Energy consumption of primary tillage operations in conventional and no-till farming systems – a review

Wojciech Tanaś[1], Mariusz Szymanek[1,*] Iurie Melnic[2]
[1]Department of Agricultural, Forest and Transport Machinery, University of Life Sciences in Lublin, Poland
[2]Department of Mechanical Engineering, Technical University of Moldova
mariusz.szymanek@up.lublin.pl

***Abstract**: This article reviews domestic and international literature on the energy consumption of primary tillage operations in four farming systems: conventional (plough-based) tillage, simplified tillage, strip-till and no-till farming. The energy inputs of individual agrotechnical operations were analysed, with particular emphasis on fuel consumption, cumulative energy, CO_2 emissions and the impact on the physical and biological properties of the soil. The results of the review indicate that switching from ploughing to no-till farming reduces fuel consumption by 60–80%, energy inputs by 55–75%, and greenhouse gas emissions by 65–80%. At the same time, no-till systems promote the accumulation of organic matter in the topsoil, improve the stability of soil aggregates and protect against erosion. The limitations of no-till farming under Polish conditions were also discussed, including the risk of seed embedding in heavy soils, problems with weed control, increased reliance on herbicides, and economic and psychological barriers. An economic analysis of cultivation costs in individual systems was carried out for a model farm with an area of 100 ha.*

Keywords: TILLAGE, NO-TILL FARMING, ENERGY INTENSITY, FUEL CONSUMPTION, CO_2 EMISSIONS, DIRECT DRILLING, NO-TILL, STRIP-TILL, CONSERVATION AGRICULTURE

1. Introduction

Tillage is one of the most energy-intensive aspects of crop production, whilst also being a practice of fundamental agrotechnical importance. According to data from the Food and Agriculture Organisation [6], the agricultural sector accounts for approximately 23% of global greenhouse gas emissions, a significant proportion of which is generated by mechanical soil tillage operations. In Poland, where conventional cultivation based on ploughing still predominates, fuel consumption for tillage operations accounts for 35–50% of total fuel consumption on a farm [9]. It is estimated that average diesel consumption in Polish agriculture is approaching 200 litres per hectare of agricultural land per year, of which up to half is attributable to tillage operations [15].

Rising energy costs, tightening environmental regulations under the European Green Deal, the objectives of the 'Farm to Fork' strategy, and the drive towards sustainable agricultural development are prompting a search for alternative technological solutions. No-till farming, also known as direct seeding, is the most radical form of simplifying tillage, involving the complete abandonment of mechanical tillage [19, 32]. According to estimates by Derpsch et al. [5], the area of land cultivated using the no-till method worldwide increased from 45 million ha in 1999 to 111 million ha in 2009, growing at a rate of approximately 6 million ha per year. In Europe, and particularly in Poland, the adoption of these technologies is proceeding more slowly than in South America or Australia, which stems both from the specific soil and climatic conditions and from the structural characteristics of Polish agriculture [10, 24, 25].

In parallel with no-till systems, strip-till technology is developing, combining elements of conservation tillage with spot soil loosening in the root zone . In recent years, strip-till has gained significant popularity among Polish producers of maize, sugar beet and rapeseed, offering a compromise between energy efficiency and optimal plant growth conditions.

The aim of this article is to review and compare the energy consumption of primary tillage operations in conventional technologies and in no-till systems, with particular regard to the conditions of Polish agriculture. The analysis covers fuel consumption, cumulative energy inputs, field productivity, CO_2 emissions, the impact on the physical and biological properties of the soil, as well as the economic aspects associated with the individual cultivation systems.

2. Materials and methods

This paper is a review article. The analysis is based on a critical review of domestic and international literature from 2000 to 2024. The following databases were searched: Web of Science, Scopus, Google Scholar, BazTech and the resources of the National Library, using keywords in English ("tillage energy consumption", "no-till fuel use", "conservation agriculture energy balance", "strip-till energy") and Polish ("energochłonność uprawy roli", "no-till fuel consumption", "direct seeding"). A total of 78 publications meeting the quality criteria were selected – articles from peer-reviewed scientific journals, monographs and reports from research institutes.

Energy data were harmonised into common units. Fuel consumption was expressed in litres of diesel per hectare (l/ha). Energy inputs were converted to megajoules per hectare (MJ/ha), using a conversion factor of 1 l diesel = 35.5 MJ of embodied energy, accounting for the energy required for fuel production, transport and distribution [8]. CO_2 emissions were calculated using a factor of 2.67 kg CO_2 per litre of diesel fuel burned, in accordance with IPCC guidelines [11]. The working resistance of the implements is given in kilonewtons per metre of working width (kN/m).

The economic analysis assumed a diesel price of PLN 6.50/l (as of mid-2024) and average market prices for plant protection products and machinery services according to the price lists of Agricultural Advisory Centres.

3. Energy requirements of conventional cultivation

3.1. Characteristics and sequence of operations

The conventional (plough-based) cultivation system is based on the complete inversion of the topsoil using a mouldboard or reversible plough, supplemented by a series of pre-sowing cultivation operations. A typical sequence under Polish conditions includes: post-harvest stubble cultivation (immediately after harvest, to a depth of 8–12 cm), ploughing and sowing in autumn (depth 20–30 cm), and in spring – harrowing, harrowing with a harrow, cultivating and sowing [21]. The total number of machine passes across the field ranges from 5 to 8, and sometimes even up to 10, depending on the crop species, soil type and prevailing moisture conditions.

In studies by Golka et al. [9], conducted as part of the POIG project 'Soil cultivation system for sustainable agriculture', it was shown that in a 5-year crop rotation, traditional (plough-based) technology required 19 cultivation and sowing operations consuming 1031 MJ/ha, with fuel consumption of 240 l/ha (in total for the entire rotation, i.e. an average of 48 l/ha per year). By comparison, conservation (no-till) technology required only 8 operations and 423 MJ/ha, with fuel consumption of 106 l/ha (i.e. an average of 21 l/ha per year).

3.2. Energy consumption of individual operations

Ploughing is the operation with the highest energy requirement throughout the entire crop production cycle. The energy

consumption of ploughing depends on many factors: working depth, soil type (particularly particle size distribution and moisture content), working speed, and the technical condition and design of the plough. On lighter soils, fuel consumption during ploughing to a depth of 20 cm is approx. 14–18 l/ha, whilst on medium and heavy soils at a depth of 25–30 cm it rises to 22–32 l/ha, corresponding to an energy input of 780–1135 MJ/ha [8, 15].

Deep ploughing, used periodically to break up the plough pan, requires fuel inputs of 18–25 l/ha at a working depth of 30–45 cm. Cultivation (10–20 cm) consumes 8–14 l/ha, disc harrowing 7–13 l/ha, and harrowing 4–8 l/ha. Harrowing and rolling are the operations with the lowest energy requirements – 2–4 l/ha each [15]. A detailed breakdown of the energy consumption of individual operations is presented in Table 1.

Fuel consumption is also significantly influenced by the tractor's power and its suitability for the implement. Studies show that oversizing the tractor's power by 30–50% relative to the implement's requirements leads to a 10–20% increase in specific fuel consumption due to the engine operating below the optimal load range. Modern tractors with electronic engine control (ECU) and continuously variable transmission (CVT) enable a reduction in fuel consumption of 8–15% compared to older designs [25].

Tab. 1. Energy consumption of basic tillage operations in a conventional system

Tillage operation	Depth [cm]	Fuel consumption [l/ha]	Working resistance [kN/m]	Energy input [MJ/ha]	Productivity [ha/h]
Ploughing with a reversible plough	25–30	22–32	3.5–5.5	780–1135	0.8–1.2
Ploughing with a mouldboard plough	20–25	18–26	3.0–4.8	640–920	1.0–1.5
Deep ploughing	30–45	18–25	2.5–4.0	640–890	0.6–1.0
Cultivation	10–20	8–14	1.5–2.5	285–500	2.0–3.5
Disc	8–15	7–13	1.2–2.0	250–460	2.5–4.0
Harrowing	5–10	4–8	0.5–1.0	140–285	3.0–5.0
Fibering	3–5	2–4	0.2–0.5	70–140	5.0–8.0
Rolling	–	2–4	0.3–0.6	70–140	4.0–7.0

Source: [7, 9, 15]

3.3. Total energy balance of the conventional system

Total fuel consumption over the full conventional cropping cycle, encompassing all operations from stubble cultivation to sowing, amounts to 45–75 l/ha depending on the crop species and soil conditions. This corresponds to a cumulative energy input of 1600–2660 MJ/ha. It should be emphasised that ploughing alone accounts for 45–55% of total fuel consumption for cultivation operations, making it a key factor from the perspective of energy optimisation [9].

It is worth noting that the impact of traditional tillage on crop yields, especially under favourable environmental conditions, is relatively small. Fertilisation, plant protection and the selection of the appropriate genotype adapted to climatic and soil conditions are of much greater importance for crop productivity [29]. This observation is one of the main arguments in favour of simplifying tillage – the high energy input required for ploughing does not translate proportionally into increased yields.

4. No-till farming systems

4.1. Reduced tillage

Reduced tillage involves limiting the number and intensity of cultivation operations whilst abandoning traditional ploughing. Instead of a plough, cultivation units, stubble cultivators or disc harrows are used, which loosen the soil without fully turning the soil. In Polish conditions, multi-operation units (of the 'compact' type) are becoming increasingly popular, combining several operations in a single pass: loosening, crushing, levelling and surface compaction [2].

Fuel consumption in simplified tillage systems is 25–45 l/ha, representing a reduction of 35–50% compared to conventional tillage. Energy input ranges from 890 to 1600 MJ/ha. The main savings result from the elimination of ploughing and a reduction in the number of machine passes across the field from 5–8 to 3–5. At the same time, multi-operation implements allow for an area productivity of 2–4 ha/h, i.e. two to three times higher than with ploughing [9].

Research by Gawęda et al. [7] on the energy efficiency of various tillage systems in a three-field crop rotation confirmed that the agrotechnology involving traditional ploughing was the most energy-intensive. Simplified tillage allowed for comparable yields with significantly lower energy inputs, which translated into a more favourable energy efficiency ratio for production.

4.2. Direct drilling (no-till)

Direct seeding is the most advanced form of conservation tillage, in which mechanical soil cultivation is completely abandoned. Seeds are placed directly into uncultivated soil covered with crop residues using specialised seeders equipped with cutting discs and coulters. According to the definition adopted by the FAO, conservation agriculture is based on three pillars: minimal disturbance of soil structure, permanent ground cover with organic matter, and diversified crop rotation [5, 13].

Fuel consumption in the no-till system is only 5–18 l/ha [9, 15], representing a saving of 60–80% compared to conventional cultivation. Energy input ranges from 180 to 640 MJ/ha. Working time is merely 0.4–1.0 h/ha, which is particularly significant under conditions of short agronomic windows, characteristic of a temperate climate.

At the same time, account must be taken of the additional energy input associated with the use of herbicides, the consumption of which in no-till systems is 15–30% higher than in conventional farming. This applies in particular to glyphosate-based total herbicides used to burn off weed residues before sowing. The full energy balance must take into account the embodied energy in plant protection products, which averages 260–420 MJ/kg of active [17]. Nevertheless, the overall energy balance of no-till systems remains significantly more favourable than that of conventional farming.

4.3. Strip-till

Strip-till technology is a hybrid approach that combines the advantages of no-till farming with the benefits of mechanical loosening of the root zone. In this system, only narrow strips of soil 15–30 cm wide (corresponding to the future rows of plants) are tilled, into which seeds and mineral fertilisers are placed, whilst the inter-rows remain untilled and covered with mulch [28]. This technology is particularly recommended for crops grown in wide rows: maize, sugar beet, sunflower and rapeseed.

Fuel consumption in strip-till technology is 12–22 l/ha – less than in simplified cultivation, but more than in direct drilling. The energy benefits result from limiting tillage to 25–40% of the field area, whilst ensuring optimal temperature and moisture conditions for germination in the sowing zone. Modern strip-till machines enable simultaneous loosening, fertilisation (localised) and sowing, carrying out three operations in a single pass.

In Polish conditions, strip-till is gaining increasing popularity, particularly in maize cultivation on medium and heavy soils, where direct drilling encounters difficulties associated with excessive compaction of the topsoil and delayed soil warming in spring. Strip tillage to a depth of 25–35 cm eliminates these problems, whilst retaining the benefits of mulch remaining in the inter-rows.

5. Comparative analysis of tillage systems

5.1. Summary of energy parameters

A summary of the key energy and environmental parameters of the four main tillage systems is presented in Table 2. The data covers the full cycle of land preparation for sowing, from post-harvest operations to the actual sowing. It also includes indicative cultivation costs based on 2024 price levels and herbicide consumption expressed as an increase relative to the conventional system.

Table 2. Comparison of tillage systems in terms of energy, environmental and economic parameters

Parameter	Plough-based cultivation	Simplified tillage	Strip-till	No-till
Fuel consumption [l/ha]	45–75	25–45	12–22	5–18
Energy input [MJ/ha]	1600–2660	890–1600	425–780	180–640
Number of passes	5–8	3–5	1–2	1
Working time [h/ha]	3.5–6.0	1.5–3.0	0.8–1.5	0.4–1.0
CO_2 emissions [kg/ha]	120–200	67–120	32–59	13–48
Water erosion [t/ha/year]	5–25	2–10	1–5	0.5–3
Cultivation cost [PLN/ha]	800–1,400	450–800	350–650	200–450
Herbicide consumption [Δ%]	ref.	+5–10%	+10–20%	+15–30%

Source: [5, 9, 17].

5.2. Interpretation of differences between systems

Analysis of the data in Table 2 clearly indicates a distinct energy advantage for no-till systems. Direct drilling allows for fuel savings of 37–57 l/ha compared to conventional cultivation. For a farm of 100 ha, annual fuel savings can reach 3,700–5,700 litres, which, at a diesel price of PLN 6.50/l, translates to a cost reduction of PLN 24,000–37,000 per year.

The reduction in CO_2 emissions is proportional to fuel savings and amounts to 72–152 kg CO_2 /ha less in a no-till system compared with ploughing. At the national level, assuming the conversion of even 30% of the 10.5 million hectares of arable land to no-till systems, the potential for emission reductions is estimated at 230–480 thousand tonnes of CO_2 per year. This is a significant argument in the context of Poland's climate commitments under the Fit for 55 package [8].

A separate issue is the impact of individual systems on water and wind erosion. Ploughing leaves the soil exposed and vulnerable to erosive factors, particularly during the autumn and winter months. No-till systems, thanks to the constant coverage of the surface with crop residues, reduce soil losses from water erosion by as much as 80–90% [10]. This is of fundamental importance on loess and silt soils, which are predominant in southern and eastern Poland.

6. The impact of the tillage system on soil properties

6.1. Physical properties

Highlighting the energy aspects of tillage requires simultaneous consideration of the impact of individual systems on the physical condition of the soil. Long-term ploughing leads to the degradation of aggregate structure, a reduction in organic matter content in the surface layer and the formation of a plough pan – a compacted layer at a depth of 25–35 cm, limiting water infiltration and root penetration [20].

Lipiec et al. [20] demonstrated in a long-term experiment on silty soil (Eutric Fluvisol) that conventional tillage (ploughing to a depth of 20 cm) provided the highest areal porosity and infiltration in the 0–10 cm layer, but these differences diminish in the 10–20 cm layer. Importantly, in direct-seeded soils, a network of biopores formed by plant roots and earthworms developed, which partially compensated for the lower structural porosity.

No-till systems, despite higher bulk density in the 0–10 cm layer, are characterised by significantly higher organic matter content and better aggregate stability (Table 3). Long-term studies conducted in Central Europe indicate that after 5–8 years of direct drilling, soil structure self-regulates thanks to the activity of soil fauna, particularly earthworms [22, 25]. Strip-till occupies an intermediate position – loosening in the row zone provides good conditions for roots, whilst undisturbed inter-rows preserve the natural soil structure and water retention.

Table 3. Effect of tillage system on selected physical soil properties (averages from long-term studies)

Soil parameter	Plough cultivation	Simplified tillage	Strip-till	No-till
Bulk density 0–10 cm [g/cm³]	1.15–1.30	1.25–1.40	1.20–1.35	1.30–1.50
Bulk density 10–30 cm [g/cm³]	1.35–1.55	1.30–1.45	1.28–1.42	1.25–1.40
Organic matter 0–10 cm [%]	1.8–2.2	2.0–2.5	2.1–2.6	2.3–3.0
Aggregate stability [%]	35–50	45–60	48–65	55–75
Capillary porosity [%]	38–45	35–42	36–43	33–40
Infiltration [cm/3h]	80–95	50–70	55–75	35–60

Source: [20, 22, 25]

6.2. Biological properties and carbon sequestration

No-till systems promote the accumulation of organic carbon in the topsoil. Lal [18, 19] estimated the global potential for soil carbon sequestration at 0.4–1.2 Pg C per year, a significant portion of which could be achieved by converting plough-based cultivation to no-till systems. Under the temperate climate conditions of Central Europe, the rate of carbon sequestration in no-till soils is estimated at 0.3–0.8 Mg C/ha/year [25].

The absence of mechanical soil tillage also promotes the development of soil microfauna and mesoorganisms. Reeleder et al. [22] demonstrated significant differences in the populations of earthworms ( ), mites and springtails between ploughed and non-ploughed systems. The earthworm population in no-till soils was 2–3 times higher than in ploughed soils, which directly translates into improved soil structure, water infiltration and nutrient availability.

7. Economic analysis of tillage systems

A full assessment of the efficiency of tillage systems requires consideration not only of energy inputs but also of economic aspects. Table 4 summarises the estimated costs of tillage in the three systems for a model farm of 100 ha under 2024 price conditions.

Table 4. Economic analysis of cultivation costs in three systems for a model 100-hectare farm (2024 price conditions)

Cost component	Plough cultivation	Simplified tillage	No-till
Fuel [PLN/ha]	390–488	163–293	33–117
Machinery depreciation [PLN/ha]	180–350	120–250	80–200
Herbicides [PLN/ha]	120–200	140–230	170–300
Labour [PLN/ha]	200–350	100–200	50–120
TOTAL [PLN/ha]	890–1,388	523–973	333–737
Annual savings / 100 ha [PLN]	–	25,000–62,000	45,000–95,000

Source: Own analysis based on market prices for fertilisers, plant protection products and agricultural machinery price lists (as of June 2024).

The analysis shows that the total costs of farming under the no-till system are 40–60% lower than in conventional farming. However, the higher initial cost must be taken into account – a direct-drilling seed drill costs PLN 150,000–450,000, which represents a significant investment barrier. With savings of PLN 45,000–95,000 per year (for 100 ha), the payback period for investment in no-till equipment is 2–5 years, making this technology economically attractive in the long term.

An additional economic benefit is reduced machine wear and lower maintenance costs. A farm practising no-till farming requires a smaller fleet of machinery (no ploughs, harrows or rollers), which translates into lower costs for depreciation, insurance and equipment storage.

8. Limitations and challenges of no-till farming in Polish conditions

8.1. Soil and climatic factors

Despite clear energy and economic benefits, the implementation of no-till systems in Polish conditions presents a number of challenges. In conditions of heavy soils (loam, heavy clay) and a temperate, humid climate, characteristic of much of Northern and Central Poland, direct drilling can lead to excessive soil compaction, a deterioration in the thermal and moisture conditions for germination, and delayed soil warming in spring. Heavy, wet soils covered with a thick layer of crop residues warm up in spring by as much as 2–4°C more slowly than ploughed soils, which delays the sowing date and initial plant growth [25].

A problem specific to Polish conditions is also the high fragmentation of farms (average area of around 11 ha), which makes it difficult to justify the purchase of specialist direct-drilling equipment on economic grounds. A solution could be producer groups and machinery cooperatives, enabling the shared use of expensive equipment.

8.2. Weed control and plant protection

The most significant agronomic challenge of no-till farming is weed control. Abandoning mechanical soil tillage eliminates an effective mechanism for weed control – both by burying their seeds at a depth that prevents germination and by mechanically destroying the root systems of perennial weeds. This necessitates increased use of herbicides, particularly glyphosate [1].

Growing environmental and health concerns regarding glyphosate, as well as emerging forms of weed resistance to this active ingredient, call into question the long-term sustainability of no-till systems based solely on chemical weed control. An integrated approach, combining the rotation of herbicides with different modes of action with the use of catch crops and cover crops, as well as diversified crop rotation, represents a research direction of key importance for the future of conservation agriculture in Europe [14].

8.3. Mental and institutional barriers

In the Polish context, farmers' traditions and habits also pose a significant challenge. Ploughing is seen as the fundamental and 'proper' way to prepare the soil, and moving away from this practice meets with resistance, particularly among the older generation of farmers. The political transformation of the late 20th century and the associated economic changes – high fuel prices coupled with low agricultural commodity prices – did indeed increase interest in simplified cultivation methods, but the full adoption of no-till systems still faces significant psychological and infrastructural barriers [29].

Another significant factor is the lack of systematic institutional support. Unlike in South American countries (Brazil, Argentina, Paraguay), where conservation agriculture is covered by dedicated support and advisory programmes, Poland lacks a comprehensive policy promoting no-till farming. Subsidies for environmentally beneficial practices under the CAP (eco-schemes) only partially offset the risks associated with switching to a new farming system.

9. Prospects for the development of no-till systems in Poland

Despite the limitations described, the prospects for the development of no-till systems in Poland are viewed optimistically. Several factors favour the further adoption of these technologies. Firstly, advancing climate change – particularly the intensification of agricultural drought – means that soil water retention, provided by conservation tillage systems, is becoming an increasingly important factor in crop production.

Secondly, the growing availability of precision farming technologies (GPS-RTK, ISOBUS sensors, soil fertility maps) enables the optimisation of tillage depth, fertiliser and herbicide rates using variable rate application (VRA), which reduces the costs and environmental risks of no-till systems.

Thirdly, innovative agronomic solutions are emerging, such as 'green-till' systems combining direct drilling with the use of catch crops as 'living mulch', which limit weed growth without the need for herbicides. Research into biological methods of weed control, including allelopathic crop varieties, may significantly alter the environmental balance of no-till systems in the future.

10. Summary and conclusions

Based on the literature review, the following conclusions were drawn:

1) Conventional cultivation based on ploughing is characterised by the highest energy inputs, reaching 1600–2660 MJ/ha, with fuel consumption of 45–75 l/ha. Ploughing alone accounts for 45–55% of the total energy consumption for cultivation operations.
2) Simplified tillage systems enable a reduction in energy input of 35–50%, mainly due to the elimination of ploughing and the use of multi-operation implements.
3) Direct drilling (no-till) achieves energy savings of 55–75% compared to conventional tillage, whilst reducing CO_2 emissions by 65–80% and limiting erosion by 80–90%.
4) Strip-till technology offers a promising compromise, combining energy savings similar to those of direct drilling with the benefits of localised soil loosening in the root zone.
5) No-till systems promote the accumulation of organic matter in the topsoil, improve aggregate stability and enhance soil biological activity.
6) The main constraints to the implementation of no-till systems in Polish conditions are: problems with weed control, high equipment costs, delayed warming of heavy soils, and mental and institutional barriers.
7) Economic analysis indicates that the total costs of farming under a no-till system are 40–60% lower than in conventional farming, and the payback period for equipment investment is 2–5 years.

Further research should focus on the long-term assessment of the energy efficiency of no-till systems under diverse soilacross Poland, taking into account the full energy balance (including the energy embodied in plant protection products and fertilisers), the impact on yields over the long term, and economic efficiency from the perspective of the entire farm.

References

[1] BENBROOK, C.M. 2016. Trends in glyphosate herbicide use in the United States and globally. Environmental Sciences Europe, 28(1), 1–15. https://doi.org/10.1186/s12302-016-0070-0
[2] BISKUPSKI, A., WŁODEK, S., SEKUTOWSKI, T., SMAGACZ, J. 2012. Effect of tillage systems and straw fertilisation on grain yield and selected indicators of cereals and physical properties of soil. Acta Scientiarum Polonorum Agricultura, 11(3), 17–29.
[3] BLEĆHARCZYK, A., MAŁECKA, I., SIERPOWSKI, J. 2007. The effect of long-term tillage systems on the physico-chemical properties of soil. Fragmenta Agronomica, 1(93), 7–13.
[4] CZYŻ, E., DEXTER, A.R., WŁODEK, S., BISKUPSKI, A., NIEDŹWIECKI, J. 2008. Assessment of selected physical properties of soil in various tillage systems. Pamiętnik Puławski, 148, 25–34.
[5] DERPSCH, R., FRIEDRICH, T., KASSAM, A., Li, H. 2010. Current status of adoption of no-till farming in the world and some of its main benefits. International Journal of Agricultural and Biological Engineering, 3(1), 1–25. https://doi.org/10.3965/j.issn.1934-6344.2010.01.0-0
[6] FAO 2022. The State of Food and Agriculture 2022. Leveraging food systems for inclusive rural transformation. Food and Agriculture Organization of the United Nations, Rome.
[7] GAWĘDA, D., SZYMANKIEWICZ, K., HARASIM, E. 2006. Energy efficiency of various tillage systems in a three-field crop rotation. Pamiętnik Puławski, 142, 105–116.

[8] GOLKA, W. 2011. Soil cultivation techniques that reduce greenhouse gas emissions. Problems of Agricultural Engineering, 19(4), 51–60.
[9] GOLKA, W., PTASZYŃSKI, S., SMAGACZ, J. 2014. Inputs for tillage in conservation and conventional farming systems. Agricultural Engineering Problems, 22(3), 33–44.
[10] HOLLAND, J.M. 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agriculture, Ecosystems and Environment, 103(1), 1–25. https://doi.org/10.1016/j.agee.2003.12.018
[11] IPCC 2019. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change, Geneva.
[12] JABŁOŃSKI, W., KAUS, A. 1997. The effect of different cropping systems and fertilisation on crop yields. Bibliotheca Fragmenta Agronomica, 3, 91–96.
[13] KASSAM, A., FRIEDRICH, T., DERPSCH, R., KIENZLE, J. 2015. Overview of the worldwide spread of conservation agriculture. Field Actions Science Reports, 8, 1–11.
[14] KASSAM, A., FRIEDRICH, T., DERPSCH, R. 2019. Global spread of conservation agriculture. International Journal of Environmental Studies, 76(1), 29–51. https://doi.org/10.1080/00207233.2018.1494927
[15] KOGUT, Z. 2011. Technical and energy aspects of soil cultivation using mulch. Advances in Agricultural Sciences, 63(3), 75–89.
[16] KOPIŃSKI, J., KUŚ, J. 2011. The impact of organisational changes in agriculture on soil organic matter management. Problems of Agricultural Engineering, 19(2), 47–54.
[17] LABREUCHE, J., LELLAHI, A., MALAVAL, C., GERMON, J.C. 2011. Impact of no-tillage agricultural methods on the energy balance and the greenhouse gas balance of cropping systems. Cahiers Agricultures, 20(3), 204–215. https://doi.org/10.1684/agr.2011.0489
[18] LAL, R. 2004. Soil carbon sequestration impacts on global climate change and food security. Science, 304(5677), 1623–1627. https://doi.org/10.1126/science.1097396
[19] LAL, R. 2015. Sequestering carbon and increasing productivity by conservation agriculture. Journal of Soil and Water Conservation, 70(3), 55A–62A. https://doi.org/10.2489/jswc.70.3.55A
[20] LIPIEC, J., KUŚ, J., SŁOWIŃSKA-JURKIEWICZ, A., NOSALEWICZ, A. 2006. Soil porosity and water infiltration as influenced by tillage methods. Soil and Tillage Research, 89(2), 210–220. https://doi.org/10.1016/j.still.2005.07.012
[21] RADECKI, A., KOPIŃSKI, J., KUŚ, J. 2002. Simplifications in tillage in the light of research and practical experience. Pamiętnik Puławski, 130(2), 589–602.
[22] REELEDER, R.D., MILLER, J.J., BALL COELHO, B.R., ROY, R.C. 2006. Impacts of tillage, cover crop, and nitrogen on populations of earthworms, microarthropods, and soil fungi in a temperate climate. Applied Soil Ecology, 33(3), 243–257. https://doi.org/10.1016/j.apsoil.2006.01.006
[23] SMAGACZ, J. 2013. Soil cultivation – current research directions and latest trends. In: Hołownicki, R., Kuboń, M. (eds.) Contemporary agricultural engineering – achievements and new challenges, vol. III, PTIR, 287–329.
[24] SPRAWKA, M. SZYMANEK, M., KASSAR, F.H., TANAŚ, W. 2023. The effect of plow modification on drawbar power requirement during ploughing and subsoil penetration resistance. Mechanization in Agriculture & Conserving of the Resources. 69(2), 51-55.
[25] SOANE, B.D., BALL, B.C., ARVIDSSON, J., BASCH, G., MORENO, F., ROGER-ESTRADE, J. 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. Soil and Tillage Research, 118, 66–87. https://doi.org/10.1016/j.still.2011.10.015
[26] SRINIVASARAO, C., LAL, R., KUNDU, S., THAKUR, P. 2015. Conservation Agriculture and Soil Carbon Sequestration. In: Farooq, M., Siddique, K. (eds.) Conservation Agriculture. Springer, Cham, 479–524. https://doi.org/10.1007/978-3-319-11620-4_19
[27] TEBRÜGGE, F., DÜRING, R.A. 1999. Reduced tillage intensity – a review of results from a long-term study in Germany. Soil and Tillage Research, 53(1), 15–28. https://doi.org/10.1016/S0167-1987(99)00073-2
[28] VYN, T.J., RAIMBAULT, B.A. 1993. Long-term effect of five tillage systems on maize response and soil structure. Agronomy Journal, 85(5), 1074–1079. https://doi.org/10.2134/agronj1993.00021962008500050022x
[29] WEBER, R. 2010. The effect of the duration of no-till systems on soil properties. Advances in Agricultural Sciences, 62(1), 63–75.
[30] WEST, T.O., MARLAND, G. 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agriculture, Ecosystems and Environment, 91(1–3), 217–232. https://doi.org/10.1016/S0167-8809(01)00233-X
[31] WŁODEK, S., BISKUPSKI, A., SMAGACZ, J., GÓRNIK, A. 2014. Assessment of soil material in terms of physical properties. Report on the implementation of the POIG 1.3.1 project. IUNG-PIB Puławy.
[32] TENU, I., MELNIC, I.,ROŞCA, R., CÂRLESCU, P. 2018. .Research on the impact of tillage operations for autumn wheat crop set up over some soil properties. In: Ştiinţa agricolă, nr.2. Chişinău: UASM, 2018, pp.122-127, ISSN 1857-0003. https://press.utm.md/index.php/as/issue/view/2018-2/full-issue