weeded lupin crop. The study presented in this paper also showed that application of herbicides significantly decreased the value of the Simpson dominance index calculated on the basis of weed biomass. This is advantageous from an agricultural point of view, because an excessive predominance of biomass of one or two species is more dangerous than a large number of seedlings of another taxon [Jastrzębska 2019]. According to many authors [Marshall 2001, Edesi et al. 2012, Jastrzębska 2019], agriculture intensification associated with the simplification of crop rotation and high consumption of industrial means of production (mainly herbicides) leads to a reduction in the diversity of weed communities and their specialization, and even to the disappearance of certain species of weeds. On the other hand, in a study by Stupnicka-Rodzynkiewicz [2004], the use of herbicides reduced the number of weeds, but not their diversity.

CONCLUSION

As it was shown in previous study [Głowacka 2013], the use of herbicides reduces the number and biomass of weeds in maize, narrow-leaved lupin and oat. Further, the prevailing opinion in the scientific literature is that the use of herbicides leads to a serious depletion of the species composition of plant communities. In the presented study it was found that chemical weed regulation by limiting the occurrence of dominant species, may contribute to greater biodiversity of the weed community in agrocenosis. The value of biodiversity indices, i.e. the Margalef index or the Shanon–Wiener diversity index, calculated on the basis of the number of weeds and their biomass was higher after the application of herbicides. At the same time herbicides significantly decreased the value of the Simpson dominance index. In our previous paper [Głowacka 2013] it was also found that dent maize/narrow-leaved lupin/oat strip intercropping reduces weed infestation in plants expressed by the number and biomass produced by the weed. In presented study it was stated that strip intercropping promotes greater biodiversity of segetal flora estimated by the different indices of biodiversity i.e. the species richness index, the Shannon–Wiener diversity index, the Margalef index, the Simpson dominance index and Pielou's evenness index. The biodiversity of weed flora in the strip intercropping of maize, narrow-leaved lupin and oat was much higher than in each of the three species grown in sole cropping. Furthermore, the diversity of cultivated plants is higher in strip intercropping. This is significant because the progressive reduction in the genetic diversity of crops poses a threat to the stability and sustainability of production systems, and numerous studies emphasize the importance of inter- and intraspecific crop diversity for increasing and stabilizing crops [Macfadyen and Bohan 2010, Lin 2011]. Thus strip intercropping is a form of intercropping that increases the biodiversity of the agrocenosis and can be an element of sustainable agriculture.

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