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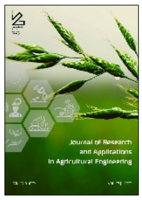

# Carbon footprint generated during plant production – literature review and own research

Michał Szaroleta[a] *
Florian Adamczyk[a]
Łukasz Mandat[a]
Roman Rogacki[a]
Tomasz Szulc[a]

[a] Division of Agricultural and Forest Machines Development, Łukasiewicz Research Network - Poznań Institute of Technology, Poznań, Poland.

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The publication is addressed to individuals and entities that deal with trade and implementation of new agricultural machinery. The paper presents identified sources causing greenhouse gas emissions into the atmosphere in the plant production process. The work was divided into several parts: the topic of gases causing the greenhouse effect was generally presented, then the gases that were most responsible for the said effect were identified. A method for determining the carbon footprint of agrotechnical treatments was also proposed, based on the results of research carried out using a machine aggregated with a tractor through a measurement frame specially designed and built for this purpose. The aforementioned work was carried out to identify and illustrate many agrotechnical treatments against a common background. The preliminary studies conducted in field conditions allow us to assess the sense of conducting this type of research based on simple to measure parameters. The aspect that remains to be solved is the development of an algorithm that, after taking into account parameters such as the value of working resistance or the type of machine, will determine the carbon footprint.

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## 1. Introduction

Stones are the mineral, One of the current challenges for agriculture is the reduction of greenhouse gases in order to mitigate climate change and adverse effects on the environment. Agriculture is the second source of greenhouse gas emissions after the energy sector, and the climate changes caused by them, manifested primarily by the increase in average temperatures leading to global warming, also cause unfavourable phenomena for agriculture itself. Extreme weather phenomena (heavy rains, droughts, hailstorms), limited water availability, intensification of fungal diseases and crop pests significantly worsen the conditions for the functioning of farms. The assessment of greenhouse gas emissions in crop production can be carried out using the carbon footprint, which means gaseous emissions of compounds causing climate warming. Hence, it was decided to review the literature in terms of the carbon footprint in crop production. In Poland, this is a significant share in greenhouse gas emissions. The carbon footprint of crop production is the sum of emissions generated at all stages, from cultivation to harvest. These are emissions generated directly during field work and transport (direct emissions) and emissions generated at the stage of production of production means (diesel oil, fertilizers, plant protection products, technical

* Corresponding author: michal.szaroleta@pit.lukasiewicz.gov.pl

equipment) used in crop production (indirect emissions). The carbon footprint is expressed in carbon dioxide equivalent (CO2 eq.), which is calculated as the product of the mass of a given greenhouse gas and the corresponding dimensionless global warming potential (GWP) over a specified time horizon, usually 100 years [10, 12, 29, 30, 31, 40, 42].

## 2. Objective of the work

The aim of the work was to determine the amount of CO2 emissions in plant production, based on data available in the literature. This estimate is to take into account both direct CO2 emissions and CO2 equivalent, which is a derivative of nitrous oxide and methane emissions. Another aim of the work was to measure soil resistance in conditions similar to real ones. A specially prepared measuring frame was used for this purpose, which allows measuring load values in several planes.

## 3. Identification of greenhouse gases and sources of their emissions in agriculture

Carbon footprint is a concept used in assessing greenhouse gas emissions and in public discussion of the actions needed to reduce the risks associated with climate change. In general terms, it means gaseous emissions of compounds that contribute to the greenhouse effect throughout the entire production and consumption cycle of products. The carbon footprint is expressed as the sum of the products of the greenhouse effect for a substance and the emission volume of the "i-th" substance. It covers both direct and indirect emissions that arise throughout the product's life cycle. It is presented in the form of indicators:

a) as total greenhouse gas emissions in kg of CO2 equivalent per unit area per year,

b) as greenhouse gas emissions in kg of CO2 equivalent per kg of product [17].

Greenhouse gas emissions in agriculture basically relate to three types: carbon dioxide, methane and nitrous oxide. In order to simplify the analysis of greenhouse gas emissions into the atmosphere, a conversion factor is used, thanks to which we can express the entire emission value as a carbon dioxide equivalent. And so: 1 kg of metal after conversion corresponds to 29,8 kg of carbon dioxide, while the emission of 1 kg of nitrous oxide corresponds to as much as 273 kg of carbon dioxide [18, 30, 31].

In 2020, the total greenhouse gas emissions in Poland were as follows: carbon dioxide 80,7%, methane 11,8%, nitrous oxide 6,1%, fluorinated industrial gases 1,4%. In total, 376.04 million tons of carbon dioxide equivalent were emitted in Poland, which was 35,1% less than in the 1988. The energy sector accounted for 81,2%, agricultural 9,1%, industrial processes 6,7%, waste management 3,0%. In agriculture, the highest greenhouse gas emissions occur from chemical processes in the soil (45,9%) and animal breeding (37,6%) [16].

According to another publication, the average value of the carbon footprint of winter rapeseed was 794,3 kg of CO2 equivalent per 1 tonne of seeds and 2441,7 kg of CO2 per 1 ha. Carbon footprint calculations for winter rapeseed in Germany in 2013 showed similar data, i.e. 740 kg of CO2 equivalent per 1t, in Finland 1480 kg of CO2 equivalent per 1t, in Canada 734 kg of CO2 equivalent per 1t. The average GHG emission rate in Poland in fertilizer production per 1t is 3,4 t CO2 equivalent (from 2,0 t CO2 equivalent for ammonium sulphate to 5,3 t CO2 equivalent for Saletrosan) [14, 17].

The use of conservation tillage reduces fuel consumption and lowers the energy input into production. This indicator is also used in LCA (Life Cycle Assessment) analyses. Comparison of energy inputs on greenhouse gas emissions in various cultivation systems showed that simplified cultivation leads to a 26% reduction in total production costs, and zero cultivation leads to a 41% decrease. The energy consumed by agricultural machinery accounts for 6-8% of total greenhouse gas emissions per kg of product. Greenhouse gas emissions in the traditional system amounted to 915g CO2e kg of the finished product; and 855g CO2e kg in a zero-till system. Another study shows that the expenditure related to field treatments in the case of simplified cultivation is reduced by 18-53%. Direct sowing reduces the energy input by 75-83% compared to traditional cultivation. The total cost of cultivation of 1 ha is reduced by 25-41%. [22, 38, 39, 41, 43].

## 3. Carbon dioxide emissions into the atmosphere during treatments related to plant production

Depending Plant production requires a number of procedures performed using machines aggregated with tractors or self-propelled harvesters powered by diesel oil, which emits carbon dioxide into the atmosphere when burned. These treatments cover the entire plant production process, from tillage to harvesting, in addition to post-harvest processing of crops. Its individual stages are:

- agriculture,
- sowing and planting,
- fertilization,

- plant protection,
- harvesting the crop.

At each stage of plant production, a number of procedures can be distinguished, which differ in the method of execution and energy consumption, which determines the fuel consumption of an agricultural tractor working with the machine or a self-propelled combine, and carbon dioxide emissions. Fuel consumption occurs not only during effective work, but also during turns in the field and breaks in work. The size and shape of the fields, the distance of the fields from the farm and the topography of the terrain, as well as the condition of the access roads have a significant impact on fuel inputs during auxiliary works. Fuel consumption for transportation increases when fields are small and farther from the farm, the terrain is hilly and the roads are rough. Sample studies show that fuel inputs for transport, depending on terrain conditions and the production profile of the farm, range from 17,6 to 45,2 l/ha [1, 3].

Tillage includes procedures related to post-harvest soil cultivation, basic tillage and pre-sowing tillage, each of which can be performed with various tools or machines, and post-harvest tillage may be preceded by grinding the post-harvest residues of the pre-crop plant, e.g. stubble that is difficult to cultivate. after harvesting corn. Another procedure related to preparing the soil for sowing or planting a subsequent crop is the sowing of catch crops intended for plowing or mulching, and it can be done with a catch crop seeder mounted on a tillage machine, which does not result in a significant increase in energy consumption. The power demand of tillage machines, and thus the fuel consumption of the cooperating tractor and carbon dioxide emissions, vary greatly. They depend primarily on soil conditions, especially soil compactness, cultivation depth and soil treatment method. Examples of studies show, for example, that during deep plowing (30 cm) on clay soil, fuel consumption was 22 l/ha, and replacing it with a cultivator loosening the soil without turning to the same depth reduced fuel consumption by 3,3 l/ha. Even greater savings (9,7 and 8,5 l/ha) were achieved by replacing deep plowing with cultivating or strip cultivation at a depth of 15 cm [5]. The lowest power demand is generated by tools that affect the soil shallowly or on the surface, performing one simple agrotechnical activity, e.g. tine harrows or tillage rollers used individually. Tillage units consisting of several working tools require greater fuel inputs during operation, especially units combining deep soil loosening and intensive soil dressing [11, 13, 15, 46, 47].

Sowing of crop seeds can be carried out with various types of seed drills, e.g. grain or precision seed drills, and planting with planters, e.g. for potatoes or vegetable seedlings. The power requirement of a seeder or planter depends primarily on the type of sowing or planting coulters and the spacing of plant rows, and thus the number of coulters necessary for a specific working width. Under comparable conditions, a classic grain seeder has similar energy consumption to a precision seeder, which has fewer sowing sections, but they are more extensive. Point sowing or planting is less energy-intensive the greater the spacing of the rows of plants sown/planted. Previous soil preparation also has a significant impact on fuel consumption during sowing or planting, e.g. classic sowing in loosened and seasoned soil consumes less fuel than direct sowing into uncultivated soil when the sowing coulters work in compact soil. Direct sowing into uncultivated soil requires greater fuel inputs than classic sowing into cultivated soil, but eliminating tillage provides significant energy savings. Sample studies show, for example, that fuel consumption during tillage and sowing of wheat using various technologies amounted to 46.6 l/ha in the case of traditional cultivation with plowing, 27,8 l/ha in the case of simplified cultivation without plowing and only 7,9 l/ha ha in the case of direct sowing [1, 6, 32, 33, 34].

The fertilization process includes the application of both organic and mineral fertilizers. It is usually carried out in several treatments, before sowing and after sowing, and sometimes simultaneously with sowing or tillage, or tillage and sowing. The power demand of the fertilizer application machine, and thus the fuel consumption of the cooperating tractor, depends primarily on the type and dose of the fertilizer applied, the method of application and the type and working width of the application machine. Fertilization also generates high fuel consumption due to equipment securing the transport and loading of fertilizer into the tank of the applying machine, as well as transport trips of the applying machine filled with fertilizer. The amounts of fertilizers used are large, the doses per 10-hectare field are approximately 8 tons of mineral fertilizers, approximately 300 tons of manure and approximately 400 m3 of slurry. Fuel expenditure on transport journeys is particularly high when spreading manure or spreading slurry, when the manure pile or slurry tank is located at a large distance from the field.

Plant protection includes comprehensive chemical protection and mechanical care to combat weeds. Chemical protection in the form of spraying with a plant protection agent is a procedure that does not require large amounts of fuel, because sprayers usually have a large working width and therefore efficiency, and their power requirement results from the rolling resistance and the drive of the pump pumping the useful liquid. The larger the capacity of the sprayer tank, the fewer additional technological trips needed to refill the spray liquid. With a frequently used dose of 250 l/ha of usable liquid, 2500 liters of usable liquid, i.e. 5500-liter sprayers, are required to spray a 10-hectare field. An alternative to chemical protection of plants with herbicides is mechanical destruction of weeds, which requires greater fuel inputs, because the working elements of tools/machines used in mechanical care have a shallow impact on the resistant soil. Such tools/machines include not only inter-row weeders, but also weed harrows that destroy weeds on the entire field surface and ridgers that, in addition to destroying weeds, form ridges in the cultivation of potatoes or root vegetables.

Harvesting, depending on the crop and its purpose, is carried out with various machines, in one or more procedures. An example of harvesting in one work pass is harvesting potatoes or sugar beets with a combine harvester performing several operations simultaneously, which usually consumes less fuel than machines performing several operations separately. In the case of grain harvesting, in addition to grain threshing, straw harvesting is also required, which also generale fuel consumption. Straw can also be left in the field as organic fertilizer, but then it requires good shredding. Depending on the purpose, corn can be harvested in one stage with a combine harvester threshing the grain or with a more energy-intensive forage harvester that cuts and grinds entire plants intended for ensiling. The largest number of treatments in separate passes requires multi-stage harvesting of green fodder intended for silage. In addition to the size of the crop and the distance and condition of the roads, the amount of fuel spent on transporting the harvested crop is significantly influenced by the equipment used (e.g. trailer capacity) and the organization of transport. For example, when harvesting a very large crop of maize for silage (up to 150 t/ha), transport and downtime may generate fuel consumption comparable to or greater than harvesting with a forage harvester [4], and poor transport organization may result in an increase in fuel consumption by up to 30% [2, 35] The weight of the crop required to be collected and transported varies greatly in the case of different crops; for a 10-hectare field with average yields in Poland, it is e.g. approx. 50 tons of grain and 50 tons of cereal straw or as many as 300 tons of potatoes.

## 4. Estimating fuel consumption and carbon dioxide emissions

Accurate determination of diesel oil consumption and carbon dioxide emissions in the entire process of growing and harvesting a specific crop is only possible on a farm using a specific technology in specific soil and terrain conditions. However, it is possible to estimate fuel inputs and carbon dioxide emissions for specific treatments related to individual stages of the plant production process, on the basis of which inputs and emissions can be forecast for the technology covering selected treatments. Table 1 lists the consumption of diesel oil during a treatment performed with a specific machine, estimated on the basis of available research results and literature data [6], information from farmers or estimated based on the power demand and efficiency of the machine, as well as the carbon dioxide emissions resulting from the combustion of diesel oil. . Diesel fuel consumption resulting from the power demand was calculated using the formula:

$$Z_{ON} = g_u \cdot N/W \quad [l/ha]$$

where:
gu [l/kWh] – specific consumption of diesel oil by the engine of a tractor or self-propelled machine
N [kW] – machine power demand
W [ha/h] – machine efficiency

The specific fuel consumption was assumed to be 220 g/kWh, i.e. 0,26 l/kWh, and the effective efficiency of the machine, in the absence of data, was calculated based on the speed and working width. In the case of active machines, the total power requirement for propulsion and traction was taken into account. Diesel consumption was expressed in liters per hectare (l/ha) and carbon dioxide (CO2) emissions in kilograms per hectare (kg/ha) for all crop production treatments. Sometimes used units of diesel consumption are kilogram per hectare (kg/ha), kilogram per working hour (kg/h) or liter per working hour (l/h). When converting these units into the unit used in the study (l/ha), it was assumed that the specific gravity of diesel oil is 0,84 kg/l, and the tractor or self-propelled combine harvester performs effective work in a specific area per hour. Each liter of burned diesel fuel causes direct emissions of 2,67 kg of CO2 into the atmosphere [8], so the fuel consumption estimated for each treatment was multiplied by the emission factor of 2,67. However, diesel fuel also causes indirect emissions related to the extraction, production and distribution of the fuel, which amount to 0,64 kg of CO2 for each liter [7, 9, 36, 37], which is much less than direct emissions. Table 1 shows indirect emissions for individual treatments, assuming emission factors of 0,64. The direct CO2 emission rate, including the production and consumption of diesel oil, is 3,31 kg CO2/l.

Table 1. Diesel consumption and carbon dioxide emissions during treatments related to plant production

| The procedure is used in plant production | Fuel consumption [1/ha] | Direct emission $CO_2$ [kg/ha] | Indirect emission $CO_2$ [kg/ha] |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| Farming | | | |
| Post-harvest cultivation with a stubble cultivator to a depth of up to 15 cm | 10 - 16 | 26,7 – 42,7 | 6,4 – 10,2 |
| Post-harvest cultivation with a disc harrow to a depth of up to 10 cm | 7 - 13 | 18,7 – 34,7 | 4,5 – 8,3 |
| Post-harvest cultivation with a rotary conditioner | 4 - 6 | 10,7 - 16 | 2,6 – 3,8 |
| Post-harvest cultivation with a mulch harrow | 1,5 – 2,5 | 4 – 6,7 | 1 – 1,6 |
| Shredding crop residues with a flail mulcher | 4 - 6 | 10,7 - 16 | 2,6 – 3,8 |
| Shredding crop residues with a rotary mulcher | 3 - 4,5 | 8 - 12 | 1,9 – 2,9 |
| Seeding plowing to a depth of up to 20 cm | 10 - 17 | 26,7 – 45,4 | 6,4 – 10,9 |
| Plowing 20-30 cm deep | 15 - 28 | 40,1 – 74,8 | 9,6 – 17,9 |
| Seasoning the soil while plowing with a tool combined with a plow | 2,5 - 5 | 6,7 – 13,4 | 1,6 – 3,2 |
| Deep no-plough cultivation with a cultivator-based unit to a depth of 15 - 30 cm | 12 - 20 | 32 – 53,4 | 7,7 – 12,8 |
| Deep cultivation without plowing with a chisel plow to a depth of up to 50 cm | 18 - 35 | 48,1 – 93,5 | 11,5 – 22,4 |
| Subsoiling to a depth of up to 50 cm | 15 - 32 | 40,1 – 85,4 | 9,6 – 20,5 |
| Strip cultivation to a depth of 15 - 30 cm | 10 - 20 | 26,7 – 53,4 | 6,4 – 12,8 |
| Shallow cultivation without plowing with a cultivator | 9 - 15 | 24 – 40,1 | 5,8 – 9,6 |
| Shallow cultivation without plowing with a cultivator | 6 - 12 | 16 - 32 | 3,8 – 7,7 |
| Tillage with a tiller | 10 - 16 | 26,7 – 42,7 | 6,4 – 10,2 |
| Cultivation with a power harrow | 8 - 13 | 21,4 – 34,7 | 5,1 – 8,3 |
| Drag dragging | 1,5 – 3 | 4 - 8 | 1 – 1,9 |
| Harrowing with a tine harrow | 2 – 4 | 5,3 – 10,7 | 1,3 – 2,6 |
| Rolling with a tillage roller | 2,5 – 4 | 6,8 – 10,7 | 1,6 – 2,6 |
| Pre-sowing cultivation with an aggregate based on a cultivator with spring tines | 4 - 7 | 10,7 – 18,7 | 2,6 – 4,5 |
| Stone collection with a scraping and collecting machine | 12 - 18 | 32 – 48,1 | 7,7 – 11,5 |
| Sowing and planting | | | |
| Sowing with a grain seeder into soil treated before sowing | 2 – 3,5 | 5,3 – 9,3 | 1,3 – 2,24 |
| Sowing with a grain seeder into uncultivated soil (direct sowing) | 3 - 7 | 8 – 18,7 | 1,9 – 4,5 |
| Sowing with a precision seeder into soil treated before sowing | 2 – 3,5 | 5,3 – 9,3 | 1,3 – 2,24 |
| Sowing with a precision seeder and applying starter fertilizer | 3 - 6 | 8 - 16 | 1,9 – 3,8 |
| Pre-sowing cultivation and sowing of grain with a passive cultivation and sowing unit | 6 - 10 | 16 – 26,7 | 3,8 – 6,4 |
| Pre-sowing cultivation and sowing of grain with an active cultivation and sowing unit | 11 - 18 | 29,4 – 48,1 | 7 – 11,5 |
| Pre-sowing cultivation and sowing of grain with an active cultivation and sowing unit | 10 - 24 | 26,7 – 64,1 | 6,4 – 15,4 |
| 1 | 2 | 3 | 4 |
| Planting potatoes with an automatic planter | 8 - 12 | 21,4 - 32 | 5,1 – 7,7 |
| Fertilization | | | |
| Spreading mineral fertilizer with a 2-disc spreader | 2 – 3,5 | 5,3 – 9,3 | 1,3 – 2,2 |

| | | | |
|---|---|---|---|
| Spreading slurry with a slurry tanker | 2 – 3,5 | 5,3 – 9,3 | 1,3 – 2,2 |
| Soil application of slurry using a slurry tanker with a disc applicator | 8 - 16 | 21,4 – 42,7 | 5,1 – 10,2 |
| Spreading manure with a spreader | 6 - 12 | 16 - 32 | 3,8 – 7,7 |
| Plant protection | | | |
| Spraying with a tractor sprayer | 1 - 2 | 2,7 – 5,3 | 0,6 – 1,3 |
| Spraying with a self-propelled sprayer | 0,5 – 1 | 1,3 – 2,7 | 0,3 – 0,6 |
| Mechanical care with a passive weeder | 2 – 3,5 | 5,3 – 9,3 | 1,3 – 2,2 |
| Mechanical care with an inter-row tiller | 3 - 5 | 8 – 13,4 | 1,9 – 3,2 |
| Chemical spraying and mechanical care | 3 - 4 | 8 – 10,7 | 1,9 – 2,6 |
| Harrowing with a weeder | 1,5 - 3 | 4 - 8 | 1 – 1,9 |
| Covering potatoes with a hiller | 4 - 5 | 10,7 – 13,4 | 2,6 – 3,2 |
| Forming ridges with a passive machine | 5 - 6 | 13,4 - 16 | 3,2 – 3,8 |
| Forming ridges with an active machine | 9 - 15 | 24 – 40,1 | 5,8 – 9,6 |
| Harvest | | | |
| Harvesting grain with a combine harvester | 10 - 18 | 26,7 – 48,1 | 6,4 – 11,5 |
| Baling straw or dried green fodder | 3,5 - 7 | 9,3 – 18,7 | 2,2 – 4,5 |
| Wrapping bales of dried forage | 2 – 3,5 | 5,3 – 9,3 | 1,3 – 2,2 |
| Corn harvesting with a tractor or self-propelled forage harvester | 25 – 35 | 66,8 – 93,5 | 16 – 22,4 |
| Harvesting green fodder with a self-propelled forage harvester with a pick-up | 6 - 10 | 16 – 26,7 | 3,8 – 6,4 |
| Mowing green fodder with a finger mower | 3,5 -6,5 | 9,3 – 17,4 | 2,2 – 4,2 |
| Mowing green fodder with a rotary mower | 5 - 9 | 13,4 - 24 | 3,2 – 5,5 |
| Tedding green fodder with a tedder | 1,5 - 2,5 | 4 – 6,8 | 1 – 1,6 |
| Raking dried green fodder | 2 - 3 | 5,3 - 8 | 1,3 – 1,9 |
| Collecting green fodder with a harvesting trailer | 8 - 13 | 21,4 – 34,7 | 5,1 – 8,3 |
| 1 | 2 | 3 | 4 |
| Destroying haulm with a shredder | 3,5 – 5 | 9,3 – 13,4 | 2,2 – 3,2 |
| Digging potatoes with a digger | 15 - 25 | 40,1 – 66,8 | 9,6 - 16 |
| Harvesting potatoes with a single-row tractor combine | 30 - 50 | 80,1 – 133,5 | 19,2 – 32 |
| Harvesting potatoes with a 2-row tractor combine | 20 - 40 | 53,4 – 106,8 | 12,8 – 25,6 |
| Topping beets with a 3-row topper | 15 - 22 | 40,1 – 58,7 | 9,6 – 14,1 |
| Harvesting topped beets with a 3-row tractor combine | 25 -38 | 66,8 – 101,5 | 16 – 24,3 |
| Beet harvesting with a 6-row self-propelled combine | 40 - 55 | 106,8 – 146,9 | 25,6 – 35,2 |

In the plant production process, the procedures that require the largest amounts of fuel and thus emit the largest amounts of CO2 are deep soil cultivation and harvesting. In the case of classic deep plowing (up to 30 cm), commonly considered a very energy-intensive procedure, diesel consumption reaches 30 l/ha, but in the case of no-plow cultivation to a depth of 50 cm, it even exceeds 30 l/ha, and the maximum is 35 l/ha. ha, causing a total direct and indirect emission of carbon dioxide of 115,9 kg/ha. However, in the case of beet harvesting, which requires topping, digging and cleaning, diesel fuel consumption on heavy soil may exceed 50 l/ha and amount to a maximum of 55 l/ha, causing a total carbon dioxide emission of 182,1 kg/ha.

Tables 2, 3 and 4 list examples of estimated minimum and maximum diesel oil consumption for selected technologies consisting of a number of treatments related to the cultivation of winter cereals, potatoes and corn for green fodder, as well as the total fuel consumption for the entire cultivation process and carbon dioxide emissions. coal: direct – resulting from fuel combustion, indirect – resulting from the extraction, production and distribution of fuel, and total emissions.

Table 2. Diesel consumption when growing winter cereals

| Procedure | Diesel consumption [l/ha] | |
|---|---|---|
| | min | max |
| Shredding crop residues after harvesting corn | 4 | 6 |
| Post-harvest cultivation with a disc harrow to a depth of up to 10 cm | 7 | 13 |
| Sowing plowing combined with preliminary soil dressing | 12,5 | 22 |
| Pre-sowing cultivation with an aggregate based on a cultivator with spring tines | 4 | 7 |
| Sowing with a grain seeder | 2 | 3,5 |
| Pre-sowing and top dressing (4 treatments in total) | 8 (4 × 2) | 14 (4 × 3,5) |
| Chemical spraying (4 treatments in total) | 4 (4 × 1) | 8 (4 × 2) |
| Harvesting grain with a combine harvester | 10 | 18 |
| Grain transport | 3,5 | 7 |
| Baling straw | 3,5 | 7 |
| Loading and transporting straw bales | 4 | 8 |
| Transport trips related to access to the field, transport of seed and fertilizer and downtime | 10 | 20 |
| Total diesel consumption | 72,5 | 133,5 |
| Direct carbon dioxide emissions $CO_2$ [kg/ha] (fuel consumption × 2.67) | 193,6 | 356,4 |
| Indirect carbon dioxide emissions $CO_2$ [kg/ha] (fuel consumption × 0.64) | 46,4 | 85,4 |
| Total carbon dioxide emissions $CO_2$ [kg/ha] (fuel consumption × 3.31) | 240 | 441,8 |

Table 3. Diesel consumption when growing potatoes

| Procedure | Diesel consumption [l/ha] | |
|---|---|---|
| | min | max |
| Shallow post-harvest cultivation with a mulch harrow | 1,5 | 2,5 |
| Spreading manure | 6 | 12 |
| Deep post-harvest cultivation with a cultivator combined with sowing catch crops | 10 | 16 |
| Discing catch crops | 7 | 13 |
| Pre-winter plowing | 15 | 28 |
| Collection of stones | - | 18 |
| Tragging | 1,5 | 3 |
| Pre-sowing cultivation with an aggregate based on a cultivator with spring tines | 4 | 7 |
| Planting | 8 | 12 |
| Forming ridges | 5 | 15 |
| Pre-sowing and top dressing (3 treatments in total) | 6 (3 × 2) | 10,5 (3 × 3,5) |
| Chemical spraying (5 treatments in total) | 5 (5 × 1) | 10 (5 × 2) |
| Destroying haulm with a shredder | 3,5 | 5 |
| Potato harvesting with a 2-row combine harvester | 20 | 40 |
| Potato transport | 10 | 20 |
| Transport trips related to access to the field, transport of seed potatoes, manure and mineral fertilizers and downtime | 20 | 30 |

| | | |
|---|---|---|
| Total diesel consumption | 122,5 | 242 |
| Direct carbon dioxide emissions $CO_2$ [kg/ha] (fuel consumption × 2.67) | 324,6 | 646,1 |
| Indirect carbon dioxide emissions $CO_2$ [kg/ha] (fuel consumption × 0.64) | 78,4 | 154,9 |
| Total carbon dioxide emissions $CO_2$ [kg/ha] (fuel consumption × 3.31) | 403 | 801 |

Table 4. Diesel consumption when growing silage corn

| Procedure | Diesel consumption [l/ha] | |
|---|---|---|
| | min | max |
| Liming the stubble | 2 | 3,5 |
| Fertilizing with slurry using a slurry tanker with a disc applicator | 8 | 16 |
| No-till cultivation with a chisel plow | 18 | 35 |
| Tragging | 1,5 | 3 |
| Pre-sowing cultivation with an aggregate based on a cultivator with spring tines | 4 | 7 |
| Sowing with a precision seeder with simultaneous starter fertilization | 3 | 6 |
| Fertilization with mineral fertilizers before sowing and top dressing (2 treatments in total) | 4 (2 × 2) | 7 (2 × 3,5) |
| Harrowing with a weeder | 1,5 | 3 |
| Destroying weeds with a weeder with a belt sprayer | 3 | 4 |
| Harvesting corn with a forage harvester | 25 | 35 |
| Transport of cut green fodder | 20 | 30 |
| Transport trips related to access to the field, transport of seeds, lime, mineral fertilizers and slurry, and downtime | 15 | 25 |
| Total fuel consumption | 105 | 174,5 |
| Direct carbon dioxide emissions $CO_2$ [kg/ha] (fuel consumption × 2.67) | 280,4 | 465,9 |
| Indirect carbon dioxide emissions $CO_2$ [kg/ha] (fuel consumption × 0.64) | 67,2 | 111,7 |
| Total carbon dioxide emissions $CO_2$ [kg/ha] (fuel consumption × 3.31) | 347,6 | 577,6 |

## 5. Methane emissions into the atmosphere during treatment related to plant production

In 2020, 44,4 million tons of methane in CO2 equivalent were emitted in Poland, of which the agricultural sector accounted for 14,2 million tons of CO2 equivalent (32%), which is mainly responsible for the intensive production of farm animals, in particular ruminants, and their intestinal fermentation. Methane emissions also come from natural swamps, rice fields, biomass burning, landfills, coal mines and natural gas drilling. [16]

Methane has a global warming potential (GWP) that is 28 times greater than CO2, and it persists in the atmosphere for up to 12 years. By far the largest methane production comes from ruminants, which have a multi-chamber stomach. These include cattle, sheep and goats. Methane in the entire chain associated with chewing food is a side effect of digestion.

Excrement, which is the second main source of methane emissions in Polish (but not only) agriculture, also decomposes in anaerobic conditions. The most undesirable action is the storage of animal excrement in liquid form. Storing them in solid form forces greater air penetration, which limits the occurrence of anaerobic conditions. [19, 26, 44]

Methane emission volume for agricultural sources in Poland according to estimates of the Institute of Environmental Protection and the Institute of Cultivation, Fertilization and Soil Science:

- intestinal fermentation 456,22 t (IUNG, 2004), 397,18 t (IOŚ, 2003)
- animal excrements 103,5 t, (IUNG, 2004), 43,72 t (IOŚ, 2003)
- burning of crop residues 0,00 t, (IUNG, 2004), 1,07 t (IOŚ, 2003) [26]

The developed and available research shows that in the context of slurry processing and subsequent management in the field, the lowest methane emission can be obtained when aerated slurry is applied (approximately 0,15 kg/Mg). The highest methane emission was in the cattle slurry facility that had not undergone any technological treatment. In general, the use of additional slurry treatment technology during storage reduces methane emissions. The most effective process for reducing methane emissions is slurry aeration. [21]

Good methane absorption and limiting its release into the atmosphere are possible in well-oxygenated soil. Methane can also be absorbed by soil microorganisms at appropriate soil temperature and moisture. There was no significant impact of cultivation method on emissions, but leaving crop residues increases methane emissions because it increases the amount of available carbon. At the same time, it should be borne in mind that an increase in rainfall, which translates into a high water content in the soil, results in lower absorption capacity of the soil [22, 28].

## 6. Emissions of nitrogen oxide into the atmosphere during treatments related to plant production

Nitrous oxide, or nitrous oxide, lasts in the atmosphere for 150 years. It is characterized by a global warming potential (GWP) that is 298 times greater than $CO_2$ and a long decomposition time - about 114 years. Actions to reduce its emissions into the atmosphere may bring significant results in reducing the greenhouse effect. $N_2O$ emissions in Poland in 2012 amounted to 95,45 Gg, i.e. approximately 29,59 million tons of $CO_2$ equivalent, which constitutes 7.4% of greenhouse gas emissions in Poland. Emissions from agriculture account for approximately 85% of national emissions, with 68% coming from soil. Direct emission of nitrous oxide is related to the transformation of nitrogen in the soil and nitrogen applied to the soil in the form of mineral and natural fertilizers.

In agriculture, the main sources of nitrous oxide emissions are: mineral fertilizers, animal excrements, soil cultivation, cultivation of plants that fix nitrogen and burning straw in fields. [23, 26, 44, 45]

Most often, $N_2O$ emissions are estimated using the Emission Factor (EF). It is assumed to be on average 1% of the amount of nitrogen used. Microbial processes of nitrification and denitrification are most important for the formation of N2O. Nitrification occurs in aerobic conditions and involves the oxidation of ammonia and ammonium salts to nitrites and nitrates with the participation of soil bacteria. When there is no access to oxygen and, additionally, incomplete oxidation of ammonium occurs, $N_2O$ or NO is produced in indirect reactions. Nitrification is a process that positively affects soil fertility because it transforms nitrogen compounds into other, easily available ones. Its total impact on nitrous oxide emissions is not significant. It is assumed that the nitrogen lost due to nitrification in the form of $N_2O$ is less than 1%. Denitrification is a process during which inorganic nitrogen compounds are reduced by anaerobic microorganisms. As a result of this process, $N_2$ is produced, and when this process is not completed, NO and $N_2O$ are released. Denitrification under field conditions increases when the concentration of nitrates in moist soil increases. This happens after applying mineral fertilizers and plowing in crop residues rich in nitrogen. Soil-related factors that have a key impact on nitrous oxide emissions are summarized in Table 5.

Table 5. Soil-related factors with a key impact on N2O emissions [27].

| Parameter | Impact on $N_2O$ emissions |
|---|---|
| soil aeration | low aeration → greater denitrification, |
| | medium aeration → higher emissions |
| soil moisture | increasing humidity → increasing emissions (decreasing at high humidity) |
| | during frequent changes → higher emissions |
| nitrogen availability | greater concentration → greater emission |
| soil texture | sand – clay → increase in emissions with increasing colloidal clay content |
| soil pH | nitrification → an increase in pH reduces emissions |
| | denitrification → increase in pH increases emissions |

| | |
|---|---|
| organic matter | increase in organic carbon content → increase in emissions |
| cultivation | leaving crop residues and roots increases emissions |
| soil temperature | temperature increase → emission increase |
| season | wet summer → higher emissions |
| | spring frost → higher emissions |
| | winter → lower emissions |

Research was also carried out during which the maximum daily emission of nitrous oxide was recorded at the level of 1,2 kg ha-1. The amount of cumulative annual emissions ranged from 1,7 to 27,6 kg ha-1. However, the annual emission expressed by the EF coefficient ranged from 0,4% to 6,5% of the applied N. It was also calculated that 77% of the annual emission was generated within 4 weeks after the fertilizer was applied, at appropriate humidity. Agricultural practices are responsible for:

- changes in soil structure,
- soil aeration,
- soil microbiological activity,
- degree of decomposition of plant residues,
- availability and degree of nitrogen mineralization,
- N2O emissions.

No-tillage and reduced tillage systems have been promoted for many years as methods that reduce erosion and increase carbon sequestration in the soil compared to the conventional system. It is estimated that no-till farming currently covers 5% to 9% of the world's total arable area. The impact of the above-mentioned systems on greenhouse gas emissions, especially nitrous oxide, has been the subject of many studies, but their results are not consistent.

Studies were carried out to determine the impact of fertilizer application on GHG emissions at four soil depths: 50 mm, 100 mm, 150 mm and on the soil surface. Total N2O emissions from no-tillage over the annual period were nearly three times higher than those from conventional tillage for all depths. A several-fold decrease in NO emissions was observed. Application of fertilizer on the soil surface or at a depth of 50 mm causes a significant increase in nitrogen oxide emissions in both cultivation methods. Fertilization at a depth of 100 or 150 mm reduces emissions of the above-mentioned substances. gases. At the same time, the fertilizer dose reduced by 10% did not result in a reduction in yield. A decrease in GHG emissions in the range of 18-31% was achieved by optimizing the fertilization method, which consisted of applying divided doses of fertilizer depending on the plant's needs. [24]

No-tillage and reduced tillage are reported to reduce emissions compared to conventional farming by 34% ten years after introduction, especially in dry climates. Fertilization below a depth of 50 mm significantly reduces N2O emissions, especially in humid climates. Nitrogen oxide emissions in dry climates increase by up to 57% in the first ten years after the introduction of simplified cultivation systems. In turn, it decreases in the longer term, i.e. over 10 years after the introduction of simplified cultivation methods, by approximately 27%. [24, 40]

Methods and techniques that reduce N2O emissions in cultivated areas include reducing and dividing doses and selecting fertilizer doses depending on the plant's needs. You can use fertilizers that contain slow-acting compounds. Deep application of fertilizer also contributes to reducing nitrogen oxide emissions. Simplified cultivation or no-ploughing requires combining it with an enriched crop rotation and simultaneous leaving of crop residues in the field, which will limit the reduction in yield. [24]

In one of the studies, an attempt was made to estimate GHG emissions for a selected technology of growing maize for silage using the LCA (Life Cycle Assesment) method. The total emission amounted to 3,38 t CO2eq·l\haThe amount of emissions in relation to the yield obtained per hectare was 56,35 kg CO2eq·ha−1. The highest emissions were related to operations related to the production and storage of fertilizers - 37.68%, followed by emissions related to cultivation – 30,32%, emissions related to fuel for the production and cultivation of silage corn – 17,69% and emissions from the group of operations related to production of mineral fertilizers – 14,24% [25].

In 2020, 22,8 million tons of CO2eq·ha−1 N2O were emitted in Poland. In Poland, the main source of emissions of this gas is agriculture (81,8%), and agricultural soils are responsible for 68.9% of emissions, while natural fertilizer management is responsible for 12,9%. [16]

According to another study, ammonia emissions are influenced by weather conditions, season, type of crop, fertilizer dose and method of application. If too large a dose of fertilizer is used and it contains a large amount of nitrogen, ammonia is also emitted through the plant leaves. The source of nitrous oxide emissions in agriculture is approximately 70% from the soil, approximately 30% from natural fertilizers and, to a small extent, straw burning in fields (less than 0,2%). The direct production of ammonia results from the storage of slurry and nitrogen transformations that take place in the soil. Indirect production takes place in the aquatic environment (groundwater, rivers and reservoirs), to which nitrogen contained in the soil reaches indirectly (leaching and surface runoff). [19]

Losses from fertilizers, which include ammonium phosphate and sulfate as well as urea and its solutions, are estimated to range from 5 to 40%. The largest losses concern the urea itself, and the loss values are closely correlated with weather conditions.

Inhibitors reduce losses by slowing down the hydrolysis of the fertilizer while still releasing ammonia. Losses from ammonium nitrate are much lower, i.e. from 0,5 to 5% of the total amount of this form of nitrogen.

The European Union's recommendations for farmers say that fertilizers based on urea should be replaced with fertilizers based on ammonium nitrate. The EU also suggests using natural fertilizers instead of mineral fertilizers. It is also important to apply the fertilizer deeply and depending on the plant's needs.

One of the simplest and at the same time effective actions to reduce ammonia emissions from urea is to mix it with the soil as quickly as possible. It results in a 50 to 80% reduction in emissions. Another, more complex operation is the injection of urea into the soil so that the injected fertilizer is as far away from the seeds as possible so as not to inhibit germination. In this way, according to research, it is possible to reduce ammonia emissions by up to 90%.

When storing natural fertilizers, it is estimated that nitrogen losses range from 2 to 30%. One of the most important mistakes during agricultural work is delaying the plowing of fertilizers after their application. If plowed in immediately, ammonia emissions can be reduced by up to 90%. [20, 37]

Legume residues (e.g. chickpeas, soybeans, peas, beans) may cause higher nitrous oxide emissions than other plant residues. It is worth remembering that legume plant residues are rich in nitrogen and cause smaller losses per unit area than those from mineral fertilizers. However, low-quality cereal plant residues, where the ratio of the amount of carbon to nitrogen contained in them is above 25, left in the field reduce nitrous oxide emissions compared to traditional cultivation [22, 41, 42].

## 7. Methodology for determining the carbon footprint using a measuring frame

At the Łukasiewicz - Poznań Institute of Technology, a measuring frame aggregated with an agricultural tractor was designed. It is characterized by a rigid structure that has successfully passed strength and fatigue tests. This design will allow research to be conducted in a fully repeatable manner. At the same time, a feature of the design is the ability to adjust, for example, the frame suspension height above the ground, regardless of the adjustment of the tractor handle, or the ability to maintain a constant height above the ground throughout the entire period of operation. The versatility of the design allows the installation of many different tools and measuring devices.

This frame will be used to study carbon footprint emissions during agrotechnical operations. The frame design allows the machine to be suspended on it using a three-point suspension system. It is equipped with measurement elements that, together with additional equipment or sensors, will allow you to measure a number of parameters important from the point of view of generating a carbon footprint.

The measuring frame is equipped with a set of seven sensors that measure forces in three planes. Six sensors are arranged symmetrically, and one centrally in the device axis. The mentioned Zemis sensors, model B3G-C3-7.5t-6B, measure the load up to 7,5t

The main feature of the measuring frame is the measurement of working resistance while driving with a suspended machine. Other measurement possibilities of the frame include: measuring the mass of a suspended field machine, determining the center of gravity of the machine or recording its inclination. Having a number of parameters measured during machine tests in conditions similar to real operating conditions, by using algorithms prepared for this purpose, it is possible to estimate carbon dioxide emissions into the atmosphere, e.g. in relation to the area or per kilogram of product. In order to determine the carbon footprint emission, it is desirable and necessary to carry out numerous tests of specific agrotechnical procedures, during which measurements of tractor loads, agricultural tools, torques and rotational speeds, and fuel consumption measurements will be made. Figure 1 shows a view of the mentioned measuring frame.

With the sensors included in the basic equipment of the frame, you can perform, among others: measuring the mass suspended on the machine frame, determining its center of gravity, and leveling the machine. The drawing below shows the cultivation unit suspended on the frame, leveled and weighed on the frame (Fig. 2) and the same unit, the mass of which was measured in a conventional way to confirm the correctness of the measurement of the measuring frame.

At the Łukasiewicz - Poznań Institute of Technology, a test was carried out to verify the measurements of ground resistance depending on the driving speed with the suspended machine. In-ground tests were carried out at speeds of 4.5; 6 and 8 km/h. As a result of the analysis of the loads recorded during the tests, a correlation was observed between the ground resistance value and the driving speed [48]. The higher the driving speed, the higher the working resistance of the ground. At the same time, the tests allowed to confirm the expected values with the actual values obtained. Figures 3, 4 and 5 show the course of ground resistance values while traveling at a speed of 4,5 and 6 km/h.In the graphs above, it can be seen that the increase in the tractor's driving speed is associated with a greater resistance force from the ground.

A noticeable decrease in resistance can be observed in the case of driving at a speed of 8 km/h, which may be related to the decreasing compactness of the ground in a given area. Negative values in the graphs correspond to the obtained force values, because during data collection, values with the opposite sign were recorded.

Table 6 shows the average values of ground resistance for trips at speeds of 4,5; 6 and 8 km/h. Three passes were made at each speed.

The data collected in Table 6 indicate a noticeable increase in the ground resistance value with increasing driving speed during work. Increasing the driving speed from 4,5 km/h to 6 km/h increases the average resistance (average value calculated from three runs) by almost 25%. In turn, increasing the speed from 6 km/h to 8 km/h means an increase in ground resistance by 14%. It would be reasonable to perform subsequent runs at different speeds to obtain an answer to the question whether the increase in ground resistance will decrease as a percentage or will increase depending on the increase in driving speed.

The statistical analysis carried out allows us to conclude that the obtained results will be within the confidence level with 95% probability.

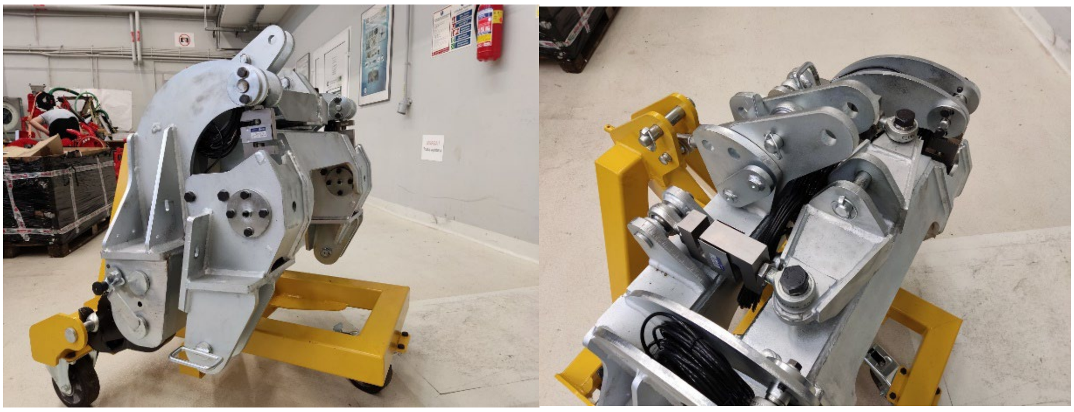

Fig. 1. Measuring frame, on the left - side view, on the right - top view.

Fig. 2. The cultivation unit suspended, weighed and leveled on the measuring frame (left) and the unit mass measured in a conventional way (right).

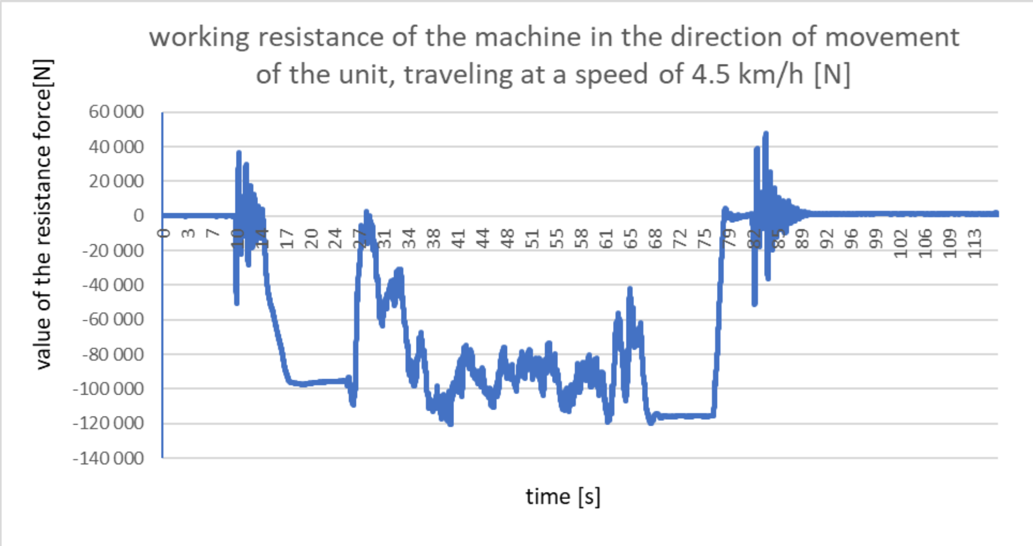


Fig. 3. The value of ground resistance obtained while traveling at a speed of 4,5 km/h

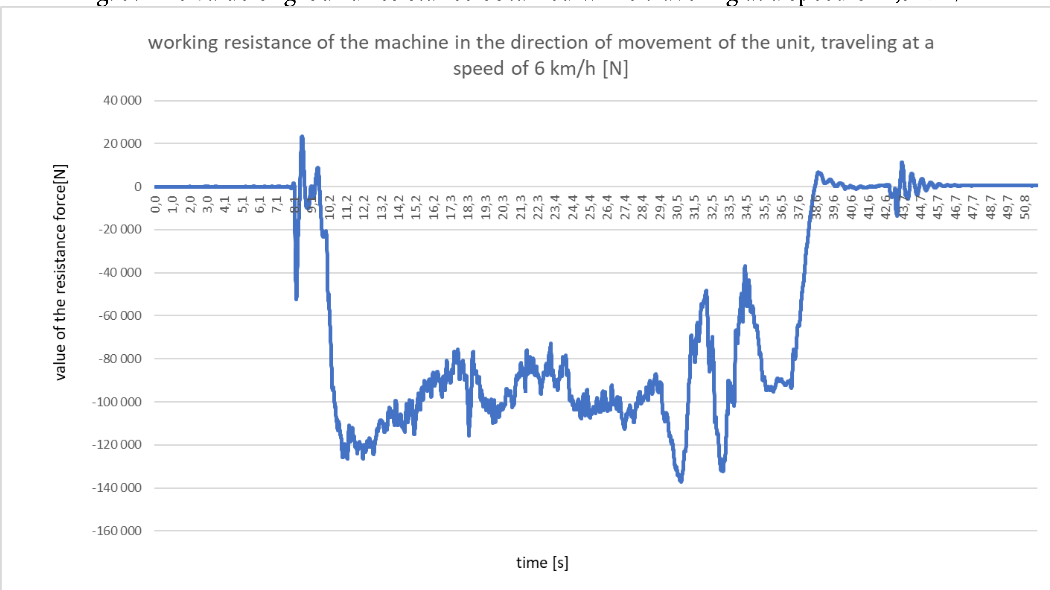


Fig. 4. The value of ground resistance obtained while traveling at a speed of 6 km/h

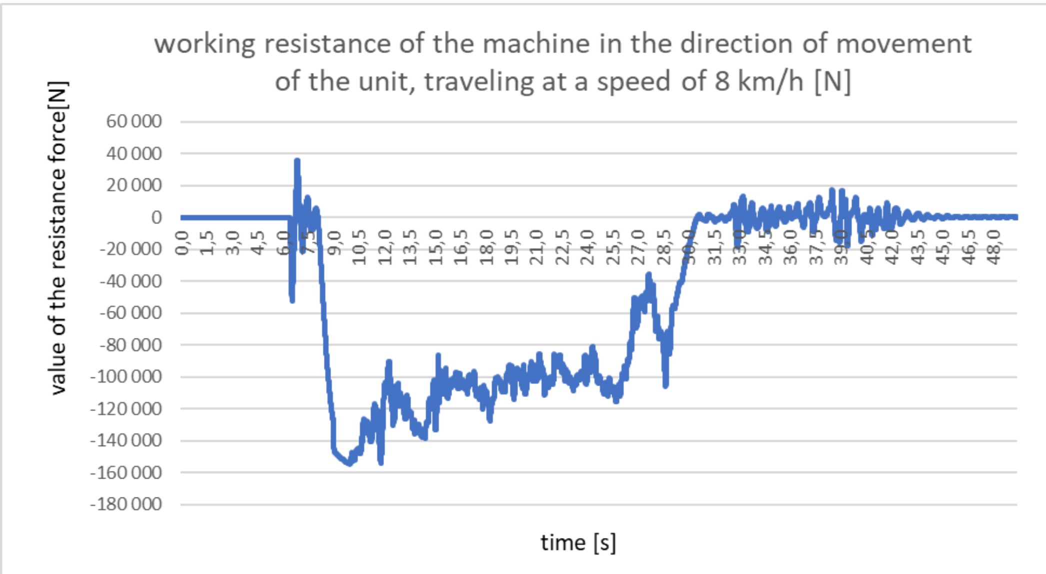


Fig. 5. The value of ground resistance obtained while traveling at a speed of 8 km/h

Table 6. The average value of ground resistance along with the average of three runs and basic statistical values

| | travel speed | | |
|---|---|---|---|
| value of ground resistance | 4,5 km/h | 6 km/h | 8 km/h |
| crossing 1 [N] | 74 144 | 94 182 | 104 506 |
| crossing 2 [N] | 68 267 | 91 834 | 108 302 |
| crossing 3 [N] | 77 291 | 88 155 | 99 708 |
| average [N] | 73 234 | 91 390 | 104 172 |
| standard deviation | 4 580,3 | 3037,9 | 4 306,7 |
| variation | 20979219,0 | 9228812,3 | 18547876,0 |
| confidence interval | | 0,95 | |
| variable T | | 3,182 | |

## 7. Conclusions

1. Reducing greenhouse gas emissions from crop agriculture: crop production emits fewer greenhouse gases than livestock production. Properly managed according to carbon farming principles, it can even provide negative emissions by sequestering carbon in the soil.

2. Monitoring and reducing fuel consumption: The most reliable way to determine CO2 emissions from crop production is to calculate based on actual fuel consumption at each stage of cultivation. It is possible to reduce fuel consumption through the use of energy-efficient machinery, proper setting of operating parameters and organization of work in the field.

3. Precise application of crop protection products and fertilizers: Precise application of herbicides, fertilizers and other crop protection products reduces their consumption and associated indirect greenhouse gas emissions, while improving fertilizer efficiency and reducing soil sealing.

4. Benefits of intercropping and mulching: The cultivation of intercrops and the use of straw for mulching, despite the additional expenditure of fuel, contribute to increasing the organic matter content of the soil, improve its structure and allow the reduction of mineral fertilizer doses.

5. Importance of organic fertilization: Fertilization with manure and slurry, despite higher fuel consumption, allows for a reduction in mineral fertilizer application rates, which has a positive effect on reducing greenhouse gas emissions. It is important to use organic fertilizers correctly to maximize their benefits.

6. Overall benefits of reducing production resources: Reducing the use of diesel fuel, mineral fertilizer and crop protection products in crop production not only reduces greenhouse gas emissions, but also protects the environment from other hazards and reduces production costs.

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