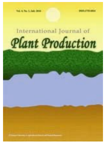

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The effects of strip cropping and weed control methods on yields of dent maize, narrow-leafed lupin and oats

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Abstract

The aim of this study was to assess the effects of strip cropping and different weed control methods on the yield and yield structure of dent maize, narrow-leafed lupin and spring oat. A split-plot design with four replications was conducted in 2008-2010. The following factors were analysed in the experiment: I. Cultivation method – sole cropping and strip cropping; II. Weed control method – mechanical and chemical. The method of cultivation was considered the main plot and the weed control methods were the sub-plot. Strip cropping significantly increased the maize yield and the percentage share of ears in the total biomass. The seed yield of narrow-leafed lupin was significantly higher in strip cropping, but only where mechanical weed control was used. Strip cropping significantly increased the plant density, seed number and weight per plant and 1,000 seed weight of lupin. Oat yield was slightly higher in the strip cropping than in the sole cropping. Strip cropping increased grain number and weight per panicle in the oat. The chemical weed control method was more favourable to the yield of maize, narrow-leaf lupin and oat than the mechanical weed control. The land equivalent ratio value (1.06) confirms that the maize/narrow-leafed lupin/oat strip cropping was more efficient than the sole cropping.

Keywords: Strip cropping; Dent maize; Oat; Narrow-leafed lupin; Weed control.

Introduction

Strip cropping is a form of mixed cropping in which several species of plants are grown side-by-side in adjacent strips. It is used in many regions to protect the soil against water and wind erosion and to reduce minerals losses due to leaching (Bucur et al., 2007; Rogobete and Grozav, 2011). This system can also be important in reducing the occurrence of pests and crop diseases (Ma et al., 2007) and has been shown to be highly effective in reducing contamination of rivers by herbicide residues from surface runoff (Holvoet et al., 2007). The plants grown in this system, for various reasons, are usually maize, soybeans or another pulse and a cereal (Francis et al., 1986; Fortin et al., 1994; Iragavarapu and Randall, 1996). Selection of plants with different cycles of development and morphology allows for more efficient use of nutrients, water and light and can reduce expenditures on crop cultivation (Fukai and Trenbath, 1993; Zang and Li, 2003). Increasing the number of species in strip cropping makes it similar to the natural ecosystem and spatial diversity can increase overall yield and affect its structure (Ghaffarzadeh et al., 1994).

In Poland, the most common and most widely used form of intercropping is the mixed intercropping of cereals or intercropping of cereals with pulses (Sobkowicz and Podgórska-Lesiak, 2007; Tobiasz-Salach et al., 2011). Intercropping has long been used in various parts of the world for the production of food and animal feed (Carruthers et al., 1998). It can increase total yield per unit area compared to sole cropping, as individual species may use different resources or the same resources may be used more efficiently (Rodrigo et al., 2001). Such mixtures are useful for sourcing of raw materials intended for animal feed. As an alternative, strip cropping offers more possibilities, as different species are sown and harvested individually and therefore may be more useful in growing plants for different purposes. In addition, studies conducted in various countries confirm the significant role of strip cropping in protecting soil against water and wind erosion (Gilley et al., 1997; Bravo and Silenzi, 2002; Chen et al., 2010). This is important in the Lublin Upland and Roztocze, situated in south-eastern Poland, as they are considered to be areas endangered by erosion (Józefaciuk and Józefaciuk, 1995). This is due to the soils derived from loess, undulating topography and economic activity–mainly agricultural–that contributes to denudation processes (Mazur, 2009). Our own research on strip cropping in these conditions indicates that this system has a beneficial effect on the yield and chemical composition of crops and reduces weed infestation. In an experiment evaluating strip cropping of maize, spring wheat and common beans, an increase was noted in the marketable yield of common bean, the percentage of ears in the total biomass and uptake and content of macro-and micronutrients in the maize (Głowacka, 2008; Głowacka, 2011). The direction and degree of the changes were markedly dependent on the nutrient and on the plant adjacent to the maize strip (Głowacka et al., 2011). The aim of the present study was to evaluate the impact of strip cropping of dent maize, narrow-leafed lupin and spring oats on the yield and yield components of these plants in the soil-climatic conditions of south-eastern Poland.

Materials and Methods

A field experiment was conducted in 2008-2010 at the Experimental Station of the Faculty of Agricultural Sciences in Zamość, Lublin University of Life Sciences (50° 42' N, 23° 16' E), on brown soil, slightly acidic (pH 1 n KCl–6.0), with medium humus content (18 g kg^{-1}), high content of available phosphorus and potassium (175 mg kg^{-1} P and 206 mg K kg^{-1}) and average magnesium content (57 mg Mg kg^{-1}). The experiment was carried out in a split-plot design with four replications. The subject of the study was the Celio variety of dent maize, the Sonet variety of narrow-leafed lupin and the Kasztan variety of spring oats. The experiment examined the following factors: I. Method of cultivation (CM): (1) single species cultivation (sole cropping), in which the size of the plots was 26.0 m^2 for sowing (4×6 m) and 22.0 m^2 for harvest and (2) strip cropping, in which the three plant species–dent maize (*Zea mays* L.), narrow-leafed lupin (*Lupinus angustifolius* L.) and spring oat (*Avena sativa* L.)–were grown side-by-side in adjacent strips 3.3 m wide. There was a distance of 55 cm between the maize and narrow-leafed lupin, 35 cm between the narrow-leafed lupin and oats and 45 cm between the spring oats and dent maize. Plot size was 13.2 m^2 for sowing 11 m^2 for harvesting. II. Method of weed control (WC): (A) Mechanical: maize–weeding of interrows twice (first in the 5-6 leaf stage–BBCH 15/16 and again two weeks later–BBCH 17/18); narrow-leafed lupin–harrowing twice (first after sowing, pre-emergence–BBCH 00-01, then after emergence, before the plant reached the height of 5 cm–BBCH 13-15); spring oats–harrowing twice (first in the one-leaf stage (BBCH 10), then in the 5-leaf stage (BBCH 15) and (B) chemical herbicides: maize–a.i. bromoxynil + terbuthylazine at 144 g ha^{-1} + 400 g ha^{-1} in the 4-6 leaf stage (BBCH 14/16); narrow-leafed lupin–a.i. linuron directly after sowing at 675 g ha^{-1} + a.i. metamitron at 2,800 g ha^{-1} after emergence, in the 2-3 leaf stage (BBCH 12/13); spring oats–a.i. 4-chloro-2-methylphenoxyacetic acid at 550 g ha^{-1} at the full tillering stage (BBCH 22/23).

In each of the crops herbicides were applied using a Pilmet Sano 2 P-030 knapsack sprayer.

Agricultural procedures

Dent maize was grown on a site where the previous crop had been oats. Mineral fertilization was applied uniformly at rates of N 140, P 35 and K 100 kg ha^{-1} (N - ammonium nitrate, P - triple superphosphate, K - potassium salt). Phosphorus and potassium fertilizers were applied once before spring pre-sowing treatments and nitrogen was applied in split applications (half before sowing and the remainder for top dressing in the 4-5 leaf stage - BBCH 14/15). The maize was sown on different dates each year depending on weather conditions–28 April in 2008, 2 May in 2009 and 5 May in 2010. The seeding rate was 110,000 seeds per hectare and the spacing between rows of maize was 65 cm. Where maize was grown alone (sole cropping), 10 rows were planted per plot, while in the strip cropping there were 5 rows per strip. Tillage was carried out in accordance with the agrotechnical recommendations for maize. The maize was harvested at the milky wax stage-BBCH 79/83.

Narrow-leafed lupin was grown on a site were the previous crop had been maize. Mineral fertilizers were applied uniformly at rates of N 20, P 26 and K 99 kg ha^{-1} (N-ammonium nitrate, P-triple superphosphate, K-potassium salt). All fertilizers were applied once before sowing. Tillage was carried out by the traditional method in accordance with the recommendations for this plant. In successive years of the study (2008-2010) lupin was sown on 11, 12 and 15 April. Seeding rate was 180 kg ha^{-1} and the spacing between rows was 20 cm. The seeds were treated with Vitavax 200 FS (a.i. carboxin 200 g dm^{-3} + thiram 200 g dm^{-3}) before sowing. Narrow-leafed lupin was grown for seeds and harvested at stage BBCH 89 in the second or last third of August.

Oats were grown on a site were the previous crop had been narrow-leafed lupin. Mineral fertilizers were applied uniformly at rates of N 60, P 22 and K 110 kg ha^{-1} (N-ammonium nitrate, P-triple superphosphate, K-potassium salt). All nutrients were applied once before sowing. In successive years of the study (2008-2010), oats were sown on 11, 12 and 15 April at a rate of 180 kg ha^{-1}. Before sowing all the seeds were mixed with Zaprawa Nasienna T 75 DS/WS seed dressing (a.i. thiram 75%). Tillage was carried out according to the agrotechnical recommendations for oats. Oats were harvested in the first or second third of August (BBCH 89).

The crops were planted in rows oriented north to south (Figure 1). In the strip cropping, maize bordered with narrow-leafed lupin to the east and with oats to the west. Lupin bordered with oats to the east and maize to the west. The eastern border of the oats was adjacent to the maize strip and the western border was next to the lupin.

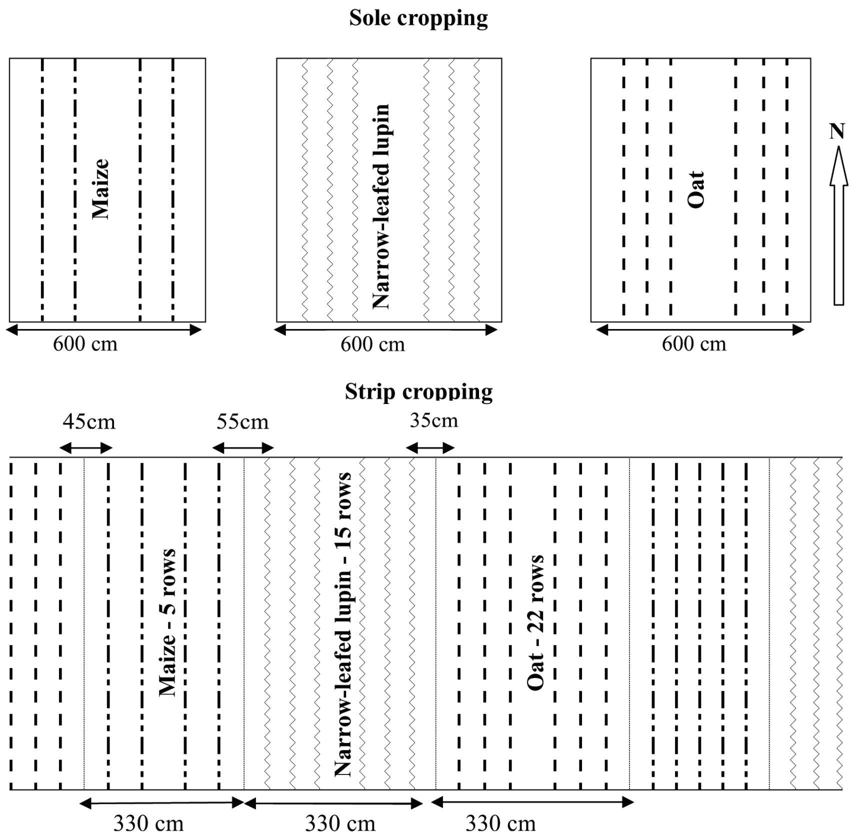

Figure 1. Row arrangements of maize, narrow-leafed lupin and oats in field experiment. In sole cropping and in strip cropping the row spacing of maize was 65 cm, while the row spacing of lupin and of oat was 20 cm and 15 cm respectively. N means north.

Weather conditions varied over the years of the study. Rainfall was lowest in the second year of the experiment (2009) and was lower than the long-term average. Moreover, rainfall was unevenly distributed over the year. A severe shortage occurred in April and July, while heavy precipitation was recorded in May and June. In the first (2008) and the third (2010) years of the study rainfall was much higher and exceeded the long-term average (383.5 mm) by 56.4-61.8 mm. Average monthly temperatures for each year were higher than the long-term average. The year 2010 was particularly warm; the temperature sum (calculated as the sum of the products of the average temperature and the number of days in the month) in the months of April-September was 3,141 ºC (Table 1).

Table 1. Rainfall and air temperature in months IV-IX as compared to the long-term means (1971-2005), according to the Meteorological Station in Zamość.

Rainfall (mm)							
Years	IV	V	VI	VII	VIII	IX	Σ IV-IX
2008	71.5	74.8	48.9	104.6	69.7	80.4	449.9
2009	15.5	102.6	124.4	24.2	48.9	34.5	350.1
2010	30.7	106.7	62.9	143.5	86.1	25.4	455.3
Means for 1971-2005	44.1	65.5	78.9	98.4	54.3	52.2	393.5
Temperature (ºC)							
2008	10.7	15.5	19.4	20.2	20.6	19.7	3031
2009	11.3	13.8	20.2	20.0	20.1	16.9	3122
2010	11.0	15.1	18.4	21.5	20.2	16.6	3141
Means for 1971-2005	7.9	14.1	16.8	18.4	17.8	12.9	2690

Before the maize harvest, plant densities, plant height and the percentage of ears, stems and leaves in the green matter were determined. For the sole cropping plots, the designated test area consisted of 2 m sections from three central rows. Plants were picked by hand and yield components were determined. In the strip cropping plots, plants were hand-picked from a 2 m length of each row and yield and its structure were determined. After mechanical harvesting, the yield of green matter was determined for each plot in the sole cropping and the strip cropping.

In the narrow-leafed lupin grown in sole cropping, plants were picked by hand from two randomly designated sampling areas of 1 m^2 on each plot. For the strip cropping plots, the sampling areas were sections 2 m long from the three rows nearest the maize strip, the middle three rows and the three rows next to the strip of oats. The decision on the number of rows for hand-picking was based on research by Gałęzewski (2006), who reported that the impact of the border effect on the yield and morphological characteristics of oat and lupin plants is reflected mainly in the first row and to a lesser degree in the second. For the plants from the sampling areas, determinations were made of plant density, plant height, first pod height, number of pods per plant, number and weight of seeds per pod, number and weight of seeds per plant and 1,000 seed weight. After harvesting with a plot combine, seed yield was determined at 15% moisture content.

Before the oats were harvested, plants were collected by hand from sample areas designated as in the case of the narrow-leafed lupin and determinations were made of the number of panicles per unit area, culm length, panicle length, seed number and weight per panicle and 1,000 grain weight. After harvesting using a plot combine, oat grain yield was determined at 15% moisture content.

LER–the land equivalent ratio–was calculated as well. LER is a measurement often used to compare the efficiency of mixed cropping and sole cropping or monoculture (Mead and Willey, 1980, Connolly et al., 2001).

LER was calculated according to the formula:

$$LER = \Sigma\ (Y_{si}/Y_{mi})$$

where:

Y_s is the yield of each species in strip cropping (per 0.33 ha),

Y_m is the yield of each species in sole cropping (per ha).

This ratio was calculated for all species (i) to determine the partial LER for each species and then the partial LERs were summed to obtain the total LER for the strip cropping (Table 2) (Mazaheri et al., 2006). A total LER of less than 1 means that the strip cropping is less efficient than sole cropping, while a total LER greater than 1 indicates that strip cropping is more efficient than growing a single species alone.

Table 2. Representative data for calculation of LER.

Crop	Yield in strip cropping (Ys)	Yield in sole cropping (Ym)	Partial LER (Ysi/Ymi)	Total LER for strip cropping
Maize	20.0	54.5	0.36	Σ (Ysi/Ymi)=1.09
Narrow-leafed lupin	15.4	42.4	0.36	
Oat	6.1	16.3	0.37	

The results were analysed by analysis of variance ANOVA using STATISTICA PL. The differences between averages were evaluated using Tukey's test. The results were tested at 95% probability (Kala, 2009).

Results and Discussion

Dent maize

Dent maize yield and yield components varied significantly depending on the cultivation and weed control methods (Tables 3 and 4). The method of cultivation did not significantly affect plant density before harvest. Strip cropping significantly increased the weight of one plant, but decreased plant height by an average of 25 cm. Decreased height of maize in the edge rows of the strip has been observed in other studies (Fortin et al., 1994; Głowacka, 2008). According to Jurik and Van (1994), reduced height of maize in strip cropping, due to the shortening of internodes, may result from changes in the microclimate of the field, mainly wind speed and access to photosynthetically active light. The greater amount of sunlight on the edge rows may promote their overall biomass accumulation, while the greater height of the inner rows apparently reflects the shade-induced stem extension later in the season, since inner rows have lower biomass than edge rows (Jurik and Van, 1994; Lesoing and Francis, 1999). Hruszka (2003) argues that chemical weed control, by reducing weed infestation, creates favourable conditions for the growth and development of maize, thus increasing plant density and height. In our study, weed control method was not found to affect plant density, but the chemical weed control significantly increased plant height (by 22.6 cm) and weight per plant (by 31%).

Table 3. Yield of maize (ton of green matter per ha).

I. Method of cultivation (CM)	II. Weed control (WC)	Years 2008	2009	2010	Average
Sole cropping (1)	A*	53.5	46.7	47.3	49.2
	B	62.6	57.2	59.7	59.8
Strip cropping (2)	A	59.7	47.8	56.1	54.5
	B	67.4	58.9	66.9	64.4
LSD (α=0.05) for CM × WC		n.s.	n.s.	n.s.	n.s
Average for factors					
Averages CM	Sole cropping (1)	58.1	51.9	53.5	54.5
	Strip cropping (2)	63.6	53.4	61.5	59.5
LSD (α=0.05) for CM		2.6	n.s.	1.9	n.s.
Averages WC	A	56.6	47.3	51.7	51.9
	B	65.0	58.1	63.3	62.1
LSD (α=0.05) for WC		0.5	1.2	1.2	0.5
Years		2008			60.8
		2009			52.7
		2010			57.5
LSD (α=0.05)					1.7

*Weed control: A-mechanical, B – chemical.

Table 4. Plant height, density and structure of maize yield (average from 2008-2010).

I. Method of cultivation (CM)	II. Weed control (WC)	Weight of one plant (g)	Plant densities (per 1 m^2)	Plant height (cm)	Percentage in green matter of (%)		
					ears	stems	leafs
Sole cropping (1)	A*	504.6	9.8	226.2	35.0	47.6	17.3
	B	704.5	10.4	253.8	35.4	47.6	16.9
Strip cropping (2)	A	547.8	10.1	205.5	37.5	46.1	16.4
	B	794.4	10.2	222.9	39.8	44.6	15.6
LSD (α=0.05) for CM × WC		n.s.	0.3	5.6	1.0	0.8	n.s.
Average for factors							
Averages CM	Sole cropping (1)	626.2	10.1	240.0	35.2	47.6	17.1
	Strip cropping (2)	694.5	10.2	214.2	38.7	45.3	16.0
LSD (α=0.05) for CM		41.4	n.s.	5.2	1.0	0.7	0.6
Averages WC	A	571.2	10.0	215.8	36.3	46.8	16.9
	B	749.5	10.3	238.4	37.6	46.1	16.2
LSD (α=0.05) for WC		31.9	0.2	4.0	0.7	0.6	0.5
Years	2008	647.0	11.0	228.7	34.5	49.7	15.7
	2009	535.2	9.7	231.2	36.5	47.1	16.4
	2010	798.9	9.7	221.4	39.8	42.6	17.5
LSD (α=0.05)		47.2	0.4	5.8	1.3	1.2	0.8

*Weed control: A- mechanical, B – chemical.

Literature data on the effects of strip cropping on the yield of maize are inconclusive. However, several authors have noted increased maize yield (by about 10-30%) in this system compared to the cultivation of maize alone (Garcia-Préchac, 1992; Lesoing and Francis, 1999). The increase in maize yield is due to its strong response to the edge effect and more efficient utilization of the greater amount of sunlight. Thus maize yield in the border rows of the strips increased significantly (by as much as 50%) and consequently the overall yield was higher (Cruse and Gilley, 1996). Light interception has been observed to be highest in the border rows in strip intercropping of cotton/wheat (Zhang et al., 2007), maize/soybean/oat (Jurik and Van, 2004) and maize/pea (Mao et al., 2012). Furthermore, the roots of one crop may grow to a greater depth than those of the accompanying crop, resulting in spatial niche differentiation in the root zone and optimization of the use of water and nutrients. Mao et al. (2012) reported that one mechanism of complementarity in maize/pea intercropping is that maize plants may extract water from the pea strip during early pea growth when the peas require little water. Cavagilia et al. (2004) also reported that wheat/soybean intercropping increased water and radiation productivity in comparison to sole cropping. The positive edge effect on maize yield is seen mainly in the border row of the strip, but sometimes it may be visible in the second row as well. The present study confirms the beneficial effect of strip cropping on maize yield. Yield of maize grown in strip cropping was on average 8% higher than in sole cropping. This was due to a significant increase in yield in the border rows of the maize strip; by 25-26.9% in the row adjacent to the narrow-leafed lupin and 15.3-17.8% in the row next to the oats (Figures 2 and 3). These differences were partly due to the adjacent plant species. The co-growth period of lupin or oat and maize was 10-11 weeks. During this phase, the maize plants gradually grow higher than the lupin or oat, capturing an ever greater proportion of the available light, water and nutrient resources (Mao et al., 2012). According to Xia et al. (2013) the mechanism behind the greater yield of maize intercropped with a crop such as faba bean or soybean may be related to the corresponding below-ground root length growth and distribution advantages at later growth stages of the maize after the plants have been harvested. There may, however, be other mechanisms behind the greater yield of maize in intercropping systems. Interaction between plants in the rhizosphere in the intercropping system can increase the availability of nutrients for the plants (Gunes et al., 2007). Legumes have the ability to recover phosphorus from unavailable forms. One mechanism is the secretion of organic acids which release phosphorus from unavailable compounds. Bean and soybean mainly secrete citrates (Nwoke et al., 2008), while lupin, field pea and faba bean mainly secrete malate (Nuruzzaman et al., 2005). Legumes may release a large number of carboxylates through their roots, which may play a significant role in increasing the availability to the plants of Fe, Mn, Zn and Ca from less soluble forms (Venkelaas et al., 2003). Maize/narrow-leafed lupin/oat strip cropping has been observed to affect the content of macro- and microelements in maize biomass (Głowacka, 2104a; Głowacka, 2014b). Maize from the edge rows bordering with narrow leafed-lupin accumulated more nitrogen, phosphorus, magnesium and calcium than maize in the border rows next to oat. Strip cropping also increased zinc, iron and manganese content in the maize. The efficiency of strip cropping also depends on the orientation of the strips. In strips running north to south there is a tendency for higher yield in the east border rows compared with the west. This is due to a faster rate of photosynthesis in the cooler mornings, when the sunlight reaches the eastern edge, than in the hot afternoons, when it falls on the western edge of the strip and can not be fully utilized by maize plants due to water stress and wilting. This is not always the case, however, as when Iragavarapu and Randall (1996) grew maize in strips with soy and wheat they found that maize yield increased by 23% in the east border row adjacent to the wheat and by 27% in the border row to the west, adjacent to the soybean strip. According to Qin et al. (2013) intercropping significantly reduced soil respiration and decreased carbon emission compared to maize or wheat monoculture.

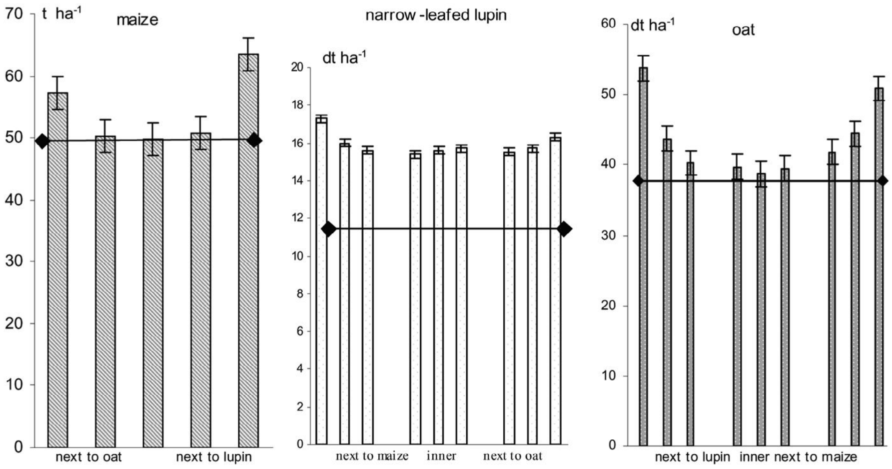

Figure 2. The influence of row position in the strip on yield of maize, oat and narrow-leafed lupin in mechanical weed control.
Note: bars represent the standard errors; ◆———◆ sole cropping.

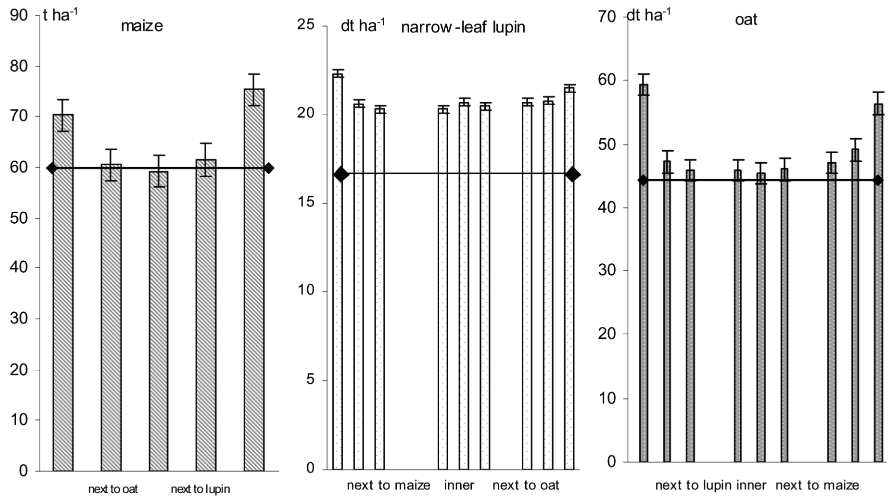

Figure 3. The influence of row position in the strip on yield of maize, oat and narrow-leaf lupin in chemical weed control.
Note: bars represent the standard errors; ◆———◆ sole cropping.

Research on strip cropping indicates the substantial influence of climatic conditions on the effect of this system on yield and on variability between years (Francis et al., 1986). Garcia-Préchac (1992) states that strip cropping of maize, soybeans and oats is more efficient than the cultivation of each species in sole cropping, but only in years with average or high humidity. In a study by Głowacka (2008), where maize was grown in strips with wheat and common beans, in the year with the most favourable weather conditions the maize yield in the strip cropping was significantly lower than in sole cropping. In the year with the least rainfall, the maize yield was slightly higher in the strip cropping, but the differences were not statistically significant. In the present study, in 2009 (the second year of the experiment) strip cropping did not significantly affect maize yield, which was the lowest of any year in the study. Not only was rainfall that year the lowest during the study, but it was not evenly distributed over the growing season. Irrespective of the experimental factors, the maize yield was lower than in the other years. Significant shortages of rainfall occurred that year in July, August and September–months in which, according to Dubas (2004), maize is particularly susceptible to water shortages. During this period the total precipitation should be about 200 mm. Lesoing and Francis (1999) obtained the greatest increase (30%) in maize yield in strip cropping in a year when rainfall was below the long-term average, but well-distributed over the growing season.

Cultivation method significantly affected the structure of the maize yield by increasing the percentage of ears, the most desirable component the yield and decreasing the percentage of stems, while the proportion of leaves remained at the same level (Table 4). A significant increase in the percentage of ears was observed in the border rows of the corn strip (Figure 4). These results are confirmed in research by Głowacka (2008). Lesoing and Francis (1999) noted a significant increase in seed weight and number in the edge rows of maize grown in strip cropping with soybeans, as well as in the number of ears per unit area. Ghaffarzadeh et al. (1997) also reported that maize plants in strip cropping with soybeans produce more seed weight in border rows.

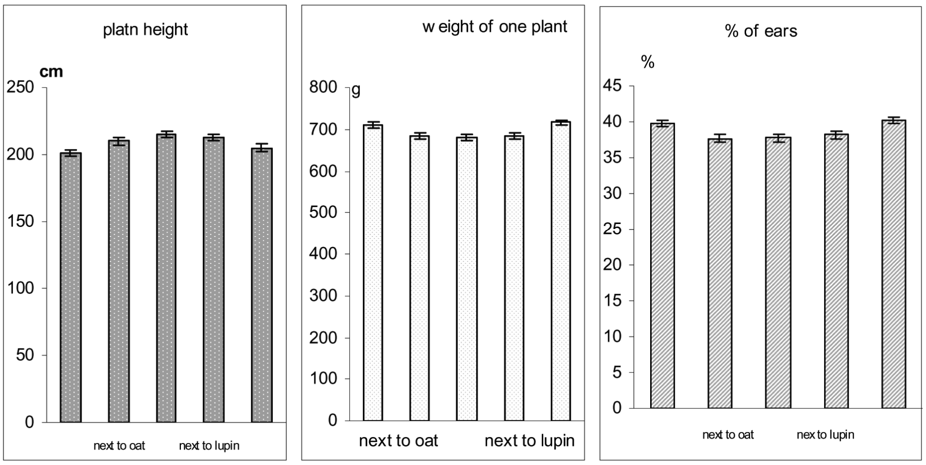

Figure 4. The influence of row position in the strips on some elements of maize yield structure.
Note: bars represent the standard errors.

In another paper (Głowacka, 2013) it was observed and discussed that the number of weeds in the plots with chemical weed control was 2.5 times lower than in the mechanically weeded plots and weed biomass was 3 times lower. Thus, the level of weed infestation resulting from the use of different weed control methods significantly affected the size and structure of the maize yield. The lowest biomass, with the smallest percentage of ears, was noted in case of the mechanical weed control. Use of chemical weed control increased yield by 20% and the percentage of ears by 3.4%. Similarly, in a study by Głowacka (2008), herbicides increased yield by 22.7% and the percentage of ears by 5.9% compared to mechanical weed control. Sowiński and Liszka-Podkowa (2007) found that yield for maize weeded chemically increased 12%, while Cox et al. (1999) noted an increase of 18%. Hruszka (2003), however, states that the most advantageous yield structure, expressed as percentage of ears and leaves (64.1%), was obtained using mechanical methods of weed control. Statistical analysis did not confirm a significant interaction between the cropping systems and weed control methods.

Narrow-leafed lupin

In the successive years of the study (2008-2010), as well as on average for the experiment, strip cropping significantly increased (by 13.7%) the seed yield of narrow-leafed lupin compared to sole cropping (Table 5). Strip cropping also significantly increased the number of plants per unit area, seed number and weight per plant and 1,000 seed weight, but did not significantly affect plant height, number of seeds per pod, or seed weight per pod (Table 6). Statistical analysis confirmed the significant interaction between the method of cultivation and the weed control methods. The beneficial effects of strip cropping on the seed yield of narrow-leafed lupin were pronounced on the plots in which mechanical weed control was used (Tables 5 and 6). This was probably due to the lower weed infestation, observed and discussed in another paper, in the lupin grown in strips and weeded mechanically (Głowacka, 2013). On these plots, strip cropping reduced the number of weeds by 14% and their above-ground dry weight by 37.6% compared to sole cropping. Where chemical weed control was used, the differences between the number and biomass of weeds were not significant.

Table 5. Seeds yield of narrow-leaf lupin (t ha^{-1}).

I. Method of cultivation (CM)	II. Weed control (WC)	Years 2008	2009	2010	Average
Sole cropping (1)	A*	15.5	10.5	11.7	12.5
	B	24.3	18.8	16.9	20.0
Strip cropping (2)	A	18.9	13.5	14.9	15.8
	B	25.4	19.8	17.6	20.9
LSD (α=0.05) for CM × WC		1.3	1.6	1.4	1.7
Average for factors					
Averages CM	Sole cropping (1)	19.9	14.7	14.3	16.3
	Strip cropping (2)	22.1	16.7	16.2	18.3
LSD (α=0.05) for CM		3.2	1.4	0.5	0.9
Averages WC	A	17.2	11.5	13.3	14.0
	B	24.8	19.3	17.4	20.4
LSD (α=0.05) for WC		2.5	1.1	0.3	0.7
Years		2008		21.0	
		2009		15.4	
		2010		15.3	
LSD (α=0.05)				1.3	

* Weed control: A - mechanical, B – chemical.

Table 6. Chosen elements of narrow-leafed lupin yield structure (average from 2008-2010).

I. Method of cultivation (CM)	II. Weed control (WC)	Height of (cm)		Number (piece)			Weight (g)			Plant densities (per 1 m^2)
		Plant	First pod	Pods per plant	Seeds per pod	Seeds per plant	Seeds per pod	Seeds per plant	1,000 seeds	
Sole cropping (1)	A*	62.1	36.9	7.2	3.5	25.5	0.5	3.5	132	91.3
	B	57.5	29.1	9.3	3,6	33.6	0.6	4.9	156	90.0
Strip cropping (2)	A	60.1	33.1	8.6	3.7	32.0	0.5	4.4	155	97.5
	B	60.5	29.7	9.6	4.1	38.7	0.6	5.0	156	95.7
LSD (α=0.05)		n.s.	0.4	0.5	n.s.	n.s.	n.s.	0.3	6.0	n.s.
Average for factors										
Averages CM	Sole cropping (1)	59.9	33.0	8.2	3.6	29.5	0.5	4.2	144	90.6
	Strip cropping (2)	60.3	31.4	9.1	3.9	35.4	0.6	4.7	155	96.6
LSD (α=0.05)		n.s.	0,4	0.5	n.s.	5.8	n.s.	02	5.0	5.0
Averages WC	A	61.1	35.0	7.9	3.6	28.8	0.5	3.9	143	94.4
	B	59.1	29.4	9.4	3.8	36.1	0.6	5.0	156	92.9
LSD (α=0.05)		n.s.	0.3	0.4	n.s.	4.4	0.02	0.2	4.0	n.s.
Years	2009	63.4	34.2	9.8	3.9	38.0	0.6	5.1	154	96.2
	2009	57.6	30.6	7.7	3.6	28.4	0.5	4.1	146	91.7
	2010	59.3	31.8	8.0	3.7	29.6	0.5	4.2	149	92.0
LSD (α=0.05)		4.7	0.7	0.6	n.s.	5.7	n.s.	0.3	4.8	n.s.

*Weed control: A- mechanical, B – chemical.

The increased narrow-leafed lupin seed yield was the result of much higher yield in the border rows, especially those adjacent to the maize strip (Figure 2). Rudnicki and Gałęzewski (2008) found that the edge effect can increase lupin seed yield up to 40% in the border row, compared to the central rows. The literature data on yield in plant species accompanying maize in strip cropping are not conclusive. Lesoing and Francis (1999) found a significant reduction in soybean yield in strip cropping with maize. This is attributed to the fact that as maize is a taller plant it considerably reduced the access of soy to light and competed with it for water and minerals. Egli and Yu (1991) also observed a decrease in soybean yield and number of soybeans due to shade. According to Jurik and Van (2004), maize will have two effects on solar access to soybean in strip cropping. First, at all times of day maize obscures a greater fraction of the sky for soybean rows closer to the maize strip, thus decreasing diffuse radiation. Second, maize to the west of soybean intercepts direct solar rays in the afternoon and progressively shades more of the adjacent soybean rows as solar elevation declines over the course of the afternoon. In the present study, narrow-leafed lupin was sown three weeks earlier than maize, which, combined with the slow initial growth of the maize, reduced competition with the lupin in the early stages of its development. In addition, the third plant–the oats–may have reduced the negative impact of maize. A lesser degree of competition from maize is indicated by the much greater number of pods per plant in the row immediately adjacent to the maize strip (Figure 5). Pavlish (1989) states that strip cropping of sorghum and soybeans significantly increases soybean yield. This is probably due to the minimized interference with the incoming light and the complementary use of other factors that affect the growth of plants. A study by Głowacka (2011) showed that strip cropping of dent maize, spring wheat and common bean may increase the marketable yield of bean seeds compared to single-species crops. However, the beneficial effect of strip cropping (expressed as higher marketable yield and a smaller percentage of waste) is clearly visible only in the case of mechanical weed control methods.

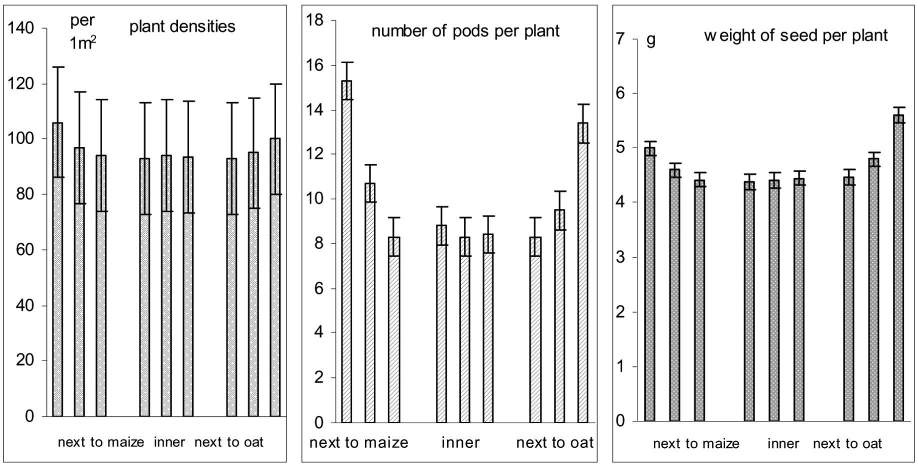

Figure 5. The influence of row position in the strips on some elements of narrow-leafed lupin yield structure.
Note: bars represent the standard errors.

Lupin, like other pulses, is susceptible to weed infestation and competition from weeds (Landroct-White and Biddle, 2007; Buraczyńska, 2011). Hence, a high seed yield can be achieved through the use of chemical weed control. In narrow-leafed lupin chemical weed control reduced the number of weeds by 37.2% and their biomass by 52.7% compared to the mechanical treatment (Głowacka, 2013). As might be expected, the lupin seed yield was significantly higher–by 6.4 dt ha^{-1} (45.7%) on average for the study–where the chemical weed control was used than for the mechanical method. This was confirmed in research by Gugała and Zarzecka (2012), who achieved yield of 1.15 dt ha^{-1} with harrowing alone and 2.36 dt ha^{-1} with appropriately selected herbicides.

Oat

Oat grain yield varied in individual years of the study and varied depending on the cultivation and weed control methods (Tables 7 and 8). Yield of oats grown in strip cropping was significantly higher (+8.7%) than in sole cropping. Strip cropping also affected yield components; it significantly increased grain number and weight per panicle, without affecting 1,000 grain weight. The positive effect of strip cropping may result from the early sowing of the oats and thus less competition in the early stages of development from the accompanying plants, in particular maize. Maize may also be a shield against the wind for the oat plants. But this is not always the case, as in a study by Głowacka (2010) strip cropping of maize, wheat and common bean resulted in a significant reduction in the yield of spring wheat. This could be due to increased competition from maize plants for light, water and nutrients in comparison with the shorter, less competitive wheat plants. This, in turn, could result in a poorer environment for the wheat plants at the edges of the strip immediately adjacent to the maize strip. Crusoe (1992), however, believes that competition between maize and cereal crops in strip cropping should be minimized, as these are plants with different cycles of development and their maximum demand for water and minerals occur at different times, as do sowing and harvest. According to Coll et al. (2012), avoiding overlapping of critical periods improves complementarities in the use of resources between intercrop components, which improves the efficiency of resource use. This is confirmed by the present study. The greater grain yield of oats in the strip cropping resulted from the higher yield of plants from the rows at the edge of the strip (Figure 6). A significant increase in grain yield was recorded in the two edge rows. Yield was 47-54.5% higher in the first row bordering with the lupin and 13-20% higher in the second row. An increase of 33-45% was noted in the first edge row of oats bordering the maize strip and a 14.4-14.7% increase in the second. When Rudnicki and Gałęzewski (2008) studied the response of oats to the border effect, they observed a significant increase in grain yield in the first edge row, by as much as 85% and a visible but not statistically significant increase in the second row.

Table 7. Grain yield of oats (t ha^{-1}).

I. Method of cultivation (CM)	II. Weed control (WC)	Years 2008	2009	2010	Average
Sole cropping (1)	A*	46.5	29.5	41.7	39.2
	B	52.0	37.8	46.9	45.6
Strip cropping (2)	A	51.5	34.5	43.8	43.3
	B	56.9	41.1	48.6	48.9
LSD (α=0.05) for CM × WC		1.5	0.7	n.s.	0.4
Average for factors					
Averages CM	Sole cropping (1)	49.3	33.7	44.3	42.4
	Strip cropping (2)	54.2	37.8	46.2	46.1
LSD (α=0.05) for CM		1.4	0.7	0.5	0.4
Averages WC	A	49.0	32.0	42.8	41.2
	B	54.4	39.4	47.7	47.3
LSD (α=0.05) for WC		1.1	0.5	0.4	0.3
Years		2008		51.7	
		2009		35.7	
		2010		45.2	
LSD (α=0.05)				2.4	

*Weed control: A- mechanical, B – chemical.

Table 8. Chosen elements of oats yield structure (average from years 2008-2010).

I. Method of cultivation (CM)	II. Weed control (WC)	Number of panicles (per 1 m^2)	Length of (cm) culm	Length of (cm) panicle	Grain number per panicle (piece)	Weight of grain per panicle (g)	1,000 grain weight (g)
Sole cropping (1)	A*	534	115.4	17.9	72.9	2.28	30.9
	B	552	120.7	16.6	68.9	2.00	32.5
Strip cropping (2)	A	549	114.2	19.3	78.2	2.73	31.4
	B	563	118.6	17.2	77.8	2.42	33.0
LSD (α = 0.05) for CM × WC		n.s.	n.s	0.6	n.s.	n.s.	n.s.
Average for factors							
Averages CM	Sole cropping (1)	543	118.0	17.2	69.9	2.14	31.7
	Strip cropping (2)	556	116.4	18.2	78.0	2.57	33.0
LSD (α=0.05) for CM		3.1	1.3	0.5	6.3	0.1	n.s.
Averages WC	A	542	114.8	18.6	75.6	2.5	31.2
	B	558	119.6	16.9	72.3	2.2	32.8
LSD (α=0.05) for WC		2.4	9.7	0.4	n.s.	0,1	0.4
Years	2008	579	129.8	18.5	88.7	2.70	32.5
	2009	514	104.5	17.0	59.2	2.10	30.4
	2010	560	122.3	17.8	73.9	2.60	33.1
LSD (α=0.05)		3.7	11.6	0.7	10.9	0.4	0.7

*Weed control: A - mechanical, B – chemical.

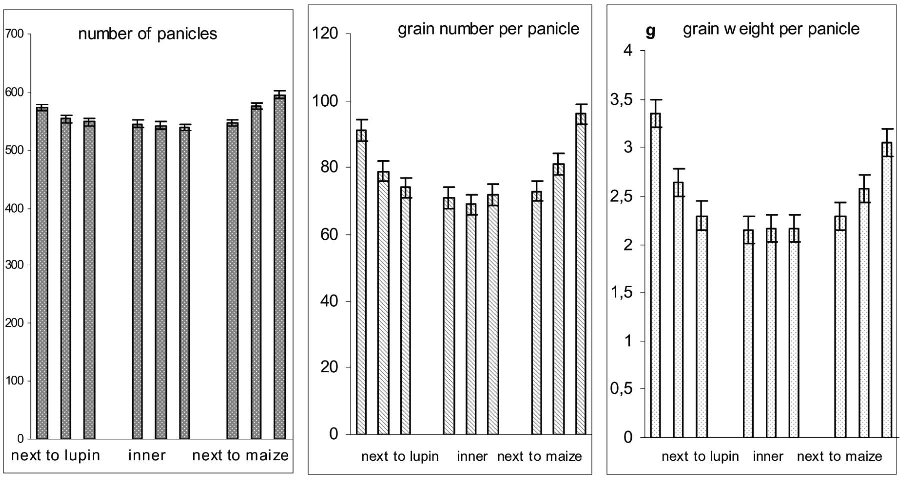

Figure 6. The influence of row position in the strips on some elements of oats yield structure.
Note: bars represent the standard errors.

Due to the early date of sowing, the rapid weight increase of the roots and aboveground parts and large leaf surface, oats are more competitive with weeds than other grain crops, so that, according to some authors, chemical weed control can be dispensed with (Idziak and Michalski, 2003). However, in the case of severe weed infestation, herbicides should be used for weed control (Leszczyńska, 2007). In the present study, significantly higher yield–by an average of 6.6 dt ha^{-1} (16.1%)–was obtained using the chemical method, which is consistent with the results of Sadowski and Rychcik (2009), while the lowest yield was noted in plots in which the mechanical method was used. Herbicide use in oat decreased the total number of weeds by 53.2% and weed biomass by 68.3% compared to mechanical weed control (Głowacka, 2013). It may also be noted that the differences between the mechanical and chemical weed control methods were smaller in the strip cropping than in the sole cropping. Strip cropping increased grain yield of oat by 10.5% where mechanical weed control was used and by 7% where the chemical method was used.

Total biological productivity of the system

Land equivalent ratio (LER) is a measure often used to compare the efficiency of sowing mixed crops with sole cropping or monoculture (Connolly et al., 2001). When Francis et al. (1986) analysed 23 different strip cropping patterns, they reported that, for 17 of these the land equivalent ratio ranged from 0.97 to 1.03, while only one LER was less than 0.95. The most beneficial patterns were as follows:

LER=1.15 → 6 rows of maize: 6 rows of soybeans

LER=1.18 → 4 rows of maize: 4 rows of common bean (Francis et al., 1986)

These data indicate that the strip cropping in these experiments ranged from about 5% less efficient to 18% more efficient than sole cropping.
In the present study the land equivalent ratio was as follows:

LER=1.14 and 1.05 (for mechanical and chemical weed control) → 5 rows of maize: 16 rows of narrow-leafed lupin: 22 rows of oats.

On average for the experiment the land equivalent ratio was 1.06, which means that the strip cropping of maize, narrow-leafed lupin and oats was 6% more efficient than the cultivation of these species in sole cropping. It is worth emphasizing that the total biological productivity of the strip cropping expressed as LER was greater for mechanical weed control than for the chemical method (Table 9). Differences in LER for different years of the study were small.

In the studies by Lesoing and Francis (1999) the LER for strip cropping of maize and soybeans was 0.99 -1.1 and for strip cropping of sorghum and soybean it was 1.02-1.04, which indicates similar efficiency of strip cropping and monoculture.

Table 9. Total LER and partial LERs for strip cropping and different weed control methods.

Weed control (II) (WC)	Year	Partial LER for			Total LER
		maize	narrow-leafed lupin	oat	
A*	2008	0.37	0.36	0.40	1.13
	2009	0.34	0.38	0.42	1.14
	2010	0.39	0.35	0.42	1.16
	Mean	0.36	0.36	0.41	1.14
B	2008	0.35	0.36	0.34	1.05
	2009	0.34	0.36	0.35	1.05
	2010	0.37	0.34	0.34	1.05
	Mean	0.36	0.35	0.34	1.05
Average		0.35	0.35	0.36	1.06

*Weed control: A- mechanical, B – chemical.

Conclusion

Strip cropping significantly increased maize yield, as well as the percentage share of its most valuable parts, i.e., the ears. There was significant interaction between the methods of cultivation and weed control with respect to yield and yield components. The beneficial effects of strip cropping on seed yield in narrow-leafed lupin were significant only where mechanical weed control was used. Strip cropping significantly increased plant density, seed number and weight per plant and 1,000 seed weight, but had no effect on plant height, number of seeds per pod, or seed weight per pod. Oat grain yield was slightly higher in the strip cropping than in the sole cropping. Strip cropping also positively affected yield components, such as grain number and weight per panicle. Yields of maize, oat and narrow-leafed lupin were significantly higher for the chemical weed control method than the mechanical method. Particularly marked differences between the weed control methods were noted in the case of the narrow-leafed lupin. It is generally noted that in strip cropping edge effects have a marked influence on the development and yield of crops in the border rows of adjacent strips. The size of the edge effect depends not only on the plant species, but also on the neighbouring plants in the strip. However, the mechanism behind these changes has not been adequately explained. Is it the result of better use of light and water in the edge rows, differences in the depth and development rate of the root system, or interspecific interaction affecting the availability of nutrients? Further studies are needed in different environment conditions to explain these mechanisms. The land equivalent ratio confirmed the greater efficiency of strip cropping of maize, narrow-leafed lupin and oat in comparison with these species grown separately in sole cropping. In the present study only spring crops were cultivated. It would be interesting to conduct strip cropping of winter crops as well. This would change the co-growth period of the plants and interspecific competition or facilitation.

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