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Research paper

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Forecasting the efficiency of agricultural production by optimising the length of plots in the terms of the profitability of reconstruction of the land layout

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Summary

This article presents a study on the impact of optimal parcel configuration on agricultural production efficiency and the profitability of land consolidation, using the example of Przysieka, a village in Poland. The research focused on parameters of spatial configuration of parcels, such as area, length, and width. Detailed studies were conducted using a synthetic measure of parcel configuration known as land distribution costs. The research found that despite a large average area of parcels, that is close to 1 ha, a significant portion of them had an inefficient spatial configuration, which significantly limited the profitability of agricultural production in the study area. To determine the profitability of the land consolidation process, a simulation of changes in parcel configuration was performed. This involved applying optimal lengths, which were estimated for each parcel while maintaining its original area. The simulation results showed a significant decrease in land distribution costs. Although this reduction was slightly below the profitability threshold for potential consolidation, the outcome is promising. The study emphasizes that the simulation considered only the change in parcel configuration, ignoring other key consolidation factors such as the reduction of land distribution and shorter distances to homesteads. The conclusions suggest that the research method used can be a valuable tool for assessing the need for consolidation actions in areas with a seemingly correct area structure. However, in order to provide a definitive answer on the profitability of the entire process, further research that includes the full range of benefits brought by consolidation is needed.

Keywords

efficiency of agricultural production • optimal plot length • profitability of land consolidation

1. Introduction

A properly shaped agricultural production space is essential for achieving measurable benefits from agricultural production. Recent decades in global agriculture have been characterised by constant transformations aimed at increasing production efficiency and the competitiveness of food products on the markets. Many of these efforts have been and continue to be difficult to implement due to existing socio-economic or infrastructural constraints. It is worth noting that the location of arable land on a farm and the shape of its boundaries play a key role in the agricultural production process, determining its profitability [Woch 2001, Rahman and Rahman 2009, Dacko et al. 2021, Bielska and Stańczuk-Gałwiaczek 2025].

Often the historical layout of cadastral parcels, characterised by mosaic patterns, irregular shapes and scattered land belonging to a single owner, continues to pose a serious obstacle to their effective development [Gniadek et al. 2013]. This problem is particularly evident in many European countries, where traditional land division has created small, narrow or poorly shaped plots [King and Burton 1982, Miraj 2017, Doroż and Taszakowski 2020, Balawajder et al. 2021]. Such layout hinders the use of modern agricultural machinery and the implementation of innovative crop cultivation technologies [Pijanowski and Sobaś 2015].

In the context of the Polish countryside, intensive transformations in the agrarian structure have been occurring for over three decades [Woch et al. 2018]. A key element of these changes is the restructuring of the layout of registered plots of land, aimed at improving agricultural production space by reducing operating costs, increasing the efficiency of agricultural machinery and optimising farm management. These measures are most often implemented as part of a land consolidation and exchange procedure, which is a key instrument for the spatial transformation of agricultural land [Muchová et al. 2016]. Land consolidation is a practice commonly used in all parts of the world [Vitikainen 2004, Brizoza and Havugimana 2013, Manjunatha et al. 2013, Leń 2018]. It results in the correction of defective boundary arrangements, resulting in the creation of a new, more optimal land arrangement that increases the productivity and profitability of farms [Gonzalez et al. 2007, Mielewczyk 2010].

Due to the varied nature of rural areas, the reconstruction of the boundary system should be preceded by a detailed analysis of the spatial structure of existing farms [Strek et al. 2019, Mika et al. 2019], using modern information technologies [Basista et al. 2023], terrain conditions, and access road networks, as well as determining the current and target levels of agricultural mechanisation. For this reason, the final results of consolidation works, such as improving the spatial and technical parameters of plots or reducing fragmentation, may not be sufficient from the point of view of the profitability of the land consolidation project [Harasimowicz 2000, Dacko et al. 2019]. It is generally accepted that the minimum area of a plot that does not generate significant production losses due to its irregular shape should not be less than 1–2 ha. However, the size of individual plots cannot be the only determinant of whether the land arrangement should be reconstructed. This feature should rather be treated as a component of a comprehensive indicator that takes into account all the characteristics of its spatial layout. Determining the optimal shape for a plot of a given size requires separate calculation procedures in accordance with the principles of optimising the shape of arable land.

When assessing the potential benefits of a possible land consolidation, it is important to ensure that the capitalised income derived from the reduction in existing costs, which result from the unfavourable distribution of land, exceeds the expenditure incurred in undertaking the consolidation process. Otherwise, the implementation of such a task may prove unprofitable.

In the case of sites with a road layout that allows the shape of existing farming complexes (compact areas separated by the existing road network) to be preserved, where the boundaries of registered plots could be changed to optimise their shape, the costs incurred will be significantly lower. It can be assumed that this scenario will apply to most properties that have already been consolidated in the past and whose current spatial structure has deteriorated to some extent due to land divisions in previous decades. The question of the rationale for consolidating such sites therefore seems justified. The answer to the question of whether a plot of land with a structure of registered parcels and a road network layout close to being correct should be subject to consolidation can be provided (as assumed) by estimating for each plot the value of the cultivation cost index. The costs depend on the spatial configuration of the parcel and comparison of the obtained values with the value of cultivation costs, which in turn are related to the spatial configuration of the parcel. This is estimated taking into account the optimal length of the parcel, which can be obtained in the optimisation process.

The aim of the study was to assess the impact of using optimal plot lengths in a potential redesign of land arrangement, while maintaining their current area structure, on changes in agricultural production efficiency.

In addition, it was assumed that an answer would be obtained to the question of whether land with a correct road layout and arable plots with an average area close to the correct size should be subject to land consolidation due to its profitability.

2. Study object

The study covered the precinct of Przysieka, part of the municipality of Kozłów in the Małopolska voivodeship in Poland (Fig. 1). This site has favourable soil conditions for agricultural production and is characterised by gentle terrain gradients, which do not present any obstacles to the organisation of farming.

The area of the village of Przysieka covers 639 ha and consists of 794 registered parcels. The existing agricultural transport network and the layout of registered parcels in the village under study were originally shaped during the consolidation process completed in the interwar period of the last century. Land divisions carried out over the last few decades have contributed to an increase in the number of plots in the village, and thus the worsening of their spatial layout.

Source: Author's own study

Fig. 1. Location of the Przysieka precinct

3. Methodology

The study began with the selection of the Qgis tool, which can be used to estimate the basic spatial and technical parameters of farming complexes and the registered plots located within them. Given the need to use cadastral data, the data obtained from the geoportal of the Head Office of Geodesy and Cartography in Poland and orthophotomaps were utilised. Stage I involved the identification of areas with plots of land being cultivated. Next, the current land use status in the village was identified, which allowed for the selection of registered plots (hereinafter referred to as plots) used exclusively for agricultural production. Other plots, such as built-up areas, forests, scrubland, water bodies and roads, were excluded from further research. The obtained result led to the identification of compact areas of agricultural use, corresponding to existing farming complexes.

In stage II, the values of elementary parameters of spatial configuration for the surveyed plots, such as area, length and width, were estimated. Due to the fact that the obtained research result should bear the hallmarks of an economic calculus, further research was conducted using a synthetic measure of plot shape in the form of cultivation costs dependent on their spatial arrangement (so-called land distribution costs), which are a universal solution in this type of studies and are estimated in grain units per 1 ha of area.

The size of the land distribution costs for a field (in this case, a registered plot) was estimated using the following formula (1) [Harasimowicz 2000]:

$$K_r = z_l l + z_b b + jp \tfrac{1}{4} l \quad (1)$$

where:

- z_l – parameter defining costs related to field length (edge losses),
- z_b – parameter specifying costs related to field width (turnarounds, edge losses, costs related to the turnaround strip),
- j – parameter specifying the costs associated with trips across the field,
- l, b, p – length [hm], width [hm], area of field [ha].

To estimate the costs incurred, the parameter values dedicated to cultivation with an 85 HP tractor: $z_l = 0.49$, $z_b = 4.19$, $j = 0.39$ and a grain yield of 5 t/ha were adopted [Harasimowicz 2000].

Due to the adopted aim of the research, the cultivation cost index for each plot was re-estimated, replacing the actual plot lengths with optimal lengths calculated individually for each plot, while maintaining its existing area. The optimal length for a plot with a fixed area was determined as follows [Harasimowicz 2000]:

$$L_{opt} = \sqrt{(z_b / (z_l/p + j/4))} \qquad (2)$$

Furthermore, maximum and minimum optimal lengths were determined for each plot. This will increase the tolerance for fitting newly designed plots with existing areas into the existing configuration of crop complexes and will not cause a significant increase in cultivation costs compared to the costs estimated with the optimal lengths taken into account. The maximum optimal length ($L_{opt\ max}$) and minimum optimal length ($L_{opt\ min}$) for each plot were calculated using formulas (3) and (4) [Harasimowicz 2000]:

$$L_{opt\ max} = \sqrt{2}\ L_{opt} \qquad (3)$$

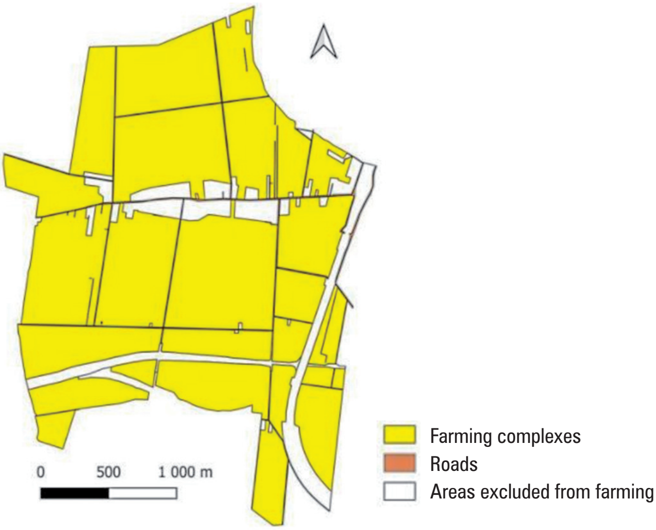
$$L_{opt\ min} = ½\ L_{opt\ max} \qquad (4)$$

Statistical and information technology tools were used to compile and present the results of potential changes to the layout of plot boundaries. These tools made it possible to determine basic descriptive statistics, create frequency distributions and correlation spread charts, and produce the necessary cartographic studies.

4. Forecast of changes in the efficiency of agricultural production using optimal lengths

The research methodology adopted in stage I allowed for the identification of 26 farming complexes in the surveyed village (Fig. 2). Due to the acceptable lengths of these complexes, varying from approximately 170 m to 300 m for grassland and from approximately 300 m to over 800 m for arable land [Pijanowski 1992], they can be considered suitable for designing a new layout of plot boundaries, taking into account the optimal plot lengths. The existing complexes have easy access to existing roads, and the mostly two-sided and, in a few cases, three-sided access to the complexes creates favourable conditions for the potential reconstruction of the layout of the current plot boundaries. Of the 794 registered plots in their current state, 563 plots, which are part of the identified complexes, were covered by detailed studies.

The basic spatial parameters for existing plots, such as area, length and width, determined in stage II, allowed for the application of a synthetic measure of their shape, namely the estimated costs of land distribution, without taking into account the distance between the plot and the settlement. This showed that the group of studied plots, despite having an average area close to the correct value of 0.95 ha, had a defective configuration in over 50% of cases (Fig. 3). The estimated costs of land distribution significantly exceed the acceptable level of 2-4 grain units per 1 ha [Harasimowicz 2000]. This information suggests the need to revise the boundaries of these plots, but does not justify the cost-effectiveness of such measures.



Source: Author's own study

Fig. 2. Layout of existing farming complexes in the village of Przysieka

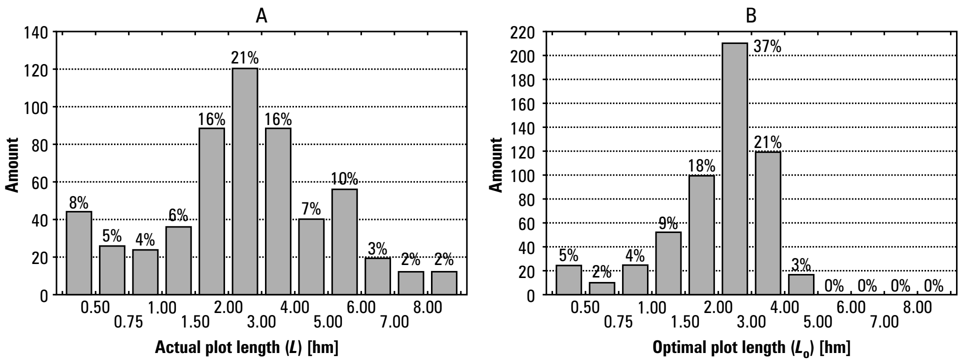


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Fig. 3. Distributions of plot sizes in specified length intervals: A. using actual plot lengths (*L*). B. using optimal plot lengths (L_o)

The possibility of keeping the existing farming complexes in their current shape means we can assume that the group of 563 plots can be subjected to an experiment involving modifying their shape. This experiment would involve replacing the current length of each plot with an optimal length, determined separately for each plot, while maintaining its current area. The result of replacing the lengths of the plots with optimal lengths is presented in Table 1. The data compiled in the table indicate that the assumed change in shape will result in a significant reduction in the average length of the plots, exceeding 60 m. Detailed information on changes in plot lengths in individual sections is presented in Figure 3. According to the data contained therein, excessively elongated plots will be eliminated, the number of plots with the shortest lengths will be reduced, and the number of plots with lengths considered correct will increase.

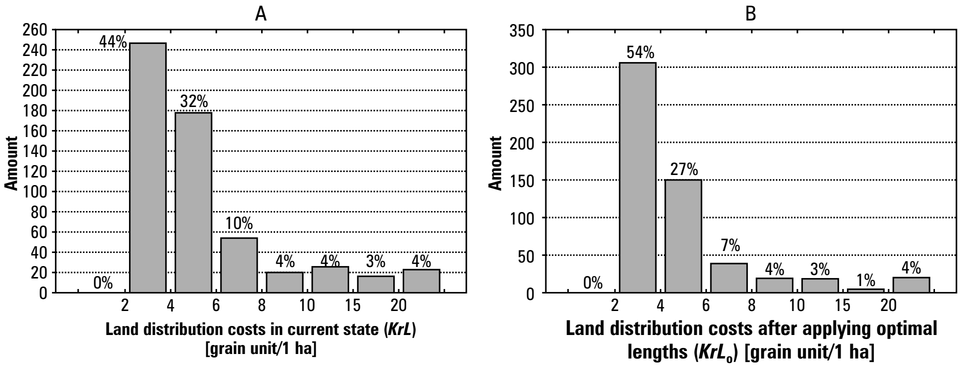
Table 1. Basic descriptive statistics of the surveyed agricultural plots in the village of Przysieka in their current and forecast state – after applying optimal lengths while maintaining the existing plot areas

Variable	Average	Minimum	Maximum
Plot area (*P*) – current state [ha]	0.95	0.01	5.64
Plot length (*L*) – current state [hm]	2.92	0.08	8.93
Optimal plot length (L_o) [hm]	2.31	0.10	4.77
Range of plot length reduction between optimal length (L_o) and actual length (*L*) [hm]	-0.61	-5.96	1.77
Maximum optimal plot length ($L_{o\ max}$) [hm]	3.25	0.15	6.72
Minimum optimal plot length ($L_{o\ min}$) [hm]	1.64	0.07	3.39
Range of optimal plot length ($L_{o\ max} - L_{o\ min}$) [hm]	1.62	0.07	3.34
Land distribution costs in current state (*KrL*) [grain/1 ha]	6.40	2.32	85
Land distribution costs after applying optimal lengths (KrL_o) [grain/1 ha]	5.54	2.22	80.95
Reduction land distribution costs (KrL_o – *KrL*) [grain/1 ha]	-0,85	–	–

Source: Author's own study

The experiment indicates a significant improvement in the parameters of plot arrangement (Fig. 4), consisting in an increase in their number in the ranges of land distribution costs considered correct, and in a significant reduction in the number of poorly shaped plots. As shown in Table 1, the introduced modification contributed to a reduction in the average cost of land distribution in the village from 6.4 grain units/1 ha to 5.5 grain units/1 ha.

It should be noted that the scale of elimination of plots with costs exceeding their acceptable level is dependent on their size. In the presented case, this constitutes a natural limitation and results (despite replacing the actual length of the plot with the optimal length) in leaving some plots with an incorrect level of land distribution costs.



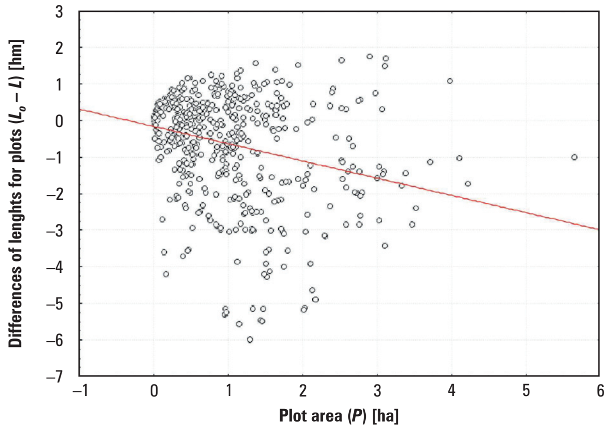
Source: Author's own study

Fig. 4. Distribution of plot sizes within specified ranges of land distribution costs: A. using actual plot lengths (L). B. using optimal plot lengths (L_o)

5. The use of optimal lengths for plots and their impact on the rationale and profitability of the consolidation process

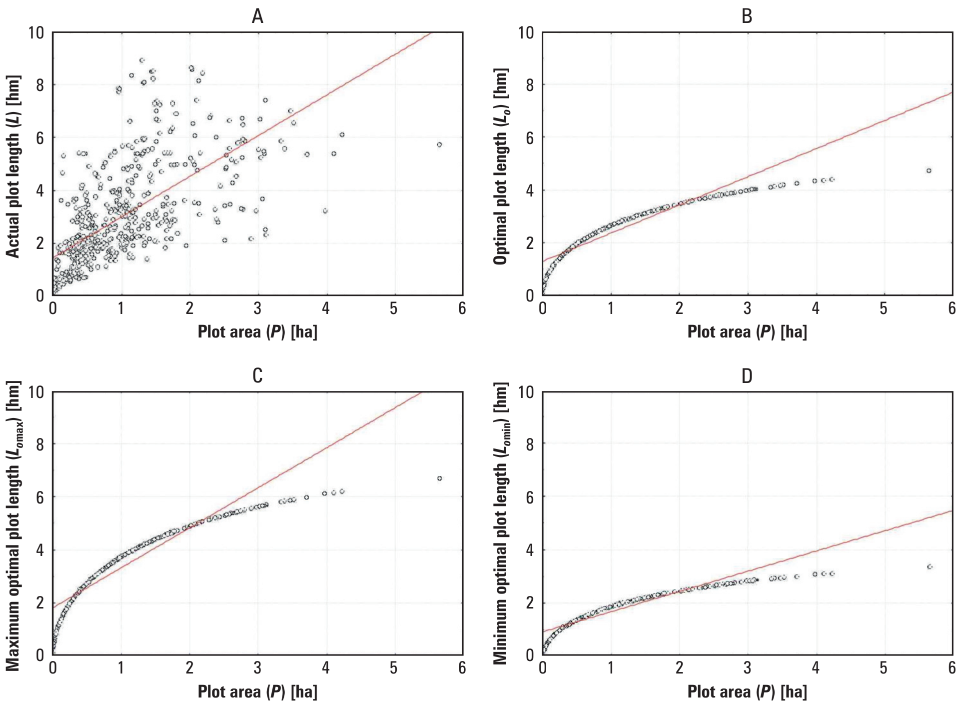
The demonstrated increase in production efficiency with the use of optimal lengths suggests that it is reasonable to take measures aimed at restructuring the examined boundary system. The detailed scope of changes in plot lengths between optimal and actual values is presented in Figure 5. The information contained therein confirms the need to restructure the shape of existing plots. The visible reduction in length for plots that are too long, up to 600 m, and the increase to 150 m for plots that are too short, means that the potential fitting of new, better-shaped plots in terms of length should not be problematic. The justification for this claim can be found in Figure 6, which presents graphs of plot area distribution in relation to actual and optimal lengths, as well as optimal maximum and minimum lengths. This information, as well as Figure 3, shows that optimal lengths will mostly range between 150 m and 400 m. This result allows, in the existing layout of farming complexes, for the design of plots with optimal lengths in the form of a single-row system with access to roads on both sides in shorter complexes, or two rows of plots adjacent to each other with their shorter sides and access to the road on one side in longer complexes.

The improvement from potential changes in plot configuration is also confirmed by the information contained in Figure 7. The visible range of changes in land distribution costs confirms the beneficial effect of including optimal lengths, reflected in a reduction in land distribution costs to approximately 2 units of grain/1 hectare. For the remaining plots, the reduction reaches up to 6 units of grain/1 ha, and in several cases, several dozen units of grain/1 ha. Considering that the profitability of the consolidation process requires a reduction in the cost index by at least 1–2 grain units/ha [Harasimowicz 2002], it can be assumed that this condition will be met. The total balance of costs between the forecast and existing states indicates that the decrease in the cost index per 1 ha in this case is 0.89 grain units/ha.



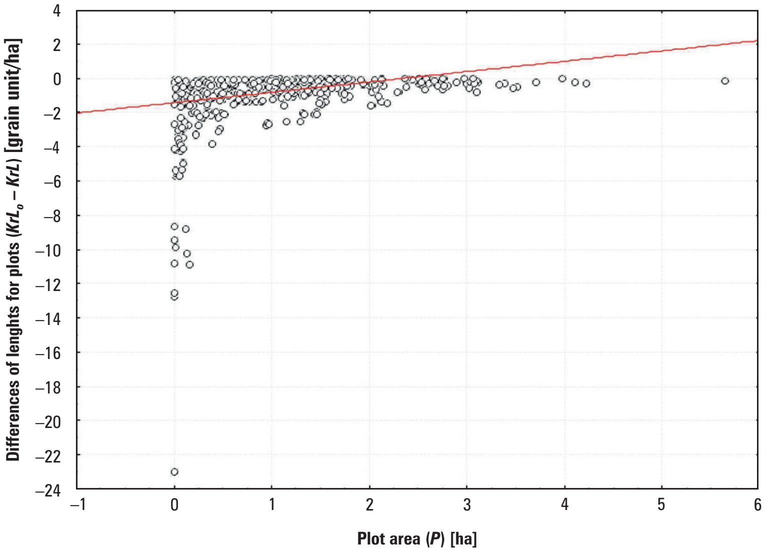
Source: Author's own study

Fig. 5. Distribution chart of plot areas (P) in relation to projected changes in plot length obtained from the difference between the optimal plot length (L_o) and the actual plot length (L)



Source: Author's own study

Fig. 6. Distribution charts of plot areas (P) in relation to: A. actual plot length (L). B. optimal length (L_o). C. maximum optimal length (L_{omax}). D. minimum optimal length (L_{omin})



Source: Author's own study

Fig. 7. Distribution chart of plot areas (*P*) in relation to forecast changes in land distribution costs obtained from the difference between land distribution costs estimated by taking into account the optimal length (KrL_o) and land distribution costs estimated by taking into account the actual length of the plot (*KrL*)

Due to the adopted research methodology, which only considered changes in plot configuration, it cannot be conclusively determined whether the reduction in land distribution costs achieved by using optimal lengths is sufficient to confirm the profitability of the consolidation process.

It should be mentioned that the threshold value for reducing the level of the aforementioned costs of land distribution, which permits to conclude that the potential consolidation will be profitable, takes into account additional components, such as a reduction in the number of plots, an increase in their area, and a reduction in losses related to the distance between the plot and the settlement. These factors are adjusted in the consolidation process, which ultimately lowers the final cost of land distribution. Considering the considerable possibility of further reduction in the level of land distribution costs and the preliminary value of such a reduction resulting from the use of optimal lengths, it can be concluded that land consolidation in the village of Przysieka will be a profitable investment. However, obtaining a clear answer requires further research, including a simulation of the reduction of unfavourably shaped plots and an assessment of their impact on the reduction of land distribution costs.

6. Summary and conclusions

The study of changes in agricultural production efficiency for a site with a correct road configuration and a plot area close to the optimal average value made it possible to identify regularities and shortcomings in the existing and simulated land layout.

The results of the study indicate that despite the high average plot size in the village, currently amounting to 0.95 ha, over 50% of plots have a flawed spatial configuration that significantly limits income from agricultural production.

A simulation of changes in plot configuration, in which the actual lengths of plots were replaced with optimal lengths (while maintaining the existing plot areas), showed a significant decrease in land distribution costs. The average cost index decreased from 6.4 to 5.5 grain units per hectare.

Based on the results, the following conclusions can be drawn.

The application of the adopted research methodology led to the conclusion that land properties with an apparently correct plot structure may require consolidation measures due to their inefficient plot configuration.

As the value of the reduction in land fragmentation was slightly lower (10%) than the required threshold value, the application of the adopted methodology did not provide clear information, which would confirm the profitability of implementing the consolidation process in the village. However, it should be noted that the simulation only took into account the change in the configuration of the plots without adjusting their fragmentation and proximity to settlements. Despite this, the obtained result does not differ significantly from the required value. Taking into account the reduction of plot fragmentation and the distance between plots and settlements in the adopted research methodology will certainly help to arrive at a clear answer as to the profitability of consolidation in the village of Przysieka.

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