

Article

Strip Intercrop of Barley, Wheat, Triticale, Oat, Pea and Yellow Lupine—A Meta-Analysis

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Abstract: The simultaneous sowing of two or more species in the same field without a fixed location in relation to each other—mixed intercropping—is associated with the problem of optimizing agrotechnics for plants with different requirements and instability of the composition of the crop. An alternative which eliminates these problems can be strip intercropping. Based on the published results of seven long-term field experiments aimed at understanding the proximity effect of various species in strip intercropping, a mathematical simulation of strip intercropping production effects was performed: oat/lupine, barley/pea, wheat/pea, triticale/pea, wheat/barley, wheat/triticale, and triticale/barley. The simulation takes into account different widths of the strips and the possibility of their separation by a path. The yield of strip intercropping consisting of cereals and legumes was similar to the average yield of both components grown in single-species crops. Separating the cereal from the legume plant by a path did not have a major effect on the total yield; however, it increased the share of the legume plant in the yield. The width of the strips was also important in terms of yield and the share of individual species in the yield, especially when strips were separated by a path. Taking into account the level of yield and the technical possibilities of optimizing agrotechnics for each of the components separately, as well as the possibility of separate harvesting, then strip intercropping and strip intercropping separated by paths, with 3 m wide strips, are justified. The analysis of the results showed that the formation of strip intercropping or strip intercropping separated by paths consisting of only two species of cereals does not bring production benefits when compared to monoculture of the individual components.

Keywords: proximity effect; border effect; intercropping; strip farming; legume; cereals



Citation: Gałęzewski, L.; Jaskulska, I.; Jaskulski, D.; Wilczewski, E.; Kościński, M. Strip Intercrop of Barley, Wheat, Triticale, Oat, Pea and Yellow Lupine—A Meta-Analysis. *Sustainability* **2022**, *14*, 15651. <https://doi.org/10.3390/su142315651>

Academic Editor: Teodor Rusu

Received: 27 October 2022

Accepted: 18 November 2022

Published: 24 November 2022

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1. Introduction

The basic reasons put forward for growing different plant species in one field at the same time are:

- Obtaining a yield generally higher or equivalent to that of pure sowing, but of higher fodder or utility quality, especially when one of the components is a legume [1–4];
- High stability of plant production in the changing weather conditions of subsequent growing seasons [5,6];
- The possibility of limiting nitrogen fertilization when one of the components is a legume plant [7–10];
- Increased efficiency in the use of solar radiation, nutrients, and water [11–13];
- Increasing biodiversity [14–16], including soil flora and fauna [17–19];
- Increasing the content of organic matter in the soil and improving the physical properties of the soil [14–20];
- Higher fore-crop value [21,22];
- Less disease and pest infestation [19,23–25];
- Generally greater resistance to weed infestation [26–29];

- Pro-ecological food production [30].

Scientific research, however, marginalizes the significance of intercropping problems that appear in agricultural practice. Consequently, intercropping is not widespread worldwide, but only regionally and mainly in small farms [31,32].

There are several reasons indicated by Mamie and Farès [33], on the example of wheat-pea mixtures, as to why agricultural practice shows little interest in this method of cultivation. The most important were a lack of industrial buyers, a lack of technical references, insufficient control of sanitary issues, unstable or insufficient yield, higher production costs, and difficulties in harvesting, storing, and sorting the yield.

Moreover, a significant limitation in the optimization of the production of intercrops is the determination of the level and method of nitrogen application. The management of nitrogen supplied in cultivation with the simultaneous optimization of its use by various species is difficult to implement [34], which is of particular importance in terms of both sustainable management [35,36] and production economics [37]. Another problem is the variable proportion of species in the yield in different years, despite the maintenance of the same agrotechnical assumptions [33], a consequence of which is a difficulty in balancing feed [38].

However, individual advantages and disadvantages have very different meanings depending on the selection of species, the way they are located in relation to each other in the canopy, and the production profile of the farm. The intercropping of different plant species in one field can be carried out in various ways [39]. The classic method of growing different species at the same time in the same field is mixed intercropping—simultaneous seeding of two or more species in the same field without a fixed location in relation to each other. This method of cultivation reveals all the advantages and disadvantages of intercropping. Other methods are row intercropping and strip intercropping (Figure 1).



Figure 1. Photograph of an exemplary strip intercropping showing the edge effect of oats and the effect of the proximity of oats and lupines.

Basically, row intercropping—alternating rows of two or more species—has the same agrotechnical limitations as mixed intercropping and is also technically difficult to sow. In the definition of strip intercropping—alternating strips of two or more species—Vandemeer [39] does not specify the maximum width of a strip of each species. Therefore, if we adopt

strips for each of the species with a width that allows for the use of optimal agrotechnics and enables separate harvesting for each species, it makes it possible to eliminate the most important disadvantages of mixed crops while maintaining their advantages in the scale of the field. In such a case, the interspecific impacts will only occur in the border rows. The immediate proximity of the cultivation strips of various species may reveal both negative and positive interspecies interactions in the zone of their contact. Separating the strips with a non-planted path makes it possible to eliminate unfavorable impacts. Additionally, the losses related to the presence of uncultivated space can be compensated for by the border effect. Plants with greater access to environmental resources along a non-planted path tend to be more lush than plants inside the canopy [40–43]. The presence of the path also allows for greater control of the application of fertilizers and plant protection products dedicated to the strip of one species and constitutes a protection zone for the strip of the other species. Since the authors in previous studies have recognized the proximity effect of rows of different plant species [44–49] in the context of interactions, it is possible and necessary to recognize this topic in terms of a simulation of their field-scale production effects, depending on the width of the strips of individual plant species. Research on the possibility of strip intercropping of plants using their biological potential for shaping the canopy and the use of environmental factors is part of the current search for solutions which limit the pressure of agriculture on the environment [50,51].

Based on the current knowledge, the authors hypothesize that the known values of proximity effect and border effect obtained in microplot experiments can be estimated for production conditions using mathematical calculations, formulating specific agrotechnical recommendations.

The aim of the meta-analysis was to indicate the production consequences of the selection of species (wheat, triticale, oat, pea, and yellow lupine) for strip intercrops for agricultural practice. The aim of this manuscript also includes understanding the influence of the width of adjacent strips of different species on the total yield of intercrops and the share of individual components in the yield. The aim of the study was also to find out the effect of introducing a path which separates adjacent strips on the crop and its composition.

2. Materials and Methods

A simulation of the yield of plants grown in the strip intercropping system on the scale of a production field was developed on the basis of experimental data obtained in plot studies [44–49]. These experiments aimed to understand the proximity effect and the border effect of different plant species. The cited works provide detailed information on methodological assumptions, habitat conditions, agrotechnical practices, measurements, and analyses.

2.1. Experiment Site

Seven multi-year long plot experiments that aimed to learn about the effects of growing plants in the strip intercrop system (oat/lupine, barley/pea, wheat/pea, triticale/pea, wheat/barley, wheat/triticale, and triticale/barley) were carried out at a Research Station (53°13' N; 17°51' E) in Poland.

2.2. Experiment Design

All seven experiments differed only in the selection of species in adjacent strips. All other methodological assumptions were the same. The basic assumptions are presented below. The experiments were analyzed as one-way in a randomized block design with 4 replications. The plots were 150 cm wide and consisted of 12 rows of plants 12.5 cm apart. The experimental factor was the location of each of the first 4 rows of plants of one species in the plot—four rows deep into the plot—from the second neighboring species (Figure 2A) or from a 50 cm wide path without overgrowth (Figure 2B). The first row (contact) was 12.5 cm away from the first row of the neighbor species or from a path. On the basis of the results of previously conducted research, the fourth row of plants—representing the

interior of the canopy—was established as not being subject to neighborly influences. The plots were situated with the longer side in the north–south direction.

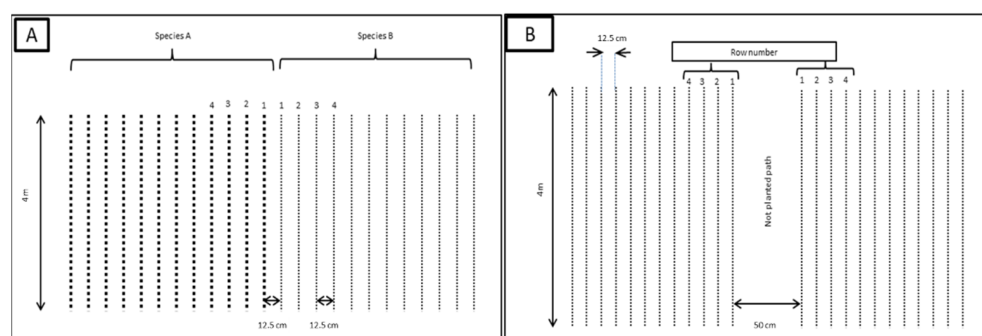


Figure 2. Single plot diagram. (A)—proximity effect, (B)—border effect.

In this study, the following objects were used for comparisons:

SI—strip intercrop with immediate proximity of the strips (Figure 2A);

SIp—strip intercrop with strips separated by a path (Figure 2B);

PSx—pure sowing, the 'x' in subscript represents the species;

Mps—the averaged total yield of pure sowing of each species for an area of 1ha (yield PSx Mg·hm^{−2}·0.5 + yield PSy Mg·hm^{−2}·0.5).

The above abbreviations have been used in the chapters: Sections 2 and 3.

2.3. Elements of Agrotechnical Practises

All plant species were sown at the same time and, depending on the year, they were sown from 25 March to 5 April. In order to obtain an equal distance between the plants in a row, cereal grains were placed pointwise on seed tapes (made of tissue paper) at a density of 45 grains·m (360 grains·m^{−2}). The sowing tapes were placed in the soil at a depth of 4 cm. Lupine and pea seeds were sown manually at a density of 10 seeds·m (80 seeds·m^{−2}).

The following cultivars were used: yellow lupine 'Lidar', spring wheat 'Bombona', spring triticale 'Dublet', spring barley 'Antek', pea 'Ramrod', and oat 'Deresz'.

In the spring, the following were applied before tillage: 30 kg P·hm^{−2}, 66 kg K·hm^{−2}, and 34 kg N·hm^{−2}. In the phenological phase, BBCH 22–25 (tillering stage) N fertilization (34 kg N·hm^{−2} dose) was applied only on cereals. A herbicide with the active ingredient-linuron (Alfalon 450 SC), at a dose of 1 dm³·hm^{−2}, was applied to each crop immediately after sowing.

2.4. Data Analysis

The strips of homogeneous plants in the strip intercropping system were narrow to allow for the possibility of revealing interactions between neighboring species. The working width of agricultural machines or their separate sections used in modern agriculture for sowing, care, and harvesting is from several to several dozen metres. In order to estimate the yields and their structure on the scale of a production field, we assumed the alternating occurrence of strips of two plant species in immediate proximity, 3 m wide each (SI), or strips (3 m wide) separated by a 50 cm-wide non-planted path (SIp). The yields were calculated for a square with an area of 1 ha, where 17 strips of each of the two species were located alternately (34 strips in total). The estimated yield of a single species in the SI—for 3 m-wide strips consisting of 24 rows—was derived from the formula:

$$\text{Yield SI} = (2 \cdot X_1 + 2 \cdot X_2 + 2 \cdot X_3 + 18 \cdot X_4) \cdot Y \quad (1)$$

where: X_{1-4} —yield in subsequent rows from the neighboring species (Figure 2).

Y—conversion factor from $\text{g}\cdot\text{m}^{-1}$ (gram per 1 running meter of a row) to the surface area $\text{Mg}\cdot\text{ha}^{-2}\cdot 0.5$ —variable depending on whether the strips were separated by a path or not

The estimated yield of a single species in PS (pure sowing) resulted from the formula:

$$\text{Yield PS} = 24 \cdot X_4 \cdot Y \quad (2)$$

where: X_4 —yield in the fourth row from the neighboring species (Figure 2).

Y—conversion factor from $\text{g}\cdot\text{m}^{-1}$ (gram per 1 running meter of a row) to the surface area $\text{Mg}\cdot\text{hm}^{-2}\cdot 0.5$

The total yield of the SI was the sum of the yields for both species (calculated from Equation (1)). The presented formulas were used to calculate the data presented in bar charts (Figures 4, 6, 8, 10, 12, 14 and 16).

Figures 5, 7, 9, 11, 13, 15 and 17 show yield simulations of both species included in the SI and the total SI yield depending on the number of plant rows in the strip. The more rows in the strip, the wider it is. The wider the strips, the smaller their number in the field. For example, in the case of a single species strip consisting of two rows in the strip, the width of the strip would be 0.25 m and the total number of strips of both species on the whole field would be 400 for species in immediate proximity, or 184 strips that are 0.625 m wide for strips separated by a non-planted path. The simulation was carried out in the range of 2–24 rows in the strip. The simulation was carried out for a square-shaped field with an area of 1 ha. Depending on the width of the stripes, the field width ranged from 97.8 to 102.0 m and the field length 98.0–102.3 m for objects without paths. For objects with paths, the field width varied between 110.5–117.0 m and the field length 85.5–95.0 m.

The estimated yield of a single species in SI depending on the number of rows in a strip resulted from the formulas:

For two rows in the strip:

$$\text{Yield SI} = (2 \cdot X_1) \cdot Y \quad (3)$$

For four rows in the strip:

$$\text{Yield SI} = (2 \cdot X_1 + 2 \cdot X_2) \cdot Y \quad (4)$$

For six rows in the strip:

$$\text{Yield SI} = (2 \cdot X_1 + 2 \cdot X_2 + 2 \cdot X_3) \cdot Y \quad (5)$$

For eight rows in the strip:

$$\text{Yield SI} = (2 \cdot X_1 + 2 \cdot X_2 + 2 \cdot X_3 + 2 \cdot X_4) \cdot Y \quad (6)$$

For a larger (even) number of rows in the strip:

$$\text{Yield SI} = (2 \cdot X_1 + 2 \cdot X_2 + 2 \cdot X_3 + (N - 6) \cdot X_4) \cdot Y \quad (7)$$

where: X_{1-4} —yield in subsequent rows from the neighboring species (Figure 2);

N—number of rows in the strip;

Y—conversion factor from $\text{g}\cdot\text{mb}^{-1}$ (gram per 1 running meter of a row) to the surface $\text{Mg}\cdot\text{ha}^{-2}\cdot 0.5$.

The Y value in the simulation was variable depending on whether the strips were separated by a path or not.

In these estimated yields, the same number of rows was always assumed for both species and the width of the strips was the same for both species.

The total unsown area on the field scale resulting from the presence of paths separating arable strips in the SIp sites was dependent on the width of the strips (number of plant rows in the strip). At the extremes, for strips with a width of 3 m (24 rows) + path, the

unsown area was $0.056 \text{ hm}^2 / 1 \text{ hm}^2$ (5.6%) and, in the case of strips with a width of 0.25 m (2 rows) + the path, the area was $0.652 \text{ hm}^2 / 1 \text{ hm}^2$ (65.2%) (Figure 3). For all estimates, it was taken into account that the path width was 37.5 cm (50 cm – 12.5 cm).

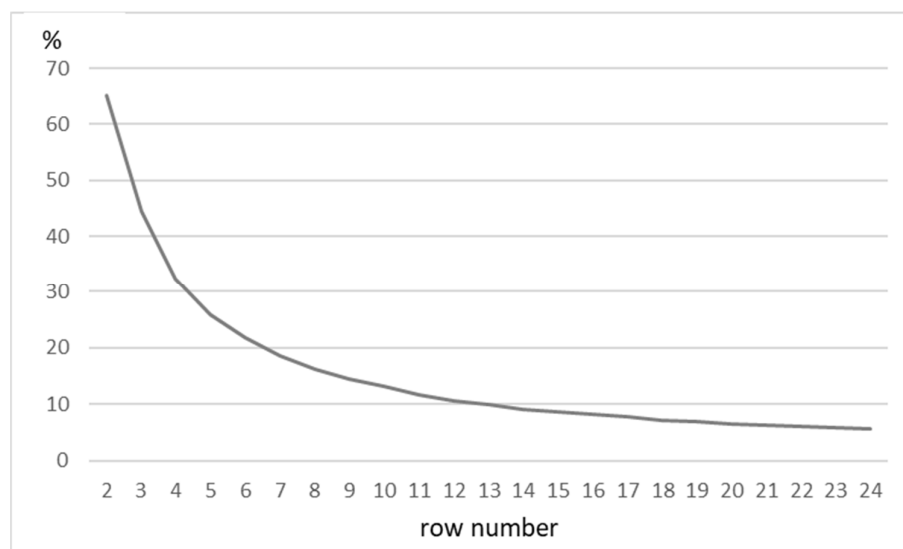


Figure 3. The share (%) of the non-planted path area in the total field area in SIp depending on the number of plant rows in each strip.

The yields of plants grown in SI and SIp in comparison to the yields of plants in pure sowing were also assessed and presented in accordance with the LER coefficient formula (land equivalent ratio) [52].

3. Results and Discussion

Strip intercropping is a common practice of intercropping for maize and soybeans. The world literature in this area is very extensive and covers many aspects, both productive and cognitive [53]. The strip intercropping of other species with maize is also practiced [54,55]. Few studies show SI results for other crop species [56,57], especially those included in this meta-analysis. Until now, only the current authors' earlier studies have addressed the problem of strip intercropping of wheat, triticale, barley, oats, peas, and yellow lupine in such a comprehensive approach. This is a problem when trying to directly compare your own results with the results of other scientific works. In the discussion, the current authors most often refer to results obtained in mixed intercropping covering the species spectrum discussed in this work.

3.1. Cereal/Pea

3.1.1. Barley/Pea

The results of the estimation of the total yield with immediate proximity of 3 m wide strips of pea and barley and the total yield with the strips separated by a path indicate only a slight difference between these objects, amounting to only $0.04 \text{ Mg} \cdot \text{hm}^{-2}$ (Figure 4). The reduction in the area covered with plants did not result in a significant decrease in the yield. The border effect is effectively eliminated by the presence of non-planted paths separating arable strips every 3 m. It should be noted, however, that the total non-planted area is small and occupies 5.56% of the total area of the field (Figure 3). In pure sowing, barley has a higher yield than pea; therefore, in SI, to a greater extent, it is barley that determines the total yield of the SI and SIp than pea. Interspecific interactions in the rows of adjacent strips do not change this situation. As a result, the barley and pea yield ratio in the total yield for both SI, SIp and Mps is approximately 2:1. However, it should be noted that the introduction of a path separating the strips results in an increase in the share of pea in the total yield by 2.0 p.p. (percentage point). The Mps of both species indicates the possibility

of obtaining a higher total yield from the same area, but only by $0.10 \text{ Mg}\cdot\text{hm}^{-2}$ (SI) and $0.14 \text{ Mg}\cdot\text{hm}^{-2}$ (SIp), with Mps having a smaller share of pea than in the SIp by 0.8 p.p.

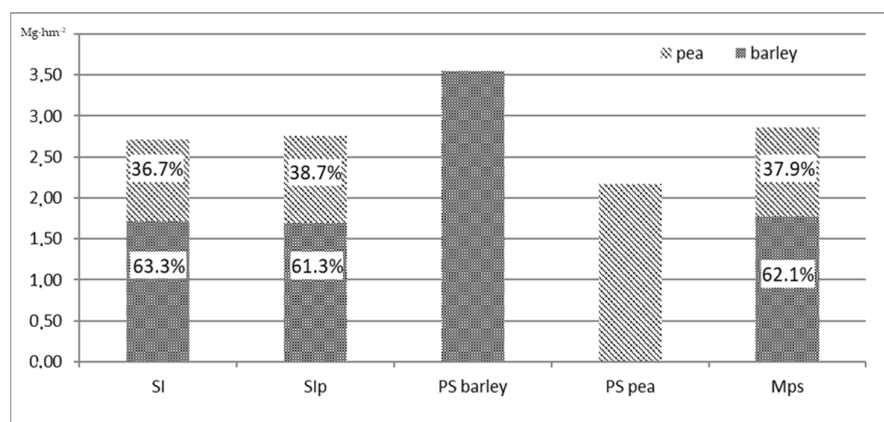


Figure 4. Estimated SI (strip intercrop with immediate proximity of the strips) and SIp (strip intercrop with strips separated by a path) barley/pea yield and yield structure against the background of pure sowing (PS) and the averaged total yield (Mps).

The simulation of the proximity of pea and barley strips of different widths indicates that reducing the width of the strips below 3 m (24 rows of plants) results in a reduction of the total yield of the intercrop, while, in the case of SI, this phenomenon is slightly more intense than in the case of SIp (Figure 5). The described dependence is more noticeable for the yield of pea than for the yield of barley. In the case of barley, with very narrow strips consisting of 2–4 rows, the presence of a path separating it from the pea turns out to be more unfavorable than immediate proximity to the pea, because such a large percentage, i.e., 32.5–65.2% (Figure 3), of the non-planted area in the scale of the entire field is not effectively compensated for by the border effect.

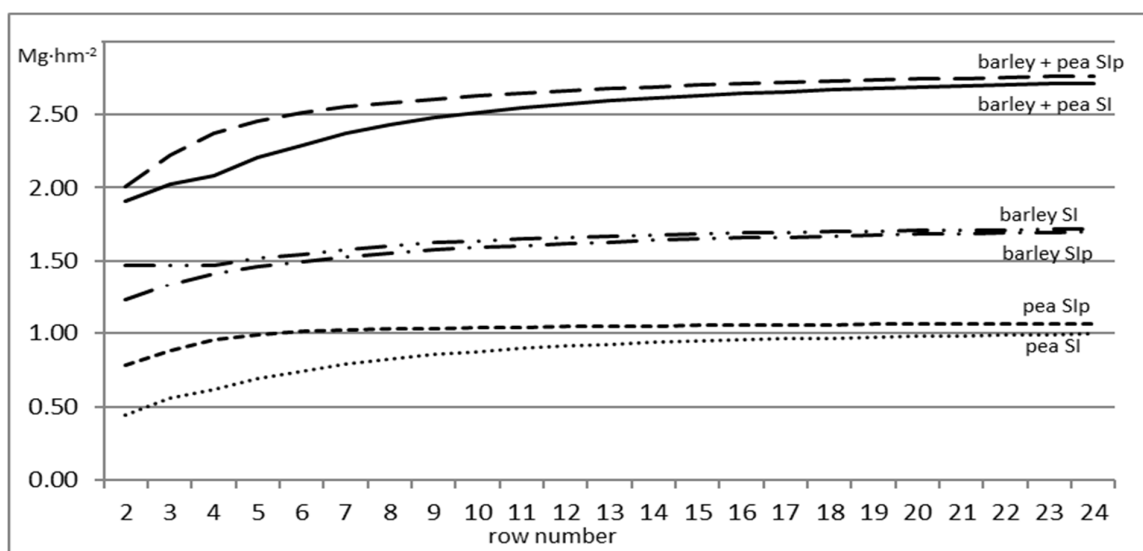


Figure 5. Estimated yield of barley (barley SI, barley SIp) and pea (pea SI, pea SIp), and their total yield (barley + pea SI, barley + pea SIp) depending on the number of plant rows in the strip and the presence of a path separating the strips.

3.1.2. Wheat/Pea

The estimated SI effects of wheat indicate that the introduction of a path separating the strips does not affect the yield, but results in a slight (2.1 pp) increase in the share of pea

seeds in the total yield (Figure 6). SIp gave similar effects to Mps in terms of yield composition, although, in this case (Mps), the average overall yield was only $0.08 \text{ Mg} \cdot \text{hm}^{-2}$ higher.

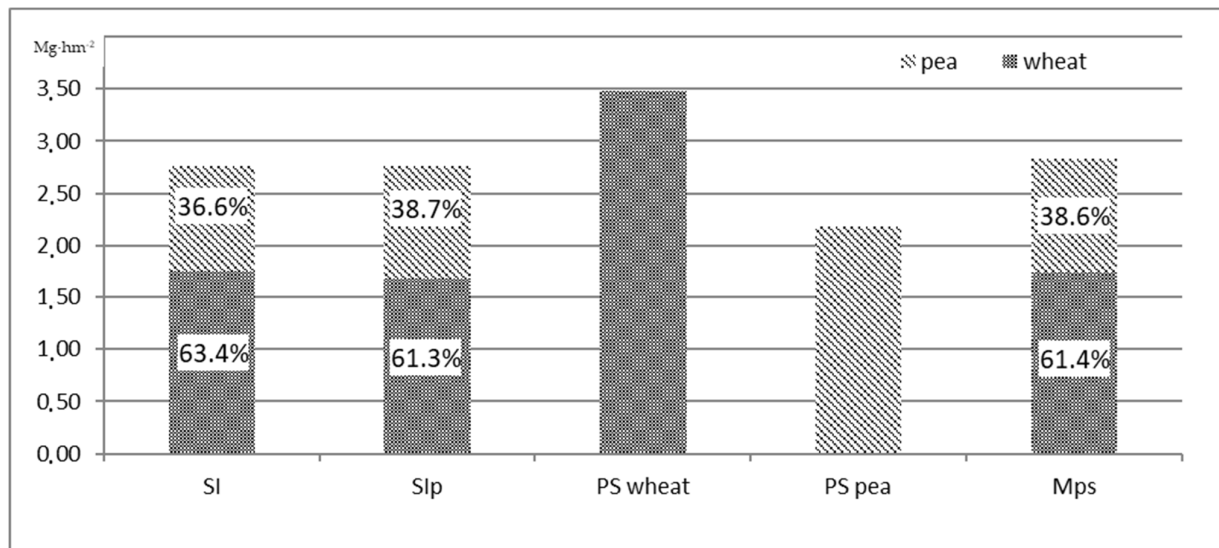


Figure 6. Estimated SI and SIp wheat/pea yield and yield structure against the background of pure sowing (PS) and the averaged total yield (Mps).

Narrowing the width of the strips turns out to have a beneficial effect on the yield of wheat directly adjacent to the peas, while it is unfavorable when these two species are separated by a path (Figure 7). The opposite is true for the pea yield. Separating the strips of adjacent species is beneficial for the yield of peas. Its decrease as a result of the decreasing width of the strips is smaller in the presence of a path—a non-planted area—than in the immediate proximity of wheat. Overall, however, due to the higher yield of wheat than pea in the total yield, reducing the width of the strips separated by a path results in a greater yield reduction than from the strips directly adjacent to each other.

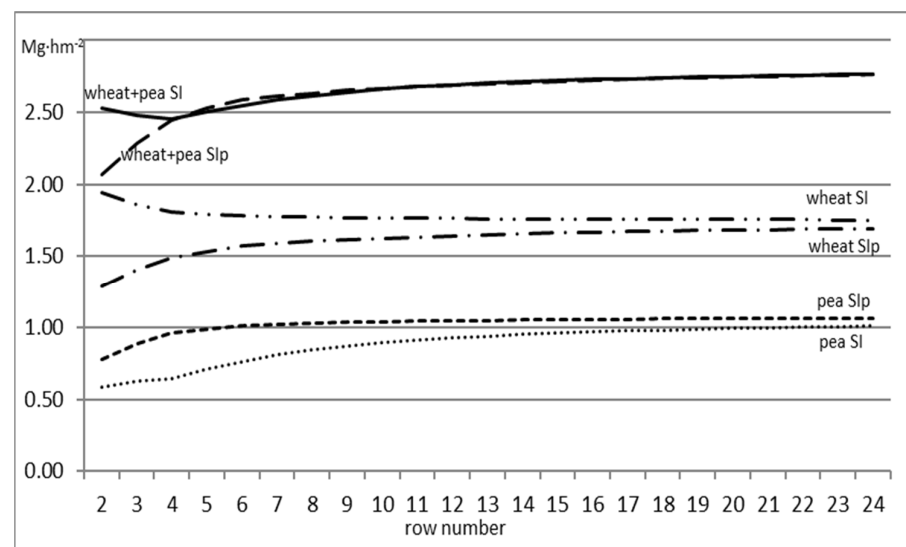


Figure 7. Estimated yield of wheat (wheat SI, wheat SIp) and pea (pea SI, pea SIp), and their total yield (wheat + pea SI, wheat + pea SIp) depending on the number of plant rows in the strip and the presence of a path separating the strips.

3.1.3. Triticale/Pea

Sowing triticale and pea in SI enables the obtaining of higher yields (over $3 \text{ Mg} \cdot \text{hm}^{-2}$) than the previously described SIs of pea with barley and pea with wheat. This situation is a result of the higher yielding of triticale under the conditions of the experiments. As a result of the higher yield of the cereal component with the same level of pea yield, the share of the legume component in the total SI yield was lower than in the case of the previously described SIs (Figure 8). The average yield of pure triticale and pea sowing was higher than that in the intercrop, while SIp gave a slightly higher share of pea in the yield.

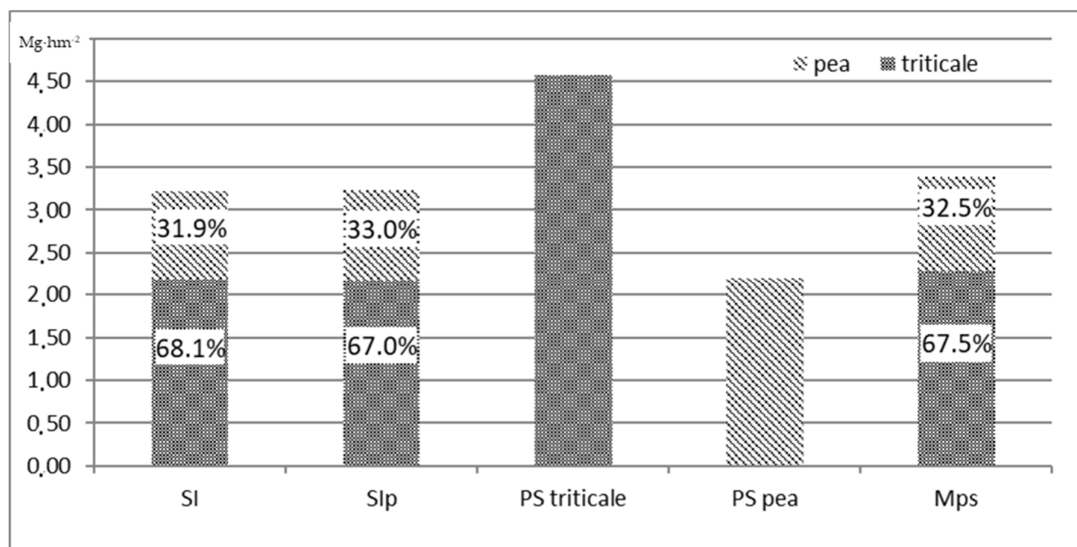


Figure 8. Estimated SI and SIp triticale/pea yield and yield structure against the background of pure sowing (PS) and the averaged total yield (Mps).

The SI yield of triticale and pea, depending on the change in the width of the strips (Figure 9), is similar to that of barley and pea SI. The narrowing of the strips results in a decrease in the total SI yield of the intercrop. A decrease below $3 \text{ Mg} \cdot \text{hm}^{-2}$ is visible for strips with a number of rows smaller than 12 when the strips of both species are in immediate proximity, while, in the case of strips separated by a path, this decrease is only visible for strips with a number of rows of 4 or less.

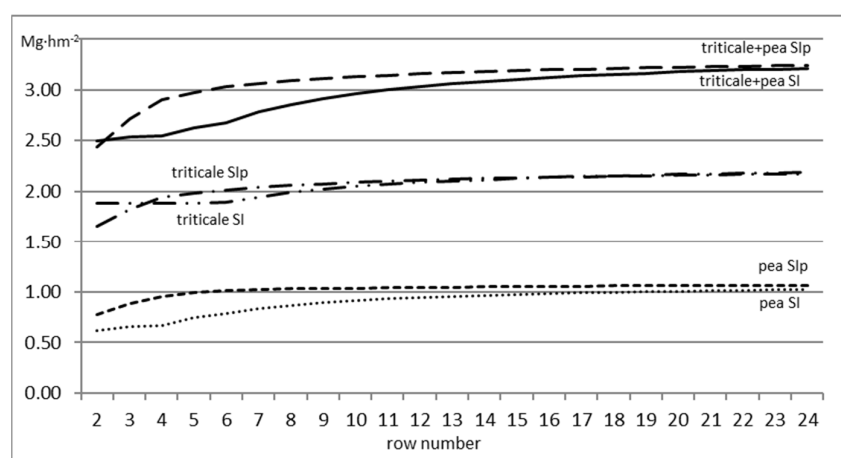


Figure 9. Estimated yield of triticale (triticale SI, triticale SIp) and pea (pea SI, pea SIp), and their total yield (triticale + pea SI, triticale + pea SIp) depending on the number of plant rows in the strip and the presence of a path separating the strips.

The joint sowing of barley with pea is one of the most commonly-practiced MI in Central Europe due to the good forage qualities of the obtained crop [58–60]. However, the coexistence of these species in one canopy is associated with a number of agrotechnical problems. One of the more important limitations is susceptibility to lodging [61,62]. In addition, the mixed intercropping of cereal and legume plants is associated with the problem of selection of herbicides and the variable composition of the obtained yield in subsequent seasons and/or in different fields. These problems in agricultural practice often limit mixed intercropping to organic farming [63] rather than to common use in conventional or sustainable agriculture. Therefore, research was undertaken on SI barley/pea in the 2/2 and 4/4 order as an alternative to mixed intercropping [57] and 1/1 in the Strip-Till one pass Technology [63].

In our own meta-analysis, it was found that PS cereals yield higher than PS pea; therefore, cereals determine the total yield of Mps to a greater extent than pea. This has also been confirmed by studies on mixed intercropping by other authors [64]. Since cereals are a stronger competitor than pea [65], the negative reaction of pea to the proximity of the cereal strips means that cereals in SI are the main determinate of the total yield. Paths separating pea strips from strips of barley, wheat, and triticale increase the share of pea in the total SIp yield. This confirms the previously quoted opinion that cereals are more competitive than pea [66]. The greater share of pea increases the forage value of the obtained SIp yield in relation to the SI yield. Three-meter-wide strips already allow for the separate harvesting of pea and cereals in agricultural practice. Additionally, the introduction of a path between adjacent plant strips reduces the risk of “contaminating” the yield of individual species, e.g., pea with wheat and vice versa. The mixed intercrop of pea with cereals is characterized by a high variability in the composition of the yield depending on environmental conditions, and this causes difficulties with the sale and balancing of feed rations, while a separation of the total yield is associated with additional costs [33]. SI with strips that are 3 m wide is a possible alternative. Reducing the width of the strips below 3 m is associated with major technical problems as a result of the non-adaptation of agricultural machinery. This has been pointed out by Van Oort et al. [66], although these authors argue that the SI benefits of wheat and maize diminish as the width of the strips increases beyond 1 m.

The field research results presented in the paper and the simulations carried out on their basis showed the validity of continuing work aimed at developing detailed recommendations and implementing the concept of strip intercrop of pea with cereals into agricultural practice. This is primarily due to the need to increase the heterogeneity of plant production. According to Siram et al. [67], it may be an effective way to mitigate the negative impact of farming on biodiversity without taking land out of production. The introduction of strip intercropping and, consequently, the reduction in the field area covered by one plant allows for a significant increase in the number of beneficial species of vertebrates and invertebrates inhabiting a given habitat. According to Siram et al. [67], decreasing field size from 5 to 2.8 ha has a similar positive effect on biodiversity to increasing seminatural cover from 0.5 to 11%. Czyżewski and Smeździk-Ambroży [68] stated that, in the diversified farms, there is higher environmental sustainability of production on lower economic efficiency than in specialized farms. However, diversified farms may achieve similar economic efficiency indicators to specialized farms.

3.2. Cereal/Cereal

3.2.1. Wheat/Barley

With 3 m-wide strips, the estimated yields of wheat and barley grown in the SI system and in pure sowing are similar and are at the level of $3.5 \text{ Mg} \cdot \text{hm}^{-2}$ (Figure 10). Also, the composition of the obtained yield is similar in all objects, and the ratio of the share of each component is approximately 1:1.

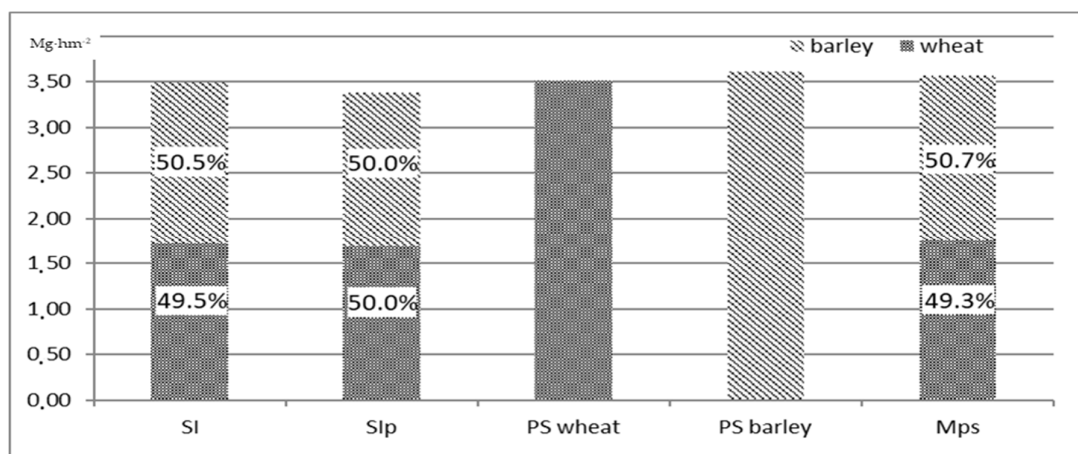


Figure 10. Estimated SI and SIp barley/wheat yield and yield structure against the background of pure sowing (PS) and the averaged total yield (Mps).

The simulations carried out show that the total SI yields decrease with the decreasing number of rows in a strip, but do not drop below $3 \text{ Mg} \cdot \text{hm}^{-2}$ in the case of the immediate proximity of the strips of both species. In the case of strips separated by paths, such a decrease is recorded at four rows in a strip (Figure 11). However, in the case of strips composed of four rows of plants and separated by paths, nearly 1/3 of the field surface is non-planted (Figure 3), and the yield decrease compared to the immediate proximity of two species was only 6.25%. This proves that the border effect plays a very important role in compensating for the presence of paths. The responses of both species to the decreasing number of rows in the strip were similar for both the strips directly adjacent to each other and for the strips separated by paths, although the estimated yield loss of the latter was greater.

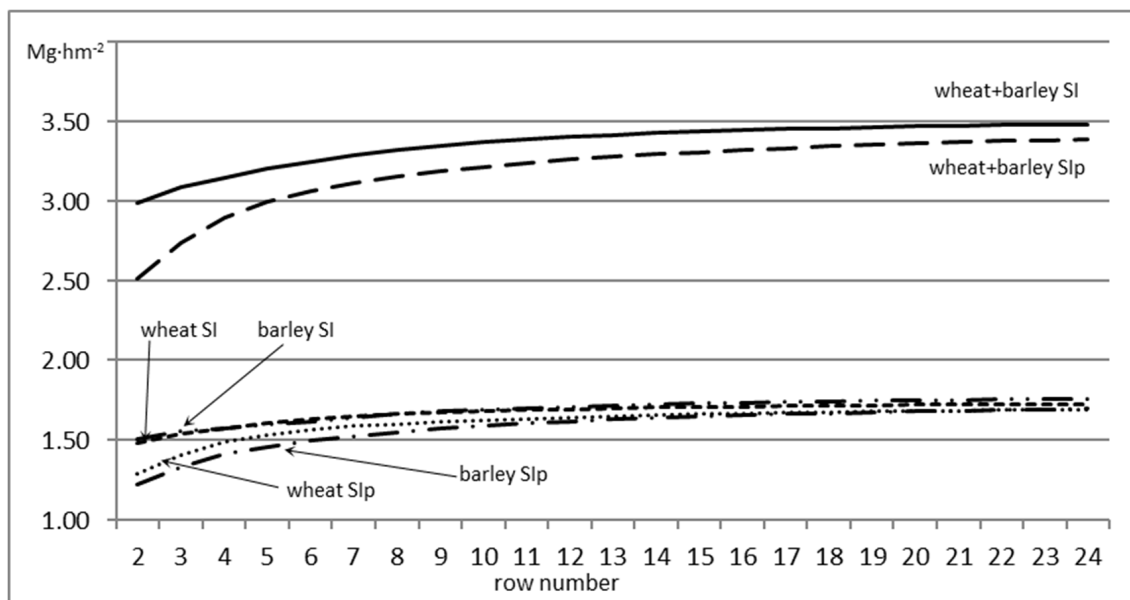


Figure 11. Estimated yield of barley (barley SI, barley SIp) and wheat (wheat SI, wheat SIp), and their total yield (barley + wheat SI, barley + wheat SIp) depending on the number of plant rows in the strip and the presence of a path separating the strips.

3.2.2. Wheat/Triticale

The estimated SI yield of triticale with wheat was higher than that of wheat with barley, which is a result of a higher yield of triticale in pure sowing than of barley. The

differences between the compared SI, SIp and Mps objects were small, and the total yields varied around $3.86\text{--}4.03\text{ Mg}\cdot\text{hm}^{-2}$ (Figure 12). Due to the higher yield of pure triticale sowing than wheat, this species had a greater share in the total yield, i.e., about 56%.

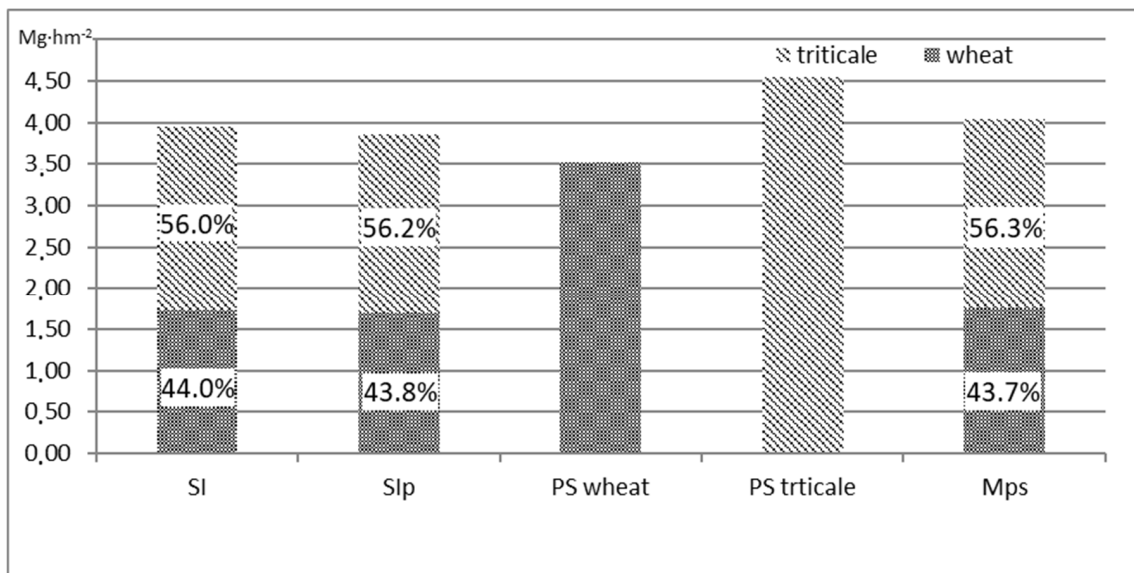


Figure 12. Estimated SI and SIp triticale/wheat yield and yield structure against the background of pure sowing (PS) and the averaged total yield (Mps).

If the number of rows in the strip of a given species is reduced to four or less, the presence of paths separating these strips is associated with a large decrease in the total SIp yield (Figure 13).

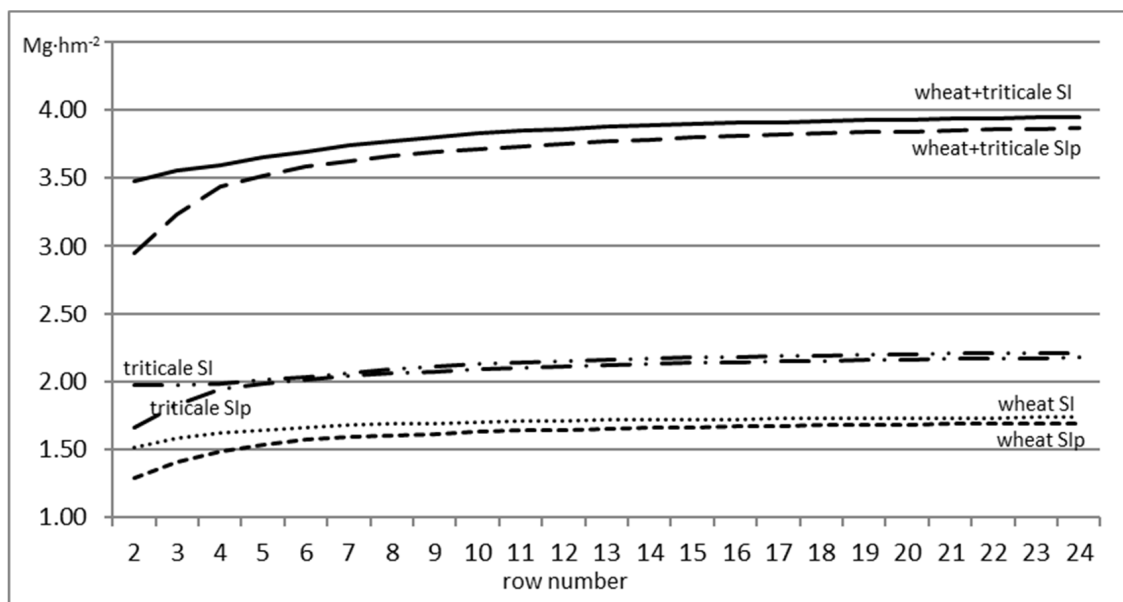


Figure 13. Estimated yield of wheat (wheat SI, wheat SIp) and triticale (triticale SI, triticale SIp) and their total yield (wheat + triticale SI, wheat + triticale SIp) depending on the number of plant rows in the strip and the presence of a path separating the strips.

3.2.3. Triticale/Barley

Estimated yields of SI and SIp of triticale with barley for strips with a width of 3 m were similar and about $0.2\text{ Mg}\cdot\text{hm}^{-2}$ lower than the average total yield from pure sowing—

Mps (Figure 14). The share of barley in the total yield was lower than that of triticale, which is the result of a greater yield of triticale in pure sowing. The interactions of neighboring plants of both species as well as the border interactions did not change these relations to a large extent. Only a slightly higher share of barley in SI was found with the immediate proximity of the strips than with their separation by the SIp path.

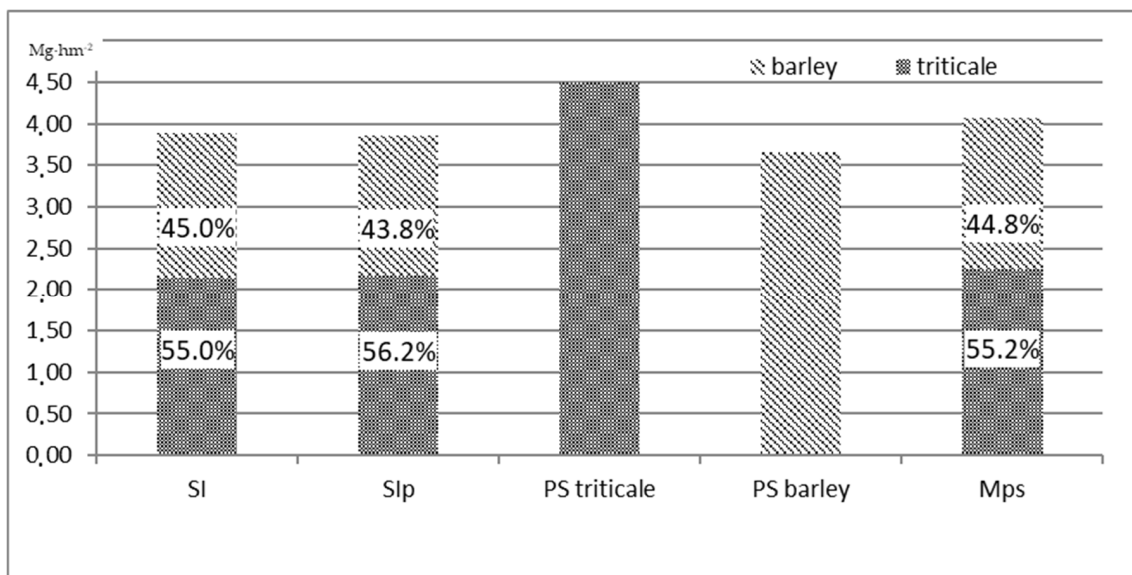


Figure 14. Estimated SI and SIp barley/triticale yield and yield structure against the background of pure sowing (PS) and the averaged total yield (Mps).

Regardless of whether the plant strips were separated by a path or not, the simulation shows a similar trend of a decrease in the total yield of SI and SIp with a decreasing number of rows in the strip (Figure 15).

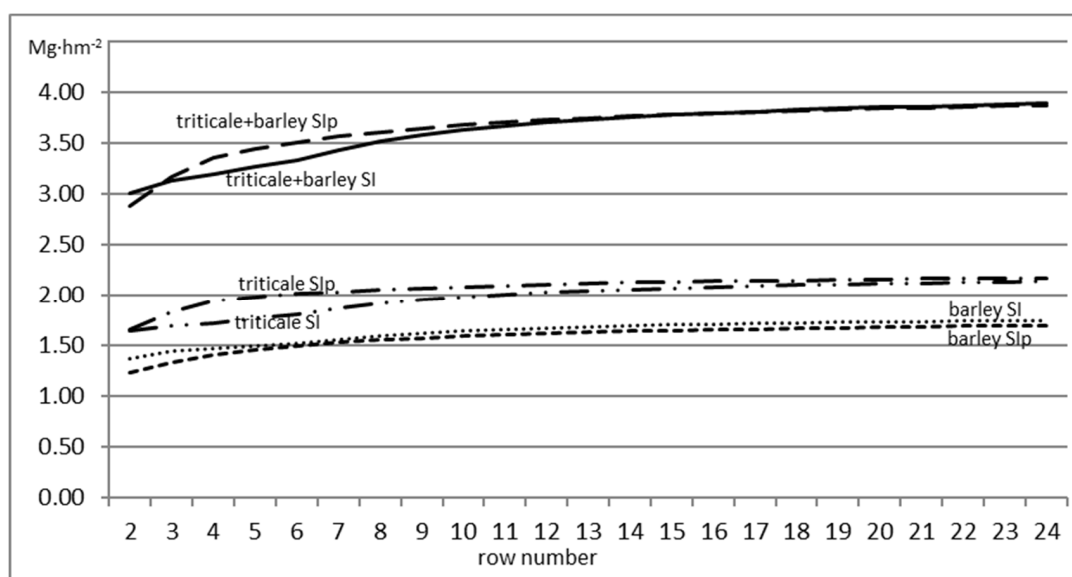


Figure 15. Estimated yield of barley (barley SI, barley SIp) and triticale (triticale SI, triticale SIp), and their total yield (barley + triticale SI, barley + triticale SIp) depending on the number of plant rows in the strip and the presence of a path separating the strips.

Cereal intercrops are of great economic importance in some countries. In Poland, MI cereals occupy the fourth place in the structure of cereal sowing, which is a result of

the desire to reduce the costs of cultivation and to reduce yield fluctuations caused by different weather conditions and soil variability within a field [69]. The mixed intercropping of two species of cereals is also cultivated in different regions of the world [70]. The legitimacy of cultivating mixed intercropping of various species of cereals is also a result of the possibility of using all the suitable agrotechnical treatments that are available in pure sowing. Considering environmental factors, cereals do not provide such significant benefits as legumes [71]. However, with the appropriate selection of species and varieties, a reduction in the spread of pathogens and pests can be expected [72]. The literature lacks sufficiently documented knowledge about the SI of wheat, triticale, and barley. Our own meta-analysis shows that SI yield is determined by the higher-yielding species, and the share of species in the total yield is very similar to Mps, which indicates the insignificance of mutual interactions in the rows of adjacent cereal crops in shaping the yield structure. The lack of positive LER, SI, and SI_p values and the small influence of the paths separating the strips of two cereals species in the context of similar agrotechnical requirements of the SI components undermine the legitimacy of this method of cultivation in relation to mixed intercropping. SI requires a greater amount of work during sowing than mixed intercropping, and this work is not justified given the forage purpose of the crop and the assumption that there is no need to separate the crop separately into species.

Despite the positive reaction of cereals to the presence of paths between species [43], with very narrow strips the ratio of the non-planted area to the planted area may be so high that it will not be effectively compensated by the border effect, which was observed in our own research.

3.3. Oat/Lupine

The estimated SI yields of oat and lupine at 3 m-wide strips were lower than the SI yields of the other plant species. The estimation indicates that the yields of SI and SI_p are greater than the Mps, and the yield of SI_p is greater than the yield of SI (Figure 16). In Mps, the share of lupine seeds in the yield is greater than in SI and SI_p.

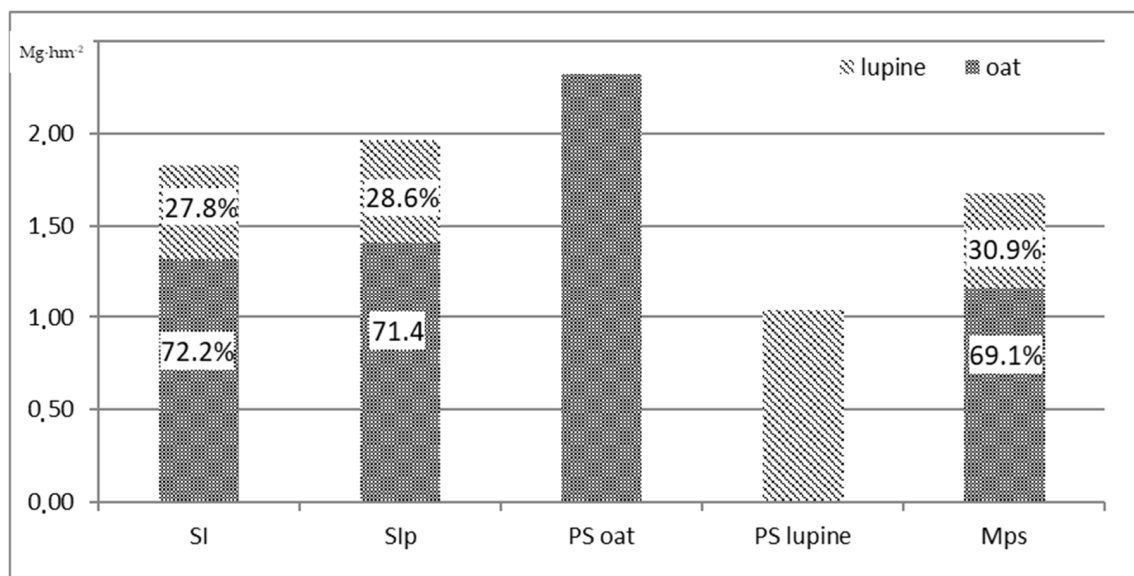


Figure 16. Estimated SI and SI_p oat/lupine yield and yield structure against the background of pure sowing (PS) and the averaged total yield (Mps).

The reactions of the SI of oat and lupine to the reduction in the width of the strips is completely different to the previously described SIs. The total (oat+lupine) SI_p yield when the strips are separated by a path practically does not change with the decreasing number of rows in the strip (Figure 17) and is similar to the oat yield in SI_p. A very strong

positive proximity effect for oat results in the fact that, despite the increasing share of the non-planted field area up to 2/3 of the total area, the total yield of oat/lupine in SI increases.

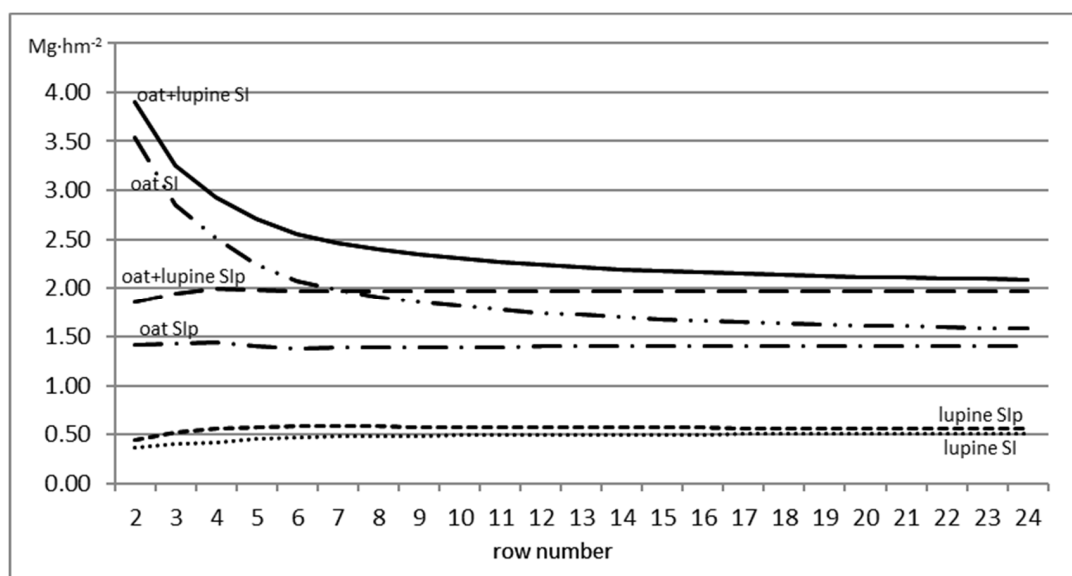


Figure 17. Estimated yield of oat (oat SI, oat SIp) and lupine (lupine SI, lupine SIp), and their total yield (oat + lupine SI, oat + lupine SIp) depending on the number of plant rows in the strip and the presence of a path separating the strips.

Oat generally has a lower yield potential than wheat, triticale, or barley. Similarly, lupine yields lower than pea. Therefore, the estimated SI yields with oat and lupine were lower than those of the remaining SIs under consideration. Such a result may also be caused by the habitat conditions, including weather conditions, in which the experiment was conducted, and which was the source of data for the research in question. The difference in the estimated SI lupine/oat yields compared to SI pea/cereals is a result of the stronger negative reaction of lupine to competition from oat [44] than from pea to the other cereals. The total yield of SI lupine/oat is greater than Mps; however, the share of lupine seeds in SI is lower than in the average yield of Mps, which is different from the SIs of pea/cereals. As a consequence, only the intercrop oat/yellow lupine LER was above 1. This shows a better use of environmental resources by SI than by pure sowing. As the border effects for oats are much more favorable than for lupine [43], the separation of lupine and oat strips with the non-planted path only slightly changed the share of lupine in the total SI yield. The lack of a reduction in the yield of oat and the total yield of the intercrop along with the reduction in the width of the strips separated by paths is mainly a result of the very strong border effects which oat plants are subject to—stronger than for other species. The very favorable effect of the proximity of lupine to the oat yield leads to the fact that the narrowing of the strips is associated with a significant increase in the yield of oat directly adjacent to the lupine.

3.4. Land Equivalent Ratio (LER)

The previously described relations of plant yields in the SI system to Mps are confirmed by the LER indicators (Figure 18). The LER for all SIs, except for SI oat/yellow lupine, was only slightly below 1. The LER index value was similar when the sown plant strips were separated by a path—SIp. Only the LER for SI oat/yellow lupine yields was above 1.

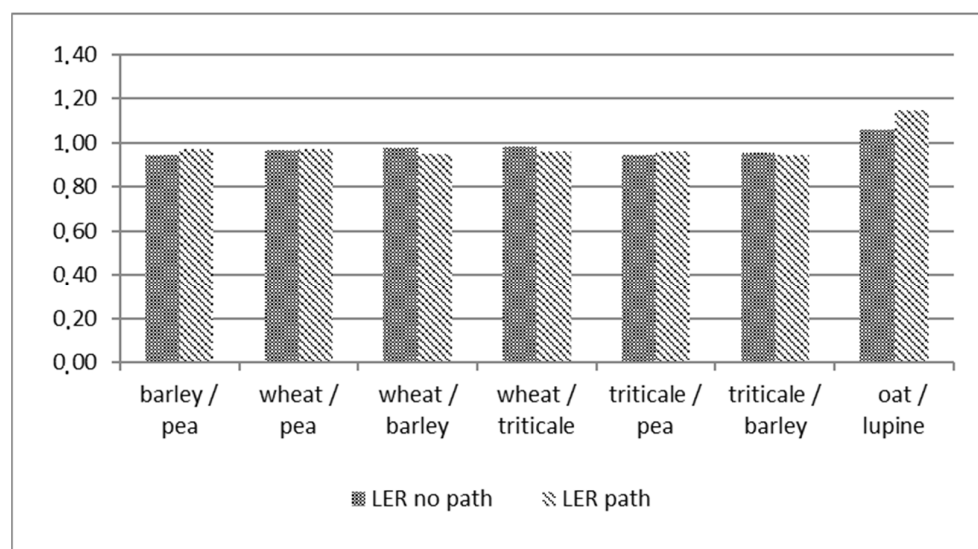


Figure 18. LER values with and without the presence of a path separating the strips.

Decreasing the width of the strips for all SIs except oat/lupine SI is associated with a decrease in LER. The introduction of a path separating the adjacent strips of cereals with peas (SIp) mitigates this trend, while a path between the strips of cereals increases the downward trend (Figure 19). In the case of oat/yellow lupine sowing, the introduction of the paths practically did not change the LER value as the width of the strips decreased down to four rows of plants. Reducing the width of the strips of oats and lupines directly adjacent to each other (a smaller number of rows) is associated with an increase in LER.

In the studies of Chen et al. [55], mixed intercropping gives a slightly higher LER than SI. However, the share of peas in the yield, and thus its fodder value, was greater for SI in the barley/pea row system in the ratio of 4/4, which is also confirmed by the results of our own research. In the case of LER of legumes and cereals, most authors argue that mixed intercropping has an LER > 1 [56,59,69,70]. In an SI of maize and wheat, the LER values exceeded 1; however, it depended on the width of the strips [66]. Musa et al. [73] indicated that the LER value depends on the spatial distribution of peas and barley in relation to each other. In the cited studies, the alternating rows of barley and pea gave an LER greater than 1; however, it was lower than for the cross sowing or mixed intercropping of these plants. The efficiency of such an intercrop is also determined by the proportion of barley and pea [74,75]. These cited results, however, do not correspond to the results of our own research, because the LER for the 3 m-wide strips of cereals and peas was lower than 1. Similar LER values to those presented here for mixed intercropping barley/pea (LER = 0.98) were obtained by Dordas et al. [65].

High LER values for mixed intercropping, well above 1, may be due to the method of nitrogen fertilization. Legumes prevent the optimal fertilization of cereals in mixed intercropping, as high nitrogen doses reduce pea yield [76]. This is of particular importance for wheat, which has high nutritional and fertilizing requirements. Although studies show that the mixed intercropping of cereals and legumes uses nitrogen better than pure sowing [7–10], one should take into account the difference between the specificity of fertilization of intercrops and their components in pure sowing in the mixed intercropping studies in relation to other specificity in studies relating to the agrotechnics of these plant species in agricultural practice. In the study of intercrops, pure sowing as a reference point for mixed intercropping generally has the same nitrogen fertilization level as mixed intercropping. On the other hand, in agricultural production technologies, pure cereal sowing has a much higher level of fertilization than mixed intercropping. Thus, the LER indicators for mixed intercropping do not have to be in line with the real production realities. Although, in the authors' own research, the cereal plants had pre-sowing and top dressing with nitrogen, which probably significantly changed the LER values, it is difficult

to consider the nitrogen dose of $68 \text{ kg N} \cdot \text{hm}^{-2}$ (the dose used in the source experiments for this meta-analysis) as optimal for cereals. It is also difficult to compare LER in mixed intercropping and SI due to the fact that, in SI, the plant density is close to the optimal one for each species and, in mixed intercropping studies, the seeding proportions are very different. Lower-than-1 LER values obtained in the authors' own research are probably a result of the unfavorable reaction of pea to the proximity of cereals, which was confirmed in earlier reports of the authors [46], and which was not compensated for by the slight positive reaction of the cereals to the proximity of peas [45,47,48]. Therefore, the more rows of pea in a unit area that are in direct contact with the cereal (reducing the width of the strips), the more the LER decreases.

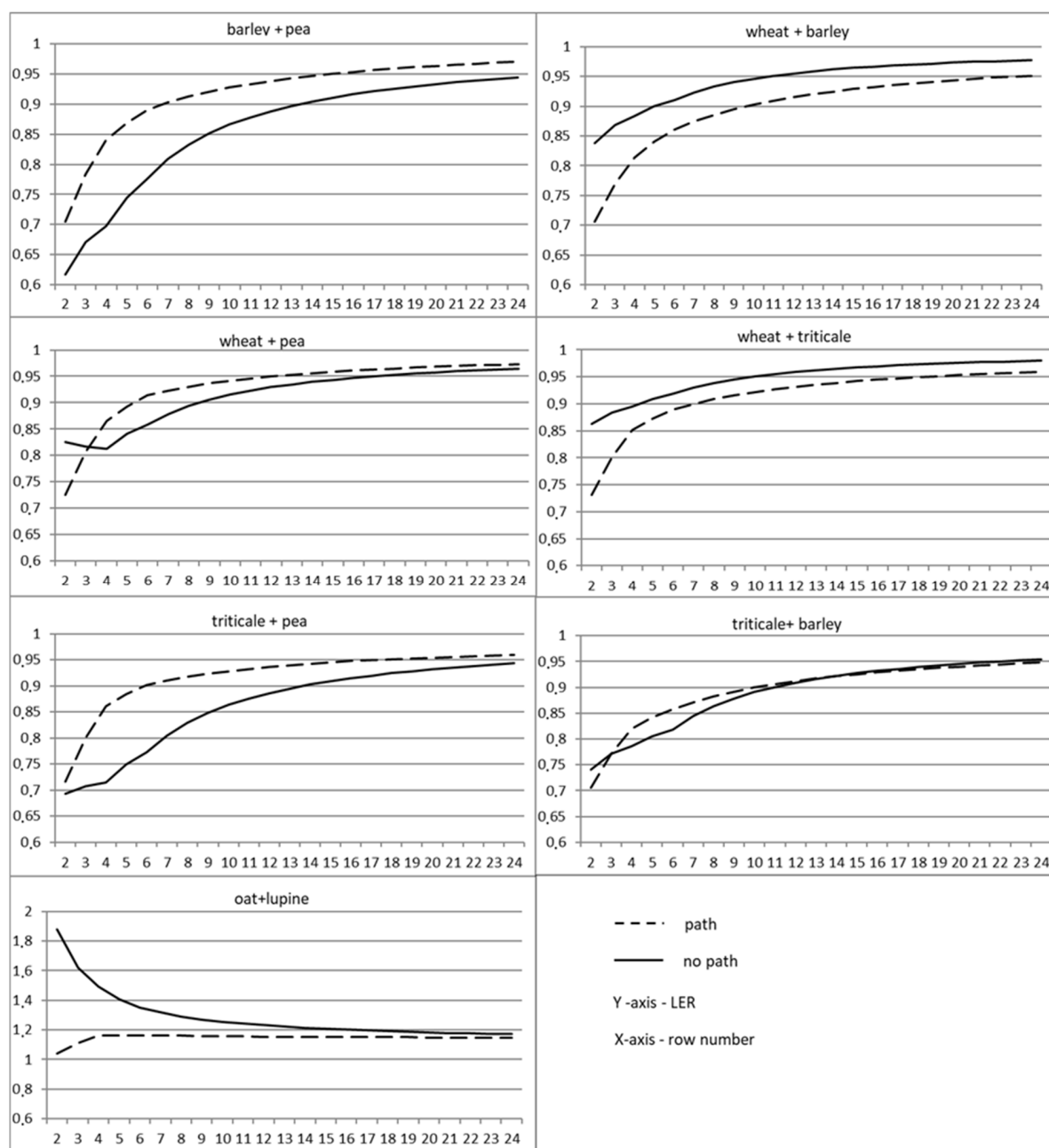


Figure 19. LER values depending on the presence of a path separating the strips and the number of plant rows in strips.

4. Conclusions

Strip intercropping is an interesting alternative to mix intercropping, especially in the case of components consisting of cereals and legumes, in particular oats and yellow lupine. The incorporation of a path separating the cereal component from the legume component does not affect the total yield, but it contributes to increasing the share of peas or lupine in the yield. The width of the belts of individual components is also important. Taking into account the possibilities of optimizing agricultural technology for each of the components separately and the production effects obtained, it is justified to create strips with a width of at least 3 m separated by a path. The analysis of the results showed that the creation of strip intercrop made of only cereals does not give any production benefits compared to mono-species crops of individual components. Further research is needed under different habitat and agrotechnical realities on the production and environmental effects of strip intercropping on major agricultural plants in various regions of the world.

Author Contributions: Conceptualization: L.G.; Methodology: L.G., I.J., D.J. and E.W.; Investigation: L.G.; Writing—original draft: L.G.; Writing—review & editing: I.J., D.J., E.W. and M.K.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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