ECOLOGICAL FOOTPRINT OF SOYBEAN PRODUCTION

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Abstract: *We researched the impact of different soil tillage of soybean production on the environment. The experiment was carried out on a larger agricultural property. The obtained data were analysed with the SPIonWeb program, whereby we obtained calculations of the ecological impacts of technical procedures on the environment during the vegetation period. The results showed that the biggest ecological footprint is represented by ploughing, followed by conservation tillage and direct seeding. We found that ploughing tillage has the largest ecological footprint at 28.2 gha (global hectares), followed by conservation tillage at 23.6 gha and direct seeding at 23.2 gha. In the future, we will have to adapt and improve cultivation techniques in the area under consideration and consider how to reduce the ecological footprint by promoting soil cultivation methods that do not increase carbon dioxide emissions.*

Key words: *Ecological footprint, conventional tillage, conservation tillage, direct sowing, soybean*

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1. Introduction

Soybean is of great importance in human nutrition and in the nutrition of domestic animals, as it contains a large proportion of protein and fat. According to Elzebroek and Wind (2008), soybean (*Glycine max(L.) Merril*) is classified as one of the oldest cultivated plants. According to records found, soybean was domesticated around 5000 years BC in the eastern part of northern China, while it was not introduced to Europe until the 18th century.

Today, soybean is the most widespread protein legume and an important oilseed in the world and sowing is increasing year by year. In 2014, 308.44 million tons of soybeans were produced in the world. It was mostly grown in the United States (35%), Brazil (28.1%) and Argentina (17.3%). In contrast to the American countries, 0.6% of soybeans (1.85 million tons) were produced in the European Union (Faostat, 2022), which explains the fact that in the last decade Europe and especially the European Union is facing a large deficit of soy protein (Dima, 2015). Despite this, there are several thousand soybean varieties registered in the European Union, most of which have been bred by selection and crossbreeding and thus adapted to different geographical areas and climatic and soil conditions. Figure 1 shows ES Mentor soybean variety used in the experiment.

Fig. 1. ES Mentor soybean variety.

1.1 Ecological footprint

Wackernagel and Rees developed ecological footprint in year 1996. It presupposes that every individual, process, activity and area has impact on the planet with natural resources, waste and use of natural processes.

These impacts can be converted into biologically productive land (such as land upon which the photosynthesis and biomass is produced). The Ecological Footprint is determined by comparing bio capacity of uncultivated land with the impact of man on nature. Bio capacity is representing biologically active areas, such as forests, pastures, fields and water surfaces. Maximum bio capacity has surfaces that leave them untreated because these increase their positive impact. These surfaces can absorb a large amount of waste and significantly reduce carbon dioxide emissions. Bio capacity is compared with the impact of humankind on nature (Global Footprint Network, 2016; Berk et al., 2016).

With the environmental footprint in agriculture, natural biologically productive areas are assessed, which are necessary to sustainably store the footprint of food production, including raw materials and energy, in the form of marine sediments. It is calculated for activity, events, products and individuals, whereby the calculation of an area of bio capacity is the available natural area for a certain production, population or individual (Stajnko & Vindiš, 2012). The Global Footprint Network also draws attention to the state of negative impacts in the environment, which states that the Earth currently needs one year and six months to regenerate from the consumption generated in one year.

More than 7 billion people currently live on Earth, and the demand for food is increasing. Intensive agriculture is no longer a model that could feed nine billion people on Earth in 2050, who will then need 9.8 billion kilograms of food every day, which is almost one more time than we produce today. Even today, its shortcomings are becoming increasingly apparent even in terms of environmental impacts, with soil pollution with mineral fertilizers, pesticides and animal excreta. Livestock fertilizers, mineral fertilizers, pesticides and fossil fuels cause emissions of ammonia and greenhouse gases such as methane, nitrous oxide and carbon dioxide (Dolinšek, 2014). The Agrometeorological Portal of Slovenia also states on its website that agriculture contributes 16.5% of greenhouse gas emissions, and the possibilities for reduction are small. The problem occurs mainly when fossil fuels used to drive machinery and the loss of organic matter due to inadequate soil cultivation (Agrometereološki portal Slovenije, 2018).

1.2 Different soil tillage techniques

Over the years methods of soil tillage varied, as they are encountered more and more new tillage technologies that are at the same time increasing the cost of fuel and labour. With the adoption of less intensive cultivation methods, many farmers realize the negative effects of conventional tillage and see the benefits of maintaining residues on the soil surface. Systems of production without tillage left on the land surface maximum of residues and often prove to be the most profitable method of production (CropWatch, 2016; Rakun et al, 2015).

There are three different tillage methods: conventional tillage, conservation tillage and direct sowing without any tillage. For conventional tillage, the soil is annual plough. Plough turns the furrow, loosens the soil of treated layer, completely cover the crop residues, manure and weeds.

Followed by pre-sowing tillage, which levelled the surface, crush lumps, if necessary, thicken the layer of soil. Followed by sowing after the harvest but stubble processing.

Conservation tillage is soil method tillage, which left on the surface the plant residues of previous crop (such as corn stalks or wheat straw), before and after the sowing of the next crop, in order to reduce soil erosion. For this purpose, it must remain covered with the remains before sowing at least 30% of the surface soil. Some conservation tillage methods renounce traditional tillage and leave seventy percent and even more crop residues on surface. Conservation tillage is especially suitable for the soil tillage where soil is exposed to erosion.

In direct sowing, we directly sow into uncultivated soil. Direct sowing is a measure against erosion on sloping lands and measures to prevent leaching of nitrate in lowland areas. The plant residues on the surface serve to protect against evaporation of moisture from the soil and increase the biological activity and the formation of humus. For direct sowing, special seed drills with circular sowing coulters are required. The spread of sowing is said to be conditioned mainly by climatic and soil conditions, but due to the lower consumption of working time and fuel, it is mainly influenced by climatic conditions. Only about 2% of agricultural land in Central Europe is cultivated according to this procedure (Stajnko, 2017).

The purpose of this study is to evaluate the ecological footprint of soybean production. This involves assessing the environmental impacts associated with different tillage methods of soybeans. The study aims to identify key factors contributing to the ecological footprint and propose strategies to mitigate negative environmental effects, thereby promoting sustainable agricultural practices. The study research questions will examine the main environmental impacts of soybean production, including land use, water consumption, and greenhouse gas emissions. It will also explore how different production practices influence the ecological footprint of soybean production, and investigate the potential benefits and challenges of implementing sustainable practices in soybean production.

2. Methods and materials

2.1 Location of the experiment

For the purpose of the research, we used the results of soybean cultivation, which was carried out on a plot owned by an agricultural company. Ploughing, conservation tillage and soybean direct seeding were carried out on the site. The soybean variety is ES Mentor (Figure 1), which follows grain corn in the crop rotation, and soybeans followed winter wheat.

Soybean production took place in the municipality of Rače - Fram, site number is 4038156 (Figure 2). The coordinates of the performed experiment are 45º 25' 30" N and 15º 42' 35" E, the native name of the field is "Gorica" and it covers a total of 94.71 ha. The average altitude of the field is 249,402 m.

Fig. 2. Location of the experiment.

2.2 SPIonWeb online program for calculating the ecological footprint

For the calculation of the ecological footprint was used SPIonWeb program, developed by Krotscheck and Narodoslawsky. SPIonWeb is a free program that calculates the ecological impact of technical processes on the environment throughout the life cycle, including raw materials and with all emissions and wastes. SPIonWeb calculates the ecological footprint with the Sustainable Process Index (SPI) method, including carbon dioxide emissions and global warming potential (GWP).

2.3 Machinery used in the experiment

Table 1 show the machinery which was used in the experiment - conventional tillage with ploughing.

Task	**Tractor**	**Machinery**	**Work produ-ctivity (ha/h)**	**Fuel consumption (l/h)**
Mulching	Fendt 722	Hammer mulcher Celli (6,5 m)	4	16
Ploughing	Fendt 818	Plough Regent 4B	0,5	13
Pre-sowing tillage	Fendt 818	Circular harrow Kverneland (4 m)	10	11
Basic fertilization	Fendt 716	Spreader Bogballe (24 m)	14	12
Sowing	Fendt 930	Lemkem sowing combination	4	28
Spraying (3x)	Fendt 716	Sprayer RAU (24 m)	14	12
Fertilization	Fendt 716	Spreader Bogballe (25 m)	14	12
Harvest	harvester Class Tucano		2	16

Tab. 1. Machinery used in ploughing.

In all three types of tillage, which are the subject of our research, we had to spray against weeds and fertilize with fertilizers. For pesticide application, we used a Fendt 716 tractor and a RAU sprayer (24 m). We also used the Fendt 716 tractor for fertilizing with a Bogballe spreader (25 m).

In conservation tillage, we used less mechanization than in conventional tillage. For basic tillage, we used a Challenger Caterpillar MT875B tractor with an engine power of 432 kW (Figure 3) and a Top Down 600 tillage machine. All other mechanization was the same as for ploughing. All listed tasks with tractors and machinery used in conservation tillage are shown in Table 2.

Fig. 3. Tractor Challenger MT875B.

Task	Tractor	Machinery	Work productivity (ha/h)	Fuel consumption (l/h)
Mulching	Fendt 722	Hammer mulcher Celli (6,5 m)	4	16
Basic tillage	Challenger MT 875	Top Down 600	4	60
Basic fertilization	Fendt 716	Spreader Bogballe (24 m)	14	12
Sowing	Fendt 930	Lemkem sowing combination	4	28
Spraying (3x)	Fendt 716	Sprayer RAU (24 m)	14	12
Fertilization	Fendt 716	Spreader Bogballe (25 m)	14	12
Harvest	Kombajn Class Tucano		2	16

Tab. 2. Machinery used in conservation tillage.

For direct sowing, we used the Lemkem Soltair 9 seeding combination, which we had to adapt to enable direct sowing in untreated soil. All agro technical measures remained the same as for the previous two types of tillage. The machines used in the experiment are shown in table 3.

Task	Tractor	Machinery	Work produ-ctivity (ha/h)	Fuel consumption (l/h)
Mulching	Fendt 722	Hammer mulcher Celli (6,5 m)	4	16
Sowing	Fendt 930	Seed drill Lemkem	4	28
Spraying (3x)	Fendt 716	Sprayer RAU (24 m)	14	12
Fertilization	Fendt 716	Spreader Bogballe (25 m)	14	12
Harvest	harveste Class Tucano		2	16

Tab. 3. Machinery used in direct sowing of soybean.

2.4 Agro technical measures in soybean production

In the experiment, we used the same amounts of herbicides for all three different soil tillage techniques. We used Sharpen 400, Harmony 50 SX and Pulsar 40 SL, which are shown in Table 4.

Sharpen 400 SC (pendimethalin) was used for the first spraying, which is used as a selective herbicide to control annual narrow- and broad-leaved weeds before emergence or immediately after crop emergence. In the second spraying, we used Harmony 50 SX and Pulsar. The mentioned herbicides can be used in split doses (split application), which is why we also used them in the second and third spraying.

Herbicide protection	Herbicide	Consumption	Herbicide	Consumption
Spraying	Sharpen 400 SC (pendimetalin)	3,5l/ha		
Spraying (split application)	Harmony 50 SX	7,5g/ha	Pulsar 40 SL	0,50 l/ha
Spraying (split application)	Harmony 50 SX	7,5g/ha	Pulsar 40 SL	0,50 l/ha

Tab. 4. Herbicides used in the experiment.

We used NPK in the ratio 6:12:24 for the basic fertilization in 350 kg/ha amount. The fertilizer contains 6.0 percent ammonium nitrogen, 12 percent phosphorus pentoxide (P_2O_5) and 24 percent potassium (K_2O).

N-Goo 40 (40% slow-acting nitrogen) was used for later fertilization. We used the amount of 150 kg/ha of fertilizer. The same amounts of fertilizers were used in all three different tillage methods.

3. Results

The highest yield was measured with conservation tillage, namely 3,875 kilograms of soybeans per hectare. Conservation cultivation is followed by ploughing, during which we achieved 3,550 kilograms of soybeans per hectare. With direct sowing, we achieved the lowest yield, namely 2,825 kilograms of soybeans per hectare.

3.1 The results of ecological footprint of conventional tillage in soybean production

The largest ecological footprint was left by the use of fossil carbon (44.00%). A larger ecological footprint was also detected in air emissions (29.20%), followed by ecological footprint in water (22.30%). The smallest ecological footprint is represented by emissions to soil (3.80%), non-renewable sources (0.60%), surface (0.20%) and renewable sources (0.00%).

From Figure 4, we can see the factors that influenced the ecological footprint of soybean cultivation when ploughed.

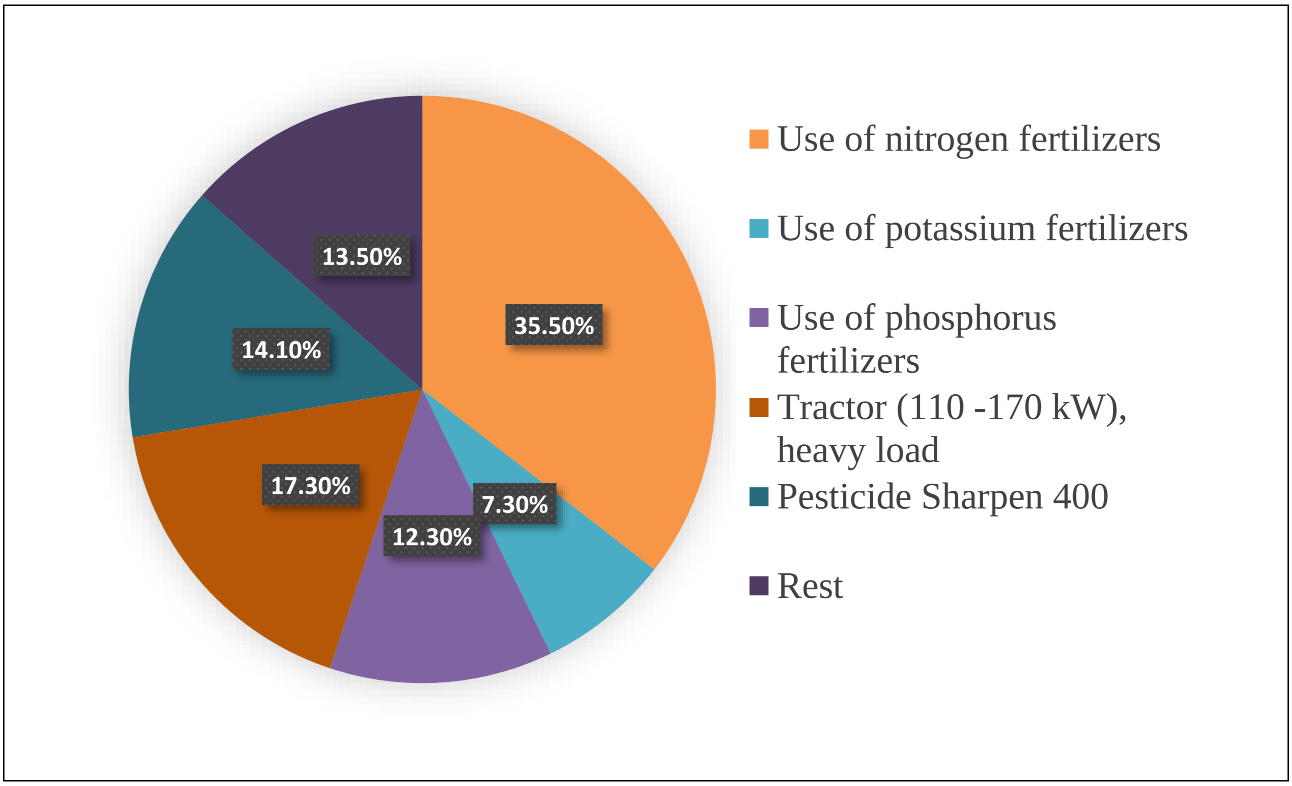

Fig. 4. The most important factors that have the greatest influence on the ecological footprint of conventional tillage.

We found that the largest ecological footprint was left by the production and use of nitrogen fertilizers (35.50%). Nitrogen fertilizers were followed by tractor use with 17.30% emissions. The herbicide Sharpen 400 SC was also used in the experiment, which affects the ecological footprint by 14.10%. 12.30% of the impact on the ecological footprint is represented by the use of phosphate fertilizers, and 7.30% by the use of potassium fertilizers. The word rest includes all other factors that we used in the ploughing experiment.

The largest ecological footprint was in the use of nitrogen fertilizers, amounting to 10.03 gha. This was followed by the use of mechanization with 4.85 gha. A larger ecological footprint is also detected with the use of the herbicide Sharpen 400 SC (3.90 gha) and with the use of phosphorus fertilizers (3.40 gha). We found that Sharpen 400 SC herbicide with active substance (pendimethalin) caused a larger ecological footprint in all three tillage methods compared to Harmony 50 SX herbicide and Pulsar 40 SL herbicide.

A larger ecological footprint was also detected with the herbicide Sharpen 400 SC, as the biggest problem is the ecological footprint in water. The Administration of the Republic of Slovenia for Safe Food, Veterinary Medicine and Plant Protection states that the biggest problem with pesticides is seepage into the soil and runoff from treated surfaces, whereby the agents can reach underground and surface water.

3.2 The results of ecological footprint of conservation tillage in soybean production

The production and use of fossil carbon (40.40%) left the largest ecological footprint in conservation tillage. There was a small difference between the air and water categories, with air emissions from conservation tillage accounting for 29.20% of the contribution to the ecological footprint, and water emissions for 25.00%. Emissions to soil (4.50%), non-renewable resources (0.70%) and surface (0.20%) make a smaller contribution. The proportion of renewable sources was not detected (0.00%).

Using the SPIonWeb program, we obtained data (Figure 5) on the most common factors that affect the ecological footprint of soil conservation tillage. The results showed that the production and use of nitrogen fertilizers had the largest ecological footprint (10.03 gha), followed by the ecological footprint of the production and use of Sharpen herbicide, which was 6.30 gha. This was followed by the production and use of phosphorus fertilizers, with 3.50 gha, and the production and use of potash fertilizers, with a value of 2.06 gha. The tractor (110-170 kW) - normal load - contributed to the ecological footprint of 1.15 gha, the combine with 1.06 gha, the other factors brought a smaller impact to the ecological footprint.

Research (Vindiš et al., 2016) also reached similar conclusions. The results showed that the production and use of nitrogen fertilizers had the largest ecological footprint, followed by the use of pesticides.

We believe that in the future we will have to pay more attention to the use of fertilizers and phytopharmaceuticals. In her research, Kosič (2014) concluded that the use of pesticides and fertilizers left a large ecological footprint. In this case, the use of Unika fertilizer left the biggest ecological footprint.

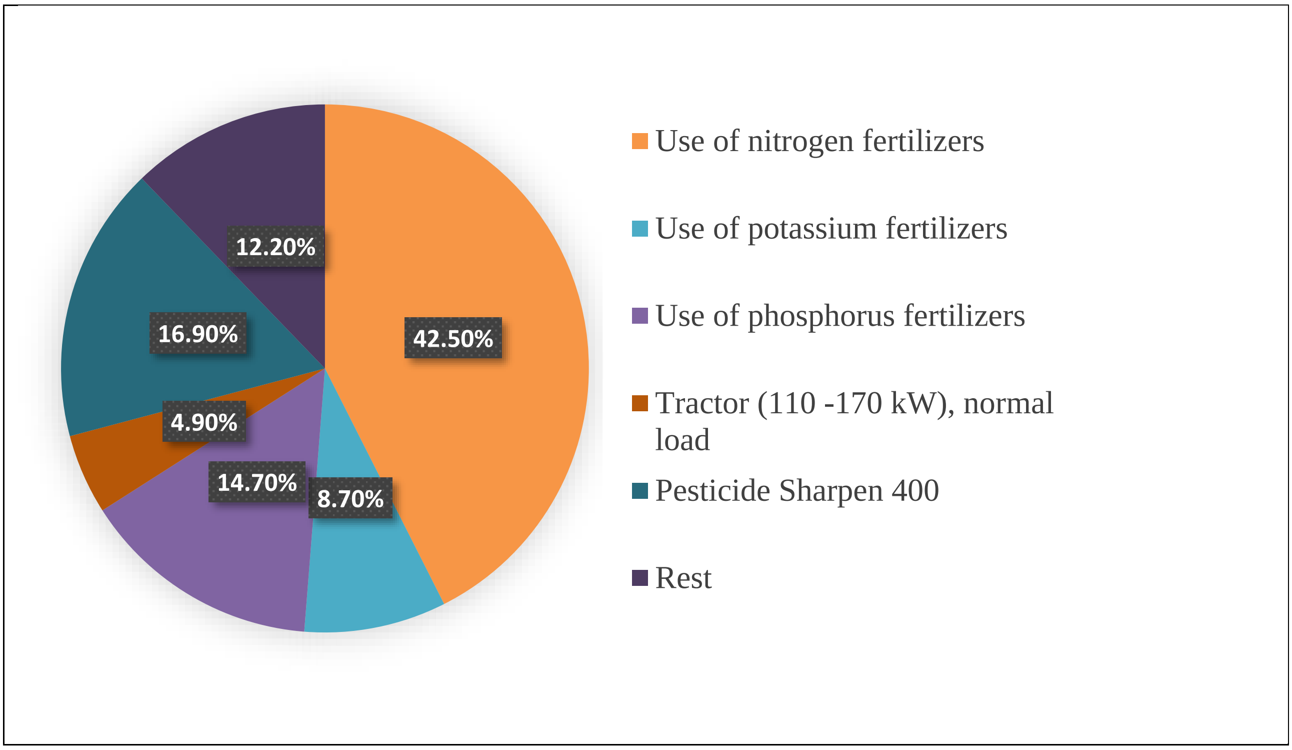

Fig. 5. The most important factors that have the greatest influence on the ecological footprint of conservation tillage.

3.3 The results of ecological footprint of direct sowing in soybean production

The results obtained using the SPIonWeb program in the direct sowing experiment also showed that the use of fossil carbon (40.00%) left the largest ecological footprint. In ploughing and conservation tillage, a larger ecological footprint of air (29.20%) and water (25.30%) was detected. A smaller share represents the ecological footprint of soil (4.60%), non-renewable resources (0.70%) and surface area (0.20%). The share of the ecological footprint of renewable resources was not detected even with direct sowing (0.00%), which means that they were not included in our process.

Figure 6 shows the share of the most important factors in direct sowing. We found that the largest ecological footprint is in the production and use of nitrogen fertilizers (43.20%), followed by the impact of the production and use of Sharpen 400 herbicide (17.20%). Sharpen herbicide is followed by the production and use of phosphorus fertilizers (15.00%) and the production and use of potassium fertilizers (8.90%). The ecological footprint of mechanization is the smallest in the case of direct sowing and is 4.60%. Other factors amount to 11.20%.

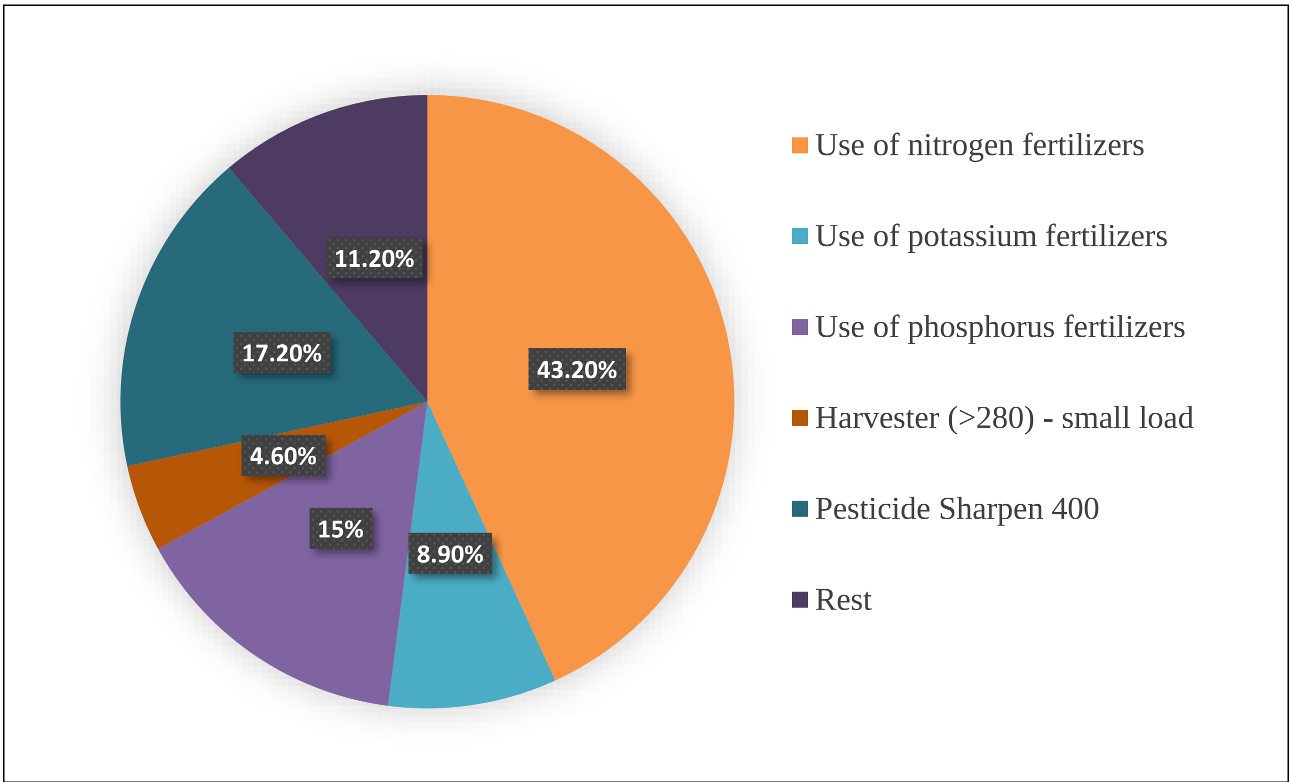

Fig. 6. The most important factors that have the greatest influence on the ecological footprint of direct sowing.

As in the case of conventional and conservation tillage, also in the case of direct sowing, we can see that the production and use of nitrogen fertilizers had the largest ecological footprint in the amount of 10.03 gha. This was followed by the production and use of Sharpen 400 SC herbicide in the amount of 3.90 gha and the production and use of phosphorus fertilizers for gha. The production and use of potash fertilizers (2.06 gha) also contributed to the ecological footprint. The share of the production and use of machinery in the ecological footprint was 1.06 gha, of which the share of heavy machinery (110-170 kW) and light-duty machinery was only 0.32 gha.

Even in the case of direct sowing, we noticed that the production and use of nitrogen fertilizers and the use of the herbicide Sharpen 400 SC brought the largest share to the ecological footprint. In all three tillage methods, it can be seen that the production and use of mechanization also influenced the ecological footprint. Nowadays, in most cases, tractors with internal combustion are used to drive machinery, which use a mixture of very different hydrocarbons for propulsion. As a result, fuels have very different physical and thermochemical properties. The course of the combustion process, the transfer and conversion of energy in the engine and the impact of the process on the environment depend on the preparation of fuels and their mixtures with the oxidant, which is usually oxygen in the air. In addition to the environmental benefits, lower fuel consumption can also have a significant impact on the economic success of an individual farm. There are many ways to save fuel when working with tractors and other agricultural machinery (Vindiš, 2014).

3.4 Comparison of environmental impacts between individual tillage methods

In table 5, we compared individual soil tillage's in terms of carbon dioxide (CO_2) emissions, environmental burden with potential global warming (GWP in kg) and SPI ecological footprint (m^2). The most CO_2 was in ploughing (912.04 kg CO_2) and the least in direct sowing (699.27 kg CO_2). We conclude that more CO_2 in ploughing is due to the production and use of heavy machinery. The highest GWP (1566.74 kg CO_2 equivalent) can also be detected during ploughing. The largest SPI environmental footprint (m^2) was cultivated with a plough (282779.58 m^2/ha), followed by conservation soil tillage (236100.48 m^2/ha), the smallest footprint was detected in direct sowing (232251.06 m^2/ha).

3.5 Impact of ecological footprint per unit yield

In the research, we were also interested in the value of the ecological footprint per kilogram of soybeans (seeds) for all three tillage methods (Table 5). We calculated carbon dioxide emissions, potential global warming burden and ecological footprint. The results were obtained by dividing the effects of individual soil tillage methods by the soybean yield achieved with each soil tillage method. The results showed that 0.26 kg of CO_2 was released into the air for a kilogram of soybeans when ploughing the soil, during conservation tillage 0.18 kg of CO_2 and when direct sowing 0.24 kg of CO_2. The GWP per unit of soy in conventional tillage is 0.44 kg CO_2 eq., in conservation processing 0.31 kg CO_2 eq. and with direct sowing 0.41 kg CO_2 eq.

Process	**Conventional tillage**	**Conservation tillage**	**Direct sowing**
Crop unit	Kg	Kg	Kg
Quantity	1	1	1
CO_2 emissions (kg)	0,26	0,18	0,24
Global warming potential GWP (kg CO_2 ecv.)	0,44	0,31	0,41
Ecological footprint SPI (m^2)	79,66	60,93	82,21

Tab. 5. Values of environmental impacts calculated per unit of yield.

4. Conclusion

The study addressed the problem of understanding the ecological footprint of soybean production, focusing on its environmental impacts such as land use, water consumption, and greenhouse gas emissions. By analysing various soil tillage techniques, the study identified key factors contributing to the ecological footprint and proposed sustainable practices to mitigate these impacts.

The results showed that adopting sustainable soil tillage techniques could significantly reduce the ecological footprint while maintaining or improving yield and profitability. The study successfully provided strategies to minimize environmental impacts, using suitable soil technique method, in our case conservation tillage in soybean production.

The results showed that the highest yield was achieved with conservation tillage (3875 kg of soybeans per ha). We conclude that conservation tillage is the optimal method of tillage in terms of the value of the ecological footprint (236100.48 m^2) and the amount of yield calculated per one hectare. The smallest ecological footprint was caused by direct sowing (232251.06 m^2), but at the same time we also produced the smallest yield of soybeans (2825 kg of soybeans per ha), while the largest ecological footprint was caused by ploughing the soil (282779.58 m^2). In our case, conservation tillage is a way to reduce the burden on the environment, but still produce enough and thus indirectly earn money. Future plans include further research on optimizing these practices and exploring their applicability to other crops.

Due to the increase in the food needs of the population and weather factors, we will have to introduce new crops and less intensive cultivation techniques into agriculture. Unfortunately, the introduction of these has already had negative consequences in the past, which are manifested by a lower content of organic substances in the soil and pollution of the soil, air and water sources due to the excessive use of fertilizers and phytopharmaceuticals. Above all, the excessive use of fertilizers already manifests itself in the increase of nitrogen and phosphorus amounts in the environment.

Building on the findings of this study, future research will focus on optimizing the sustainable soil tillage techniques, identified to further reduce the ecological footprint of soybean production. This will involve conducting field trials to test the effectiveness of these practices in different environmental conditions and regions. Additionally, the research will explore the integration of advanced technologies, such as precision agriculture and biotechnology, to enhance sustainability and productivity. The next step will be to expand the scope of the study to include a comparative analysis of the ecological footprints of other major crops. This will help in understanding the broader implications of sustainable agricultural practices across various types of crops. Furthermore, collaboration with policymakers and industry stakeholders will be pursued to develop guidelines and policies that support the adoption of sustainable practices in agriculture.

Ultimately, the goal is to create a comprehensive framework for sustainable crop production that can be applied globally, contributing to food security and environmental conservation.

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