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# Review of current knowledge on strip-till cultivation and possibilities of its popularization in Poland

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**Abstract.** In this review paper strip-till has been characterized from the point of view of the latest scientific research and practical justification of the advisability of using and popularizing this cultivation method in Poland for various crop species. Analysis of scientific literature has shown that strip-till has a beneficial effect on crops and soil properties. It reduces the number of tillage operations, and thus labour costs and fuel consumption. Further improvement of strip-till cultivation should be related to the improvement of seeding units designed for this cultivation technology, as well as to the implementation of precision farming solutions related to the application of fertilizers and their effective use by plants. In connection with the implementation of cultivation technologies improving soil quality and reducing the negative impact of agriculture on the environment, strip-till technology has a chance to be much more widely used in Poland and may replace traditional plough tillage.

**Keywords:** cultivation systems, soil cultivation, soil protection, carbon sequestration, carbon farming

## INTRODUCTION

Cereals prevail in cropland of Poland, occupying about 70% of the arable land. Wheat is currently the most popular cereal in Poland, occupying 30% of the sown area. As it is a cereal of great importance for feeding the Polish population and at the same time of the largest acreage among the cereals, it is important to apply appropriate crop management techniques. Apart from cereals, rapeseed and root crops, mainly sugar beets, as well as the expanding area under legume plants are of great economic importance. The cultivation systems used should combine economic efficiency with the lowest possible negative impact on the environment. The application of different production technologies used for tillage has a great influence on the economic situation of most farms. According to studies on the subject, soil tillage is one of the treatments that has the strongest influence on economic efficiency of cereal production technology, especially wheat. Tillage aims to optimize soil productivity by changing its physical, chemical and biological properties. The most common is plough tillage. The use of plough tillage creates favorable conditions for the development of the plant root system, but increases costs and accelerates the mineralization of organic matter (O'Brien, Daigh, 2019). This method (plough) of tillage is the most popular in Poland. The high costs of traditional tillage, associated with significant labour and very high energy inputs, have led to the increasing use of alternative systems of ploughless tillage or tillage simplification (Kiryluk, 2016). Studies have also shown that the elimination of ploughing reduces about 20 l of diesel fuel consumed per 1 ha of tilled soil (Białczyk et al., 2008). The use of modern technologies in soil and plant cultivation contributes to changes in soil environment. The changes are related to humus depletion, deterioration of physical and water properties and biological properties of soils (Kiryluk, 2016). According to research, tillage simplifications properly performed allow not only to reduce production costs, but also to achieve ecological objectives, related to reducing nutrient losses or limiting the rate of humus mineralization (Jaskulski et al., 2012). In recent years, a new solution in no-till practices has become available to growers – zonal till or strip-till. It involves deep cultivation of only narrow strips of land into which grain is then seeded. This method can be an effective tool to ensure economic viability and at the same time reduce the negative impact on the environment. In recent years particularly intensive research has been undertaken on the possibility of implementation and popularization of strip cropping of cereals in Poland. The results of research carried out in this field have shown that this method of cultivation may gain wider popularity in farming practice, and particularly

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large positive effects in its application can be expected in inferior sites and years with less favorable weather patterns (Różniak, 2016). This is also confirmed by studies of other authors conducted in other countries (Cociu, 2010; Jha et al., 2011). One of the elements supporting the introduction of strip-till cultivation in Poland is also the European Union policy related to ecoschemes. Within the framework of the Common Agricultural Policy, ecoschemes involve additional payments. The aim of the ecoschemes, as a payment of the 1st pillar of the Common Agricultural Policy, is to encourage the largest possible group of farmers and thus to make them widely used on farms. They are supposed to achieve the highest efficiency in terms of positive environmental and climate impact. Strip-till cultivation is included in the scope of ecoschemes payments, which is of great importance in encouraging farmers to introduce this type of cultivation. The aim of this paper is to summarize the current knowledge on strip-till approach as based on scientific research and the potential for development of this method of soil tillage in Poland.

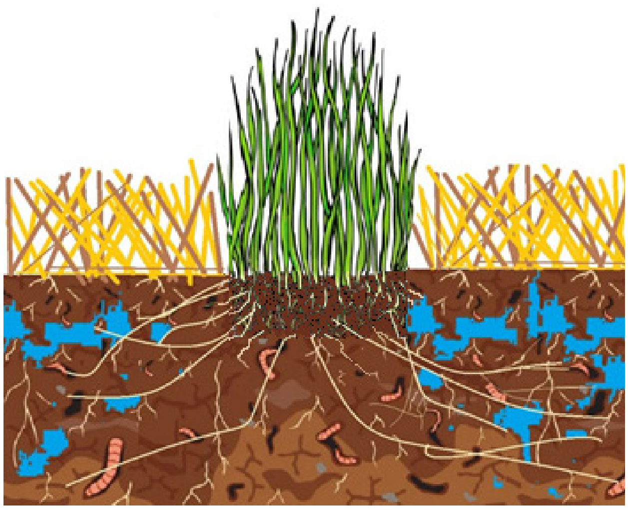

Figure 1. Strip-till with cultivated plant row and inter-rows where water reserves are stored (own elaboration)

## STRIP TILL CHARACTERISTICS

Strip-till is a combination of two distinct tillage systems, combining their advantages. The technology originated in the second half of the 20th century (Bolton, Booster, 1981). A strip-till unit cultivates narrow strips of soil along with seeding, leaving uncultivated strips in between. This causes the soil in the tilled strips to become loosened without turning it over (Nowatzki et al., 2017). This makes good conditions for the development of the plant root system, while leaving the uncultivated strips as a moisture reservoir for the root system. The problem of conserving soil water in the optimum amount for plant growth plays an increasingly important role on many farms around the world, and strip seeding is one of its key solutions. Uncultivated strips of land on which crop residues remain contain reserves of water available to the root system (Jaskulski, 2019) (Fig. 1). In the United States, where strip sowing has become very popular, cultivated strips are about 30 cm wide and uncultivated interrows with crop residue left are 20 cm wide (Morris et al., 2010). Eventually, of the total cultivated area, less than 50% is cultivated and the remainder is left uncultivated with crop residues left on the surface (Celik et al., 2013). Cultivation may take place in the fall or spring depending on soil conditions. The crop residues left behind effectively protect this soil strip from excessive heating and water loss through evaporation (Fig. 2). Taking into account increasingly frequent agricultural

Figure 2. Stubble and crop residues in uncultivated soil strips and wheat plants in the cultivated strip (photo: author).

droughts, the importance of strip-till is a solution that can be much more widely used in Poland. Tilled strips of soil, which is loosened and aerated, make more favourable conditions for germination. The cultivated strips heat up more and thus the seeds have more favourable conditions for the initiation of the germination process (Jaskulska, Jaskulski, 2020). Uncultivated strips of land covered with stubble and crop residues are left in between. In the period between harvesting of the preceding crop and sowing of the successive crop, no tillage operations are carried out. Therefore, the field surface should be covered with mulch, e.g. straw shredded by a combine harvester. Tillage can be done in one or two steps. Single-stage cultivation consists in the aggregate seed drill performing both loosening of the soil strips and sowing at the same time. On the other hand, two-stage cultivation consists in dividing the loosening of soil strips into two separate operations, and then carrying out the actual sowing after marking out the cultivation strips. Two-stage strip-till seeding is most often performed on heavy and wet soils. This is because the initial loosening of the soil creates better air conditions due to partial drying of excess water and better warming of the soil (Jaskulska, Jaskulski, 2020). Strip seeding can therefore be an alternative to the introduction of total no-till on heavy soils (Licht, Al-Kaisi, 2005). Ploughless cultivation on heavy clay soils is the best tillage system for wheat and oilseed rape (Giannitsopoulos et al., 2019). On heavy soils, combining full tillage with no till offers the chance to create favorable conditions for the crops to grow, while at the same time there is still the possibility of using a cultivation system that benefits the environment by, among other things, accumulating organic matter and organic carbon (Giannitsopoulos et al., 2020).

The widespread adoption of strip-till technology made it necessary to develop suitable tillage and seeding units specifically designed for the system (Myalo et al., 2019). Historically, there were no machines available to apply strip-till seeding. The first attempts of strip seeding were made in maize production. These experiments were conducted at the Department of Agronomy, Poznań University of Life Sciences in 2006. In the experiment, a strip-till unit was used, which consisted of a disc cutter, a tine, harrowing discs and a string roller (Piechota, 2011). The first attempts to introduce strip tillage were modeled on solutions from the United States, where strip sowing had been already used since the 1980s in maize cultivation (Piechota, 2017). Nowadays, in Poland as well as in other countries of Eastern Europe, the interest among farmers has significantly increased, and seeding-cultivation units manufactured by the Polish companies Mzuri-Agro, Agro-line and Czajkowski-Maszyny are available (Piechota, 2017). They are used successfully in various European countries such as: Poland, Ukraine, Lithuania, Czech Republic, Slovakia, eastern states of Germany, Belarus, Serbia and Romania (Jaskulska, Jaskulski, 2020). The growing interest in strip cropping is also expanding to other countries. This is especially true in Russia, where attempts are being made to construct their own tillage and seeding units that can be used for strip tillage (Boikov et al., 2021). The equipment used in strip tillage should be characterized by edges of sufficient sharpness and ability to crush the topsoil, as well as uniformity of tillage depth and width of the cultivated strip and flatness of the cultivated surface, and it should prevent clogging of the working bodies with plant residues and soil (Alimova et al., 2021). Thus, it is important to properly adjust the coulters and their design to effectively carry out the tillage procedure in the strip (Lei, 2019). In the future perspective, there is a possibility to further improve the design of strip-till sowing machines including the possibility of applying precision seeding and fertilization (Talarczyk, Łowiński, 2018). In connection with the growing interest in strip-till cultivation, it creates an opportunity for Polish machinery manufacturers to expand the offer of domestic machinery as well as the possibility of selling them abroad.

## LABOUR INPUT AND COST IN STRIP-TILL CULTIVATION

The pressure to protect the environment and at the same time achieve the best possible economic results in crop production has led to the development of tillage systems that minimize the costs associated with cultivation. The choice of a specific cultivation method depends on many factors, and one of the main arguments taken into account is economic efficiency. In the case of strip-till technology, the availability of new cultivation machinery on the Polish market is a positive aspect. Still, the cost of their purchase often exceeds the financial possibilities of small farms. The efficiency of investment effort taken is determined by the scale of production and the possibility of using the on-site facilities within the farm. It refers especially to machines and devices whose rational use requires an adequate area of arable land (Dziwulski, Szymańska, 2020). On the other hand, on the positive side, the design of machines adapted to strip-till and the possibility of performing several tillage operations at the same time cause the fuel cost and labour input to decrease (Hoque, Miah, 2015; Myalo et al., 2019). A study by Jha (2011) found that the total time and cost of tillage and seeding treatments with strip-till machine was 5.09 $h \cdot ha^{-1}$, which was 72.23 percent less than time required by plough tillage of wheat but 28.83 percent more than no-till. In addition to performing simultaneous strip till and seeding, there is the possibility of simultaneous localized fertilization, which further reduces the costs associated with fuel consumption and labor (Talarczyk, Łowiński, 2018). The use of strip till technology saves more than 20 liters of fuel per hectare compared to reduced tillage and 30 fuel per hectare compared to conventional plow tillage (Jaskulska, Jaskulski, 2020). Różniak (2016) comparing fuel use in winter wheat, found that replacing tillage with strip-till reduced fuel use by 25 liters per hectare. In the case of sugar beet cultivation, strip-till reduces fuel consumption by 38% compared to conventional ploughing (Jaskulska et al., 2017). In the case of strip-till in rapeseed, it is possible to save 63% fuel consumption compared to conventional ploughing (Saldukaitė et al., 2022). Strip-till of faba bean also brings fuel consumption savings of 56–63% compared to conventional ploughing (Afify, 2021). As reported by Lekavičienė et al. (2019), the design of tillage units for strip-till cultivation is important for fuel consumption. The cited authors by changing the elements of strip-till aggregates such as: angle of attack (10°, 15° and 22.5°), coulter penetration depth (0, 100 and 200 mm) and operating speed (1.3, 1.9 and 2.5 m $s^{-1}$), showed that increasing the angle of attack between row discs had no significant effect on diesel consumption, while increasing the operating speed and depth of penetration of the sowing coulter significantly elevated diesel consumption. Similarly, Mudarisov et al. (2020) found that fuel consumption in strip-till technology also increased with increasing speed and angle of attack of the redrails. An increase in speed from 0.5 to 2.5 m $s^{-1}$ leads to an increase in tractor fuel consumption by 70–80%.

## EFFECT OF STRIP-TILL APPLICATION ON YIELD AND YIELD QUALITY IN SELECTED CROPS

Strip-till was pioneered in the USA, where a good solution was sought to the problems associated with the use of direct seeding of maize in no-till. The problem was due to reduced yields as a result of poorer crop emergence. The emergence was, in turn, hindered by crop residues laying on the field. The reduction of planting density also resulted in a lower yield. Therefore, strip-till technology started to be used. Using this method, maize grown in tilled strips yielded better than in the no-till system (Reeves, Touchton, 1986). It has been recognized that this tillage system works well for maize, providing higher yields than the no-till system, while having positive effects on water retention capacity and increasing soil organic matter (Allmaras, Dowdy, 1985). The first scientific papers presenting results from strip-till were also concerned with maize. These were undertaken to compare a no-till system and strip-till. The results showed that grain yield was higher in strip-till due to an increase in plant density per square meter (Piechota, 2011). In the case of maize, adequate soil heating during the plant germination period is influential. A suitable aggregate should push crop residues away from the cultivated strip as much as possible. Removing the residue allows the soil to warm up better by up to several degrees compared to an uncultivated strip with stubble left. Soil temperature in tilled strips can be higher than in ploughed soil and especially in no-till (Table 1). The top layer of soil in strip-till technology at the depth of 5 cm may have even 1.4–1.9 $^{o}$C higher temperature than in traditional ploughless

Table 1. Soil temperature depending on cultivation system (own elaboration based on Nowatzki et al., 2008).

| Tillage system | Soil temperature | |
|---|---|---|
| | Year | |
| | 2006 | 2007 |
| Plough | 14 | 20 |
| No-till | 13 | 18 |
| Strip-till | 15 | 22 |

tillage (Licht, Al-Kaisi, 2005). In addition, crop residues protect plants under unfavorable conditions from excessive soil moisture loss. Under rainfall deficient conditions, strip-till combines the benefits of higher temperature and moisture to increase the number of germinating seeds and subsequent planting density (Nowatzki et al., 2008). Soil warming in strip-till technology is also influenced by weed control, which is important for soil warming in cultivated strips. This is especially important for maize, which has quite high soil temperature requirements during the emergence period. Better soil warming in cultivated rows where maize seedlings grew compared to uncultivated rows was also confirmed by Piechota et al. (2013). Additionally, weed control is an important aspect that promotes soil warming and better growth of maize seedlings. In a strip-till system, weed control in maize improves soil warming to higher temperatures. The best way to control weeds in this cultivation system is herbicide application. The use of mechanical weed control can reduce soil temperatures compared to herbicide control (Piechota et al., 2013). Other research conducted on maize has also shown superior grain yield in a strip-till system (Potratz et al., 2020). Strip-till appears to be the best cropping system for maize. Especially when weather conditions are not favorable, maize yields are higher than in conventional plough tillage, and under optimal weather conditions yields can be comparable (Demmel et al., 2012). Sorghum is a species related to maize, with similar agronomic requirements and crop management practices. In Poland, this crop is not currently cultivated over a large area, but may increase its cultivation area in the future. Sorghum can also be grown in a strip-till system. Similar to maize, positive effects associated with higher grain yields predispose sorghum to strip-till cultivation (Sainju et al., 2005a). In addition, sorghum in strip-till during dry periods showed higher yield and higher water use efficiency (WUE) compared to conventional plough crop (Darapuneni et al., 2017). Grain sorghum yields higher in strip-till than it does in conventional plough crop (Godsey et al., 2015).

Other cereals, both spring and winter, can be grown in strip-till. Research shows that wheat grown in strip-till produces a higher yield than wheat grown in no-till and conventional plough system. A study by Jaskulska et al. (2020) showed that winter wheat gave the same grain yield as that grown in the plough system. However, the grain yield obtained was 10.4 % higher than in the conventional no-till. The higher grain yield obtained by Jaskulska et al. (2020) in the strip-till technology resulted from better emergence of wheat grains which translated into a higher number of ears and grain weight per ear. The results of the study conducted by the cited authors related to better emergence may be associated with higher soil moisture found under strip-till cultivation. Similarly Hossain et al. (2005) found higher grain yield of wheat in strip-till in comparison with conventional (plough) cultivation. The factor that is important and differentiates the yield obtained and its quality is the genetic factor – variety. This is indicated by numerous studies on the yield of individual wheat varieties, both by the Research Centre for Cultivar Testing and scientific research (Noworól, 2018; Wicki, 2017). Advances in breeding new varieties of wheat, resulted in yield stability. Selection of an appropriate variety is among the non-input factors influencing crop yield, but it must be linked to optimally selected cultivation technology and prevailing habitat conditions (Wojtkowiak et al., 2018). Given that unfavorable weather conditions during the growing season will become more frequent, research to identify the methods most effective for such conditions, seems to be very justified. Previous research showed that the genetic factor may have been behind differentiating production and economic effects in reduced tillage on. This is due to their physiology-related ability to grow and develop at a certain density. Strip sowing creates a special situation for wheat plants, which is that plants sown in two rows next to each other are separated by an interrow of greater width. This fact indicates the need to determine physiological parameters of plants growing under such conditions. As shown by Jaskulska and Jaskulski (2021), winter wheat and barley plants grown in strip-till contained more chlorophyll in their leaves and had higher leaf stomatal conductance, which indicates more favorable conditions for photosynthesis. Moreover, the role of genetic factor in shaping cereal canopy productivity results from different resistance of cultivars to stem base and root diseases, i.e. those which find better conditions for growth and development under conditions of limited cultivation. The occurrence of fungal diseases causes not only negative effects in the form of grain yield reduction, but also deterioration of its quality (Korbas et al., 2008), and a special role in reducing the quality of grain falls to diseases caused by fungi of the genus *Fusarium* (Wegulo et al., 2011), due to the secondary metabolites produced by them – mycotoxins. Moreover, taking into account the studies conducted by other authors indicating that both cultivation simplifications (Pabin et al., 2007; Wesołowski, Cierpiała, 2011) and genetic factor (Murawska et al., 2014; Sobolewska, Jaroszewska, 2016) have a great influence on yield and quality-related parameters determining their baking value. The results obtained by Różniak (2016) showed the beneficial effect of strip-till technology on winter wheat plants, its yield and grain quality was revealed mainly in years with cultural and habitat conditions not conducive to yield. The study by Jaskulska et al. (2018) showed no effect of cultivation method (strip-till vs. plow tillage) on wheat grain quality traits such as grain protein and gluten content, sedimentation value, bread volume and weight. The authors found that grain quality was more influenced by weather conditions in particular years. Likewise, in barley, a beneficial effect of strip-till on yield was reported especially in years with rainfall deficits (Jaskulska et al., 2019).

Rape is also an important crop in Poland. The area sown to rapeseed in Poland in 2020 was 981 thousand hectares (Statistical Yearbook of Agriculture, 2021). So far, rapeseed has been grown in traditional ploughing cultivation, but in recent years the number of studies on the possibility of growing this crop in strip-till has increased. As shown in the study by Jaskulska et al. (2018) winter rapeseed responds differently to the plough and strip-till cropping systems. Under favorable conditions, when temperature and rainfall are conducive to plant emergence, the plow tillage system is more favorable. On the other hand, the strip-till system creates better conditions for germination when the air temperature is lower and rainfall deficiency occurs. A higher plant density was obtained and in addition the plants were characterized by a higher uniformity of growth. The yield of rapeseed in strip-till cultivation was 8% higher than in conventional ploughing (Bečka et al., 2021). A positive effect of strip-till cultivation was obtained by Sokólski et al. (2018) noting a higher yield of rapeseed in strip-till compared to ploughing by 0.16 tons per hectare and no-till by 0.29 tons per hectare. However, there is a possibility of modifying the strip-till method by applying conventional ploughing and sowing seeds in strips over the entire field. That modified strip-till resulted in a yield higher by 0.06 tons per hectare compared to conventional strip-till and ploughing (Bečka et al., 2021). The use of strip-till in oilseed rape at the same sowing density gives a higher yield than the traditional plowing system. This provides the opportunity to make better use of expensive seed material, reducing costs and increasing income (as a result of the better oilseed rape yield). Schwabe et al. (2021) using the same sowing rate of 50 oilseed rape seeds per $m^2$ obtained a 5.2% higher yield in strip-till than in conventional tillage. The crops differed in the plant row spacing when the strip-till had an interrow spacing of 50 cm compared to 12 cm in conventional sowing. Wider interrows in strip-till can facilitate access to light. In addition, in strip-till, creating better growth conditions before winter influences greater winter hardiness of rapeseed plants (Jaskulska et al., 2018).

Legumes, including soybean, are becoming more and more popular in Poland due to the demand for fodder protein. Especially the soybean area is increasing systematically. There are no Polish studies on strip-till cultivation of soybean. However, where the acreage of this plant is large, it is also grown in strip-till. Numerous studies show a beneficial effect of strip-till cultivation in soybean production on its grain yield (De Felice et al., 2006; Farmaha et al., 2012; Potratz et al., 2020). In addition, strip-till cultivation of soybean has good effects related to yield quality. Seeds from strip-till soybean contain more oil and protein compared to no-till (Farmaha et al., 2012). This increases the protein yield per hectare which is particularly important in terms of forage use of this crop for forage protein production. Soybean is mainly used as an oilseed crop, hence higher oil content in the seed is important for seed quality, but the remaining post-extraction soybean meal after oil pressing is an important protein component for feed production. Besides strip-till cultivation of cereals and legume crops, the possibility of growing mixtures of these species seems to be an interesting alternative. Jaskulska et al. (2022) conducted interesting research on different variants of sowing barley and peas. The researchers used strip-till cultivation in pure sowing of barley and peas as control treatments, alternate strip-till sowing of a strip of peas and barley and mixed strip till sowing of peas and barley simultaneously. The results of the experiment showed that the mixed cropping (pea + barley) in strip-till resulted in a higher grain yield compared with the pure crop by 8.5% for barley and 10.2% for pea. The mixed strip-tilled crop gave a protein yield per hectare similar to that of peas in pure sowing, but 109 kg per hectare higher than that of barley in pure sowing. The grain crop from the cereal and legume mixtures is used for feed production. This offers the prospect of increasing fodder protein production while protecting the environment and maintaining biodiversity.

In addition to cereals, rapeseed and legume crops, sugar beet can also be grown in strip-till technology. The number of seeds germinated in the plough and strip-till system is comparable, similarly, plant density shows a comparable result with a tendency in favor of strip-till (Jaskulska et al., 2017). In the strip-till system, sugar beet also shows a number of other positive characteristics. As stated by Górski et al. (2022) root yield of different sugar beet varieties was 6.6% higher in strip-till compared to plow tillage. The researchers also reported higher sugar content in the roots of beet grown under strip-till by 8.2%. A study conducted by Afshar et al. (2017) showed that sugar beet root yield was higher in strip-till (5% and 3%) compared to plowed and no-till. Nowatzki et al. (2008) showed no difference in beet root yield in conventional plow-till and strip-till. Similarly, Stevens et al. (2006) found no differences in sugar beet root yield, but yield quality associated with higher sugar content was more favorable in strip-till. The cited studies indicate that it is possible to use strip-till technology in sugar beet cultivation, which reduces the costs associated with cultivation and fuel consumption, and at the same time does not reduce the yield, and may have a positive effect on its quality. However, the negative aspects of strip-till sugar beet cultivation related to soil type should also be kept in mind. On sandy loam soils, it is more advantageous to break up the topsoil earlier to create better conditions for the germination of sugar beet seeds (Laufer, Koch, 2017).

The above-mentioned results of scientific studies confirming a positive effect on yield and its quality in the main groups of plants grown in Poland (wheat, maize, rapeseed, soybean and curly beet) give, at the same time, the possibility of arranging a diversified crop rotation and avoiding monoculture. The results obtained with a mixture composed of peas and barley were also favorable (Jaskulska et al., 2022), which also contributes to the development of this technology by including other cereal-legume mixtures to be grown under strip-till regime.

## EFFECT ON WEED INFESTATION

Due to the fact that strip-till is a special type of tillage that combines plowing and no-till, weed infestation can be a problem. The ploughless system is often characterized by higher weed abundance. The system itself affects the species diversity and biomass of weeds (Małecka-Jankowiak et al., 2015). Traditionally, weed control has been the primary reason for tillage, but with the increasing number of herbicides available, opportunities to reduce tillage with more effective weed control have become easier. As reported by Hendrix et al. (2004), weed infestation was the same in strip-till and in ploughed maize, while weed pressure was greater in the no-till system. In maize, Polish studies indicate that herbicide weed control is more beneficial, which is associated with higher efficacy and better soil warming (Piechota et al., 2013). Effective weed control is an important element affecting later yield. Better germination of maize increases plant density and allows the plants to compete more effectively for light with weeds. When applying herbicide treatments in strip-till, it is extremely important to select the right herbicides for the crop (Zahan et al., 2017; Soltani et al., 2022). Some weed species are able to adapt to the specific cropping system and herbicide (active ingredient) used and produce resistant ecotypes. In addition, in strip-till technology, crop residues left on the surface can impede the penetration of the active liquid by creating a protective umbrella over weed seedlings and hindering their control (Culpepper et al., 2007). Increased weed pressure in strip-till can reduce wheat yield, especially in subsequent years. Giannitsopoulos et al. (2019) observed increasing pressure of field bindweed in subsequent years in wheat grown in strip-till. A good way to reduce weed pressure in strip-till is to apply nitrogen fertilizer directly to the crop strips, avoiding application to the inter-row. This method of fertilization significantly reduces weed pressure and lowers herbicide use (Nelson, 2015). In strip-till sugarbeet, the greatest threat is foxtail millet, whose density is higher than in conventional plow tillage (Wenninger et al., 2019).

## IMPACT OF STRIP-TILL ON SOIL PROPERTIES

One of the benefits of strip-till is that it improves soil health by restoring natural soil processes and restoring soil fertility. Harvest residues and stubble left on the soil surface reduce wind and water erosion. In addition, the depressions in the cultivation strips allow more snow to accumulate in winter, and crop residues between the strips prevent it from blowing away from the field. Crop residues left behind enrich the soil with organic matter. Organic matter and its slow decomposition increase the organic carbon content of the soil and enhance biosecretion of carbon dioxide. Strip-till is one method of increasing carbon biosequestration comparable to total no-till (Dębska et al., 2020). Additionally, cover crops can be used to increase soil fertility and carbon biosequestration. As indicated by the study of Sainju et al. (2005b) the application of a catch crop composed of vetch and rye in sorghum and cotton crops can increase soil organic carbon biosequestration compared to conventional plough tillage. The use of strip-till technology increases the amounts of total organic carbon (Fernández et al., 2015), but also its content in organic matter fractions, except for humates (Dębska et al., 2020; Jaskulska et al., 2020).

The differentiation of strip-till into cultivated and uncultivated strips also changes the physical properties of the soil. Soil in cultivated strips has lower compaction and consequently higher total porosity. In subsequent years of conservation tillage, the proportion of water-stable aggregates increases, which has a positive effect on soil quality (Giannitsopoulos et al., 2019; Jaskulska, Jaskulski, 2019). The use of strip-till technology reduces water erosion of the soil through leaching of soil particles. Compared to plow tillage, it is a far superior alternative for soil water erosion control (Herout et al., 2018).

Improved soil quality and productivity is also associated with increased abundance of mesofauna and soil microorganisms. The available crop residues on the soil surface and the presence of uncultivated strips of soil are beneficial for earthworm life. Their increased number is beneficial for organic matter cycling. Jaskulska et al. (2020) showed that in the soil cultivated with strip-till technology the abundance of earthworms is twice as high as in the no-till system and four times as high as in the plough tillage. Also Giannitsopoulos et al. (2019) confirmed the beneficial effect of crop residues left on the surface on earthworm abundance. Crop residues left on the soil surface also enrich microbial life. As shown in a study by Różniak (2016), after three years of strip-till technology, the number of total bacteria on the soil surface was higher than on ploughed and no-till sites. Similarly, Jaskulska et al. (2020) found higher total numbers of bacteria, cellulolytic microorganisms, and fungi after eight years of strip-till than in plow-till. The increase in soil microbial abundance in subsequent years of strip-till technology was also confirmed by Jaskulska and Jaskulski (2019). The above-quoted scientific research results show that the application of strip-till has a multifaceted positive effect on the soil. Due to the loss of organic matter from soils in Poland, the spread of this cultivation method can have a positive impact on the soil environment and improve soil fertility. This method can be considered as one of the methods of regenerative agriculture.

## STRIP-TILL PRECISION FARMING

Adequate fertilization levels are important for yield quantity and quality. However, overuse of mineral fertilizers has negative environmental effects. Currently, a restriction on the use of mineral fertilizers is being introduced as a result of the introduction of administrative decisions related to the Green Deal, so rational fertilizer management is necessary to maintain high yields while minimizing the negative effects of overuse of artificial fertilizers (Matyka, 2021). Efficient use of fertilizers must be based on rational application, especially when there is high soil variability in the field. Strip-till technology can be used to reduce fertilizer and yield losses. As shown in the study of Jaskulska et al. (2019) strip-till reduces plant variability and yield within the field, especially under unfavorable environmental conditions. Thus, it is one of the elements of rational crop management. An important benefit is also the possibility of applying localized fertilizer close to the root system, which can increase the efficiency of nutrient use by the plant. However, applying fertilizer too close to the root zone can cause a negative effect. As shown by Adee et al. (2016), too close an application in strip seeding of fertilizer can result in lower yield as a result of reduced maize planting density. The researchers recommend applying fertilizer at a distance of 10 cm from the maize crop row in strip-till. The use of mineral fertilizers together with sowing and their appropriate dosage to individual parts of the field is a promising solution, which gives a chance to reduce the use of fertilizers and losses caused by their over-application. Strip-till technology provides an opportunity to further improve this type of practice without yield deterioration with simultaneous economic and environmental benefits (Talarczyk, Łowiński, 2018). In strip-till, it is also possible to effectively use nitrogen from natural fertilizers such as manure. However, as shown in a study by Pietzner et al. (2017), it is more beneficial to apply manure to crop rows with plants. This method of manure application increases nitrogen utilization while reducing NH3 and N2O emissions. It is also possible to apply manure into the root zones of crop rows with plants to provide organic matter and plant nutrients (Darapuneni et al., 2019). Replacing mineral nitrogen with nitrogen from natural fertilizers including manure in strip-till can be beneficial both in terms of reducing mineral fertilizer use and soil properties without negative effects on the environment and crop yield (Battaglia et al., 2021). In recent years, there has also been increasing interest in the use of hydrogels. Their topsoil application is expected to improve water retention and assist agriculture in the fight against drought. Hydrogels for agricultural applications are dedicated to favour the environment while allowing to reduce the negative effects of drought. Scattered hydrogel application can be ineffective. In strip-till technology, it would be more beneficial to apply them in rows where crops are grown. Proximity to the root system would allow more water to be retained and increase water use by plants. The use of hydrogel is particularly important in years with rainfall deficits (Grabiński, Wyzińska, 2018). However, it would always be important to precisely restore strips with cultivation and leave the same strips uncultivated. Technological solutions related to the use of GPS technology can be helpful here. By precisely guiding the machines in the field, it would be possible to always recreate the same tillage pattern without disturbing the soil structure in the uncultivated strips. Taking into account the benefits of strip-till technology and the possibility of its further improvement by precise fertilization, the use of mineral and natural fertilizers and the application of hydrogels, it gives a chance to increase yields while optimizing costs and reducing the negative impact of agriculture on the environment.

## CONCLUSIONS

Strip-till is an intermediate tillage method that combines elements of both plowing and no-till technologies. Creating the right conditions for germination and temperature rise in cultivated strips with plants gives them more favourable conditions for development. The uncultivated strips provide moisture storage and have a positive effect on soil properties. Strip-till technology also has the advantages of reducing costs and fuel consumption, but also has a positive impact on the environment by reducing $CO_2$ emissions into the atmosphere. It also has a positive effect on the sequestration of carbon in the soil. It is a method with many advantages. The available seeding units on the Polish market make it possible to implement this cultivation system on a large scale in Poland. However, a limitation is the high price of strip-till equipment, which for small farms is a price barrier to the introduction of this cultivation method. An alternative is the possibility of renting strip-till cultivators. The emphasis on environmental protection by the European Union as well as the maximization of the yield in connection with the protection of soil and environment is also a factor that may cause the expansion of strip-till cultivation in Poland.

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