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Research into Comparative Performance of Different Tillage and Fertilization Systems Applied to Grey Forest Soil of Forest Steppe in Grain Crop Rotation

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ABSTRACT

The paper summarises the results of the comprehensive scientific research carried out in the form of a two-factor stationary experiment (5 primary tillage systems × 3 fertilization systems) with rotation (2016–2020) of cereal crops (winter wheat – grain maize – spring barley – soybean) in grey forest fine sand and light loam soil. The effectiveness of the tested agricultural production method has been proven by the amplitudes of the actual cropping capacities: winter wheat – 2.80–5.00 t·ha^{-1}; grain maize – 4.16–8.89 t·ha^{-1}; spring barley – 1.78–4.45 t·ha^{-1}; soybean – 1.02–3.17 t·ha^{-1}. The rehabilitation of the physical, agrochemical and biological status of the edatope and the consolidation of the physiological processes in the grain cenoses achieved by the systemic approach to the soil tillage and fertilisation have provided for an increase in the natural biological potential of the plough land by a factor of 1.3–1.8 (from 2.96 to 5.21 t·ha^{-1} of grain units, units for the equivalent measuring of different plant cultivation products). Factographic justification has been provided for the environmental, technological and technical-and-economic feasibility of implementing agronomic technologies based on the adaptive combination of mouldboard and non-mouldboard tillage (to a depth of 6–45 cm) and organic and mineral fertilization system (6.5–7.0 t·ha^{-1} of plant cultivation by-products + $N_{70}P_{58}K_{68}$). In this case, the effective fertility of an area unit in crop rotation reaches 5.72 t·ha^{-1} in grain units, the production cost of raised grain – 117 €·t^{-1}, the earning capacity – 788 € (ha·year)$^{-1}$, the level of plant cultivation profitability – 139%. In the comparable alternatives of the system-based soil tillage (every-year ploughing, subsurface blade tillage and especially tillage with disk implements), the indices estimated above are significantly lower.

Keywords: agrotechnology, alternative tillage, fertilization, productivity, soil physics.

INTRODUCTION

The transition of the agricultural sector to the market relations from diverse initial positions stipulates the coexistence of functionally different farming systems even within the same specific soil and climate region. The use of predominantly hybrid approaches is based on the following farming concepts: conventional, intensive, adaptive, soil protecting, ecological, resource conserving, balanced, sustainable, renewable, organic, environmental etc. (Baig & Gamache, 2009; Larocque, 2020). However, in all these cases, the rational combination of the mechanical tillage, fertilization, crop rotation and plant protection modules is an indispensable attribute of their efficiency. Today's spectrum of the practical agronomic process solutions employed by economic entities is strikingly wide. While the majority of small and middle-size commodity producers have access to only some elements of agronomic innovations, major agricultural holdings extensively apply the whole package of state-of-the-art solutions, such as: controlling the navigation of combined tilling, sowing and harvesting tractor-implement units with the use of the Differential Global Positioning Systems (DGPS), sensor diagnostics of the soil and crop conditions with the use of unmanned aerial vehicles etc. (Glinski et al., 2013; Kaminskyi et al., 2015; Medvedev, 2015; Daponte et al., 2019; Tarariko et al., 2019).

The priority trend of conservation agriculture includes three fundamental principles: a) minimum tillage (mulch-, strip-, ridge-, no-tillage seeding); b) specifically designed cycling of crops in the crop rotation system; c) continuous protection of the soil surface by the vegetating plants and their residues (Morgan, 2005, 2006; FAO, 2014, 2015; Gonzalez-Sanchez et al., 2015; Kassam et al., 2015; Marandola et al., 2019; Stanojevic, 2021).

Several researchers (Morgan, 2005; Friedrich & Kassam, 2009) point out that the implementation of the latest agronomic technologies takes place in the evolutionary way with imperative fulfilment of the preparatory and transition period conditions (cultivation, logistics and information support, staffing, meeting the social and economic demand). That is demonstrated by the propagation of no-till systems (official statistics on these technologies have been recorded since 1982), which – despite the boom in their advertising – currently cover only about 160 million ha, i.e., 12% of the world cropped land, while in Europe this figure is under 3% (Baker et al., 2007; Derpsch, R., Friedrich, T. 2009; Lindwall & Sonntag, 2010).

In the countries of Eastern Europe, the zone-adapted variable-depth tillage of the soil in field crop rotation systems with the use of all types of implements (chisel plough, plough, subsurface blade cultivator, heavy cultivator, disc tiller, compactor etc.) has been prevailing and, according to the long-term forecasts, will continue to dominate in the future. There are high hopes for the use of multifunctional modular combine units with the aim of the sparing use of resources and energy per unit of marketable output and the comprehensive remediation of agronomic landscapes. The need to substantially update the primary agronomic process procedures and tools is becoming relevant in view of the undesirable climate aridisation, the technical modernisation of the field husbandry, the universally adopted use of crop husbandry by-products in the capacity of fertilisers and also – due to the conflicts of the land laws (Farooq & Siddique, 2014; Kolomiiets et al., 2019; Kaminskyi et al., 2021).

The aim of the current study was to improve the performance of alternative tillage and fertilization systems in the grain crop rotation cycles used in the grey forest soil of the Forest Steppe region.

MATERIALS AND METHODS

The research was carried out over the 2016–2020 period in the stationary experimental field of the Department of Tillage and Weed Control, NAAS Institute of Field Husbandry National Research Centre, established in 1969 in the grey forest coarse dust and light loam soil in the northern area of the Right Bank Forest Steppe region. This paper refers, in particular, to the results of the sixth stage (reconstruction) of the stationary two-factor experiment: 5 alternative tillage systems using different production processes × 3 fertilization systems in the short grain crop rotation cycle, specifically: winter wheat – grain maize – spring barley – soybean.

The tilled soil layer (within the depth range of 0–45 cm) featured low natural fertility, because the grain-size composition was dominated by the fine sand fraction (53–56%), while the contents of silt particles (13–18%) and physical clay (22–24%) were insufficient for accumulative paedogenesis. That had been proven by the high steady-state bulk density equal to 1.50 ±0.1 g·cm^{-3}, the low humus content at a level of 0.9–1.3%, the sub-acid reaction of the soil solution at pH_{kcl} – 5.1–5.4; H_r – 1.7–2.0 mg·(eq.)$^{-1}$ per 100 g of soil, the low base saturation rate (V – 75–79%), the insufficient content of exchange potassium (70–120 mg·kg^{-1} of soil) and the high content of labile phosphorus (165–180 mg·kg^{-1}) according to the Kirsanov method. The following soil ecology indices had also been taken into account: the field water capacity at 22%, the available water range at 17%, the soil workability state water content at 14.5%, the annual total photosynthetically active radiation at 2.000–2.100 MJ·m^{-2}, the total of effective temperatures > 10 °C at 2.500 °C, the total precipitation at 350–670 mm, the hydrothermal factor at 0.8–1.3, the average soil quality index at 41–47 points, the bioclimatic potential at 2.1 (100 points).

The total area of a single plot was 200 m^2, the recorded area – 48 m^2. The field experiment investigations were carried out with three replications using a split-plot design. In the design, the experiment alternatives were arranged in three rows systematically shifted relative to each other. The primary soil tilling was done with the use of PN-3-35 plough, PCh-2,5 chisel plough, PShchN-2,5 subsurface slitting cultivator, KPE-3,8 heavy erosion-preventive cultivator and BD-2,4 disk tiller. For the pre-sowing cultivation, an AKG-3 combined pre-sowing unit was used.

The following released cereal crop varieties were grown in the experiment: Polesskaya 90 winter wheat; Sontsedar spring barley; Arnica and Muza soybean; Oster mid-season maize hybrid. In order to protect the sowed plants against weeds, pathogenic agents and pests, an integrated protection system employing the present-day inventory of pesticides was used.

The statistical validity of the research results was assessed in terms of their variation range, standard deviation (*S*) and coefficient of variation (*V*, %) with the use of the PC and the Statistica 6.1 software.

RESULTS AND DISCUSSION

The agronomic meteorological conditions in the growing period (April-September): the mean monthly air temperature (18 °C) was 2.4 °C higher than the long-term standard air temperature, while the precipitation was noticeably deficient comparing to the long-term standard – 156 mm against the normal 379 mm. At the same time, substantial variations were recorded in the atmospheric soil moistening: excessive – by a factor of 1.5–2.0 (May 2016 and 2020, June 2018); insufficient (– 42–44% during June-July) and critically deficient – in August, when the long-term mean precipitation was equal to mere 22 mm (one third of the standard figure).

The type of the soil-forming process that takes place under the conditions of its cultivation directly depends on the input of the energy material – the mass of by-products, which in the experiments varied within the range of 9.16–11.05 $t \cdot ha^{-1}$ (Table 1) reaching the maximum in the case of the combined tillage system and incrementally decreasing after the conventional mouldboard ploughing (– 6%) and deep and shallow subsurface loosening (– 8.0 and – 12.9%, respectively). In the yield of the post-harvest plant biomass, the share of top residues reached 61.7–62.3%, the rest was root residues.

The mathematical assessment of the mass of by-products by means of statistical analysis has proven that the mass of plant residues on the average for the experiment was within the range ($\bar{X} \pm S\bar{x}$) of 6.24 ± 0.21 at a standard deviation (*S*) of 0.48 $t \cdot ha^{-1}$. The average mass of root residues was significantly smaller, it was equal to 3.81 ± 0.11 $t \cdot ha^{-1}$ at a standard deviation of 0.26. It should be noted that both the indices featured insignificant variation, as indicated by the coefficients of correlation equal to 7.6 and 6.7%, respectively.

Taking grain maize cultivation (the most intensive primary tillage system) as an example, it has been established that only deep ploughing ensures the relatively uniform distribution of the unmarketable part of the preceding winter wheat harvest in the 0–30 cm layer. In the case of subsurface (non-mouldboard) tillage models, especially the annual disk harrowing to a depth of 6 to 12 cm, the

Table 1. Mass of by-products in crop rotation farming with different tillage systems [$t \cdot ha^{-1}$], 2016–2020

Primary soil tillage	Mass of unmarketable part of harvest			± to (from reference)$^{-1}$
	Aftermath residues	Root residues	Total plant residues	
Mouldboard variable-depth to depth of 10–30 cm (reference)	6.53	3.96	10.49	–
Subsurface blade variable-depth to depth of 10–30 cm	6.12	3.75	9.87	-5.9
Adaptive to depth of 10–45 cm	6.89	4.16	11.05	5.3
Shallow disk to depth of 10–12 cm	6.02	3.68	9.70	-8.0
Surface disk to depth of 6–8 cm	5.66	3.50	9.16	-12.7
$\bar{X} \pm S\bar{x}$	6.24±0.21	3.81±0.11	10.05±0.33	–
V, %	7.6	6.7	7.3	–
S	0.48	0.26	0.73	–

Note: mean air-dry weight for four crops against organic and mineral background, that is, by-products + $N_{70}P_{58}K_{68}$.

typical result is the near-surface concentration (73–82%) of the mass of by-products and simultaneously the energy exhaustion of the 10–30 cm soil layer (Fig. 1).

The research carried out in the past resulted in determining the optimum bulk density of the tilled soil layer in the period of active organogenesis: winter wheat 1.23–1.38 g·cm^{-3}, spring barley, panicum, sugar beet and maize – 1.10–1.36 g·cm^{-3}. At the end of the crop growing period, it is acceptable for the soil to become compacted to a level of

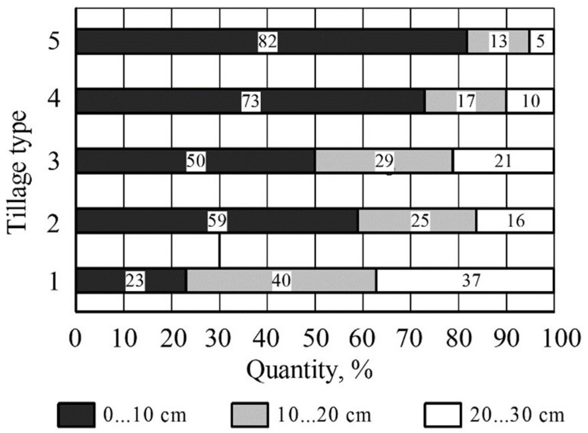

Figure 1. Distribution of winter wheat after harvesting residues between soil layers after tilling soil for grain maize [% of total mass of residues], 2016–2020: 1 – 28–30 cm ploughing; 2 – 28–30 cm subsurface blade tillage; 3 – 42–45 cm chisel tillage; 4 – 10–12 cm disk tillage; 5 – 6–8 cm disk tillage.

1.45–1.50 g·cm^{-3}. This is directly related to the actual averaged (four crops) dynamics of the bulk soil density in relation to the applied tillage system (Table 2).

In particular, a significant decrease has been observed in the compaction of the 0–10 cm layer by the time of complete seedlings: from 1.36 g·cm^{-3} (variable-depth ploughing in crop rotation) to 1.27–1.28 g·cm^{-3} after applying combined and subsurface blade soil tillage technologies, further to 1.25–1.26 g·cm^{-3} in the case of annual shallow disk tillage in crop rotation. That is, the decompression effect due to the near-surface concentration of the aftermath plant residues from the preceding crops has been observed in practice.

In the middle of the crop growth period (time of flowering-grain formation) the above-mentioned relation becomes levelled off. At the same time, in the case of long-term non-mouldboard tillage to a depth of 6 to 12 cm, the lower part of the active root habitable layer (10–40 cm) remains compact at the first two recorded stages (1.36–1.50 g·cm^{-3}), as compared to the ploughing case (1.32–1.43 g·cm^{-3}), while by the time of harvesting it becomes abnormally over-compacted (1.52–1.56 g·cm^{-3}), which is due to the worse accumulation of the atmospheric precipitation by the soil in the case of constant shallow non-mouldboard soil tillage (Marshall et al., 1996; Jury & Horton, 2004; Shukla, 2014; Souza et al., 2021).

Table 2. Bulk soil density in main grain crop growth stages, 2016–2020

Systems of soil tillage in crop rotation	Soil layer cm	Bulk density, g·cm^{-3}		
		Seedlings	Flowering	Complete ripeness
Mouldboard variable-depth, 10–30 cm	0–10	1.36	1.38	1.44
	10–20	1.32	1.36	1.42
	20–30	1.39	1.43	1.49
Subsurface blade, variable-depth, 10–30 cm	0–10	1.28	1.34	1.41
	10–20	1.35	1.40	1.48
	20–30	1.43	1.47	1.52
Adaptive, 10–45 cm	0–10	1.27	1.32	1.40
	10–20	1.34	1.39	1.45
	20–30	1.40	1.44	1.50
Shallow disk, 10–12 cm	0–10	1.25	1.35	1.39
	10–20	1.36	1.45	1.50
	20–30	1.45	1.49	1.54
Surface disk, 6–8 cm	0–10	1.26	1.35	1.40
	10–20	1.38	1.47	1.52
	20–30	1.47	1.50	1.56

Note: against background of mean by-product amount used in crop rotation at 6.5–7.0 t·ha^{-1} + $N_{70}P_{58}K_{68}$.

The conclusion of the above-said is that the theoretically possible increase of the mass of by-products from 3.0 t·ha^{-1} (soybean) to 20.0 t·ha^{-1} (maize) is accompanied by the temporary decompaction of only the 0–10 cm soil layer (by 0.1 g·cm^{-3} or 4.9%). The cause of that is obvious – the mass of the edatope solid phase is almost 75 times greater than that of the plant residues. Moreover, the latter are subject to continuous three-dimensional (physical and biochemical) destruction, which minimizes the expected development of the "skeleton effect". This conclusion does not apply to the technologies of direct sowing with the projective cover of the soil surface with plant residues at more than 70–80%, where mulching, shading, micro-climate etc. work in unison.

It should be noted that such an index of the physical mechanical properties of the soil as its hardness, is of great informative value, because it adequately and promptly diagnoses the forces required for wedging, shearing, cutting and crumbling in the operation of the tilling implement as well as the seed germination conditions and the possibility for root fibrillae to "populate" the inter- and intra-aggregate space. It is generally accepted that for high quality crumbling, the mechanical impact by the implement has to be in accord with the total shearing and rupture resistance and cohesion of the soil aggregates with minimal parameters at the lower plastic limit point (0.6–0.9 HB or 2.94–3.24 MPa for absolute measurement of the researched edatope). Depending on the agronomic background, the hardness of tilled soil has to be within the range of 0.2–0.59 MPa. The tentative optimal parameters of the soil hardness, at which the additional loosening becomes unnecessary for the majority of chernozem soil types, are as follows: primary tillage for winter crops < 0.98 MPa, for spring crops 0.98–1.96 MPa, pre-sowing cultivation 0.49–0.78 MPa, interrow cultivation 0.39–0.54 MPa, hardness of the plough pan < 2.94 MPa (Medvedev, 2013). Regrettably, there is no data here about the required phytosanitary soil conditions and the use of different masses of by-products.

In Figure 2, the soil hardness diagrams are presented for a tilled soil profile in the area of maize drills against the organic and mineral agronomic background. It has been established that at the initial stage (seedlings), the hardness of the 0–10 cm soil layer does not depend on the tillage method and is insignificant – 0.21–0.42 MPa (Borys & Küüt, 2016). The 10–30 cm soil layer after shallow disk tillage differs substantially by its higher mechanical resistance equal to 0.36–0.64 MPa, as compared to the other primary soil tillage systems. In the adaptive tillage system used in crop rotation, after a single use of chisel ploughing before sowing grain maize, the minimal weighted mean hardness of the 0–30 cm soil layer settles at a level of 0.34 MPa, which is by 37% lower, than in the case of annual ploughing.

At the complete grain ripeness stage, the penetration resistance of the upper 0–15 cm soil layer in the case of deeper tillage systems increases to 1.27–1.47 MPa, after

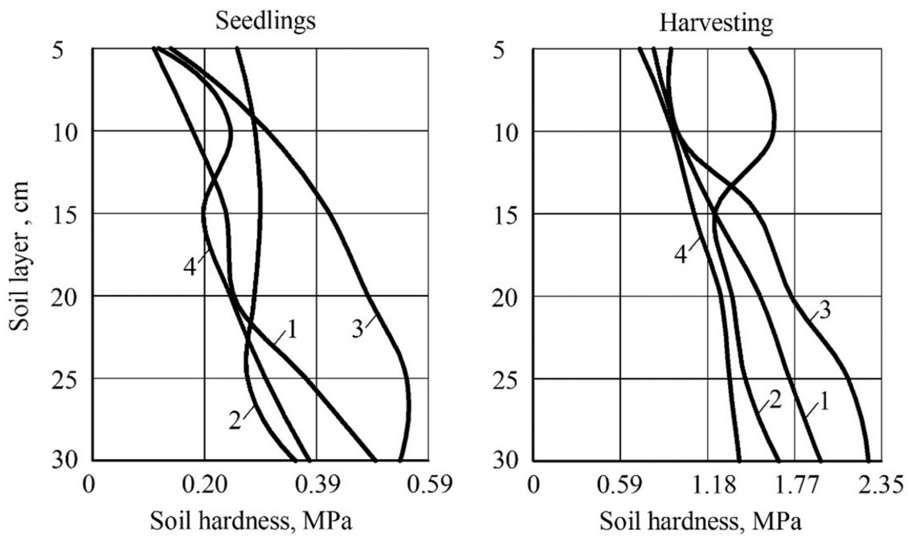

Figure 2. Soil hardness in grain maize field in relation to primary tillage system and use of by-products as fertiliser, MPa, 2016–2019: 1 – 28–30 cm ploughing; 2 – 10–12 cm disk tillage; 3 – 28–30 cm subsurface blade tillage; 4 – 42–45 cm chisel tillage

shallow disk tillage – to 0.78 MPa, but deeper in the profile (18–30 cm) – to 1.78–1.96 MPa and a critical limit of 2.45 MPa, respectively, in inverse relation to the soil water content.

For assessing the soil water content parameters of the experimental field, the own criteria have been used basing on the optimal hydrological conditions of a field: water permeability > 60 mm·h^{-1}, available water reserve within the range of 0.6–1.0 of field water capacity in the 0–40 cm soil layer – 47–70 mm and 170–220 mm – in 1 m layer, precipitation assimilation factor > 0.7, water content of the aeration zone 15–23%, of the soil workability state – 14–15%.

The initial reserve of soil water (Table 3) at the stage of the spring resumption of winter wheat growth in the 0–40 cm soil layer against the background of variable-depth tillage in crop rotation (108 mm) significantly exceeded the level of the subsurface blade cultivation system (8%), the shallow disk tillage (14%) and to the maximum – after surface disk tillage (16%). The same pattern was observed in the 1 m soil layer: 200, 178 and 162–168 mm, respectively. Therefore, decreasing the depth of non-mouldboard soil loosening impairs the inter-seasonal atmospheric precipitation assimilation by 11–19% and has a negative effect on the ontogenesis of plants at the stages of full tillering – stem elongation.

By the time of harvesting, the reserve of available water in soil substantially decreased with all tillage systems, while partial differences between alternatives were observed as a result of the unequal water consumption by the plants for producing a unit of biomass.

The satisfactory provision of water in the 0–40 cm active root habitable layer in this period (45–68 mm), which was, however, different among the alternatives, indicated the characteristics of the aftereffect on the reproduction processes and the final yield of winter wheat produced by each of the tested soil tillage systems. In the cases of variable-depth subsurface blade and shallow disk cultivation, the water stock averaged for the growth period was 4–16% lower in comparison to the traditional and adaptive soil tillage technologies. The critical dehumidification of the soil (–15 – 23% in the 0–40 cm soil layer and 14–19% in the 0–100 cm soil layer) was observed as a result of long-term surface disk tillage in crop rotation, which correlated with the deterioration of the physical condition of soil in this case.

In the field of spring barley, the initial reserve of available water (0–40 cm) was equal to 70–98 mm – a sufficient level for the vital functions of plants, irrespective of the tested soil tillage models, while the maximum humidification of the soil profile (0–100 cm) was provided by the differentiated tillage in crop rotation. In particular, a positive aftereffect (restoration of favourable agrophysical condition of the soil) was produced by deep chiselling before sowing grain maize – 179 mm, which was by 23–44 mm or 17–32% greater than in the case of long-term subsurface blade or disk tillage.

In the course of the barley grain formation, the whole root habitable soil layer was to a significant extent drying out as a result of the undesirable combination of the biotic and natural factors: the intensive water consumption by the plants and the deficit in atmospheric precipitation in May-June (25–41% of the normal amount). The great residual water stock both in the 0–40 cm (60–73 mm) and in the 0–100 cm (90–108 mm) layers

Table 3. Reserve of available soil water in grain crop plantings at different primary tillage systems, mm, 2016–2020

System of soil tillage in crop rotation	Soil layer, cm	Winter wheat		Growing period average			Spring barley		Growing period average		
		Growth resumption	Harvesting	mm	± to (from reference)$^{-1}$		Seedlings	Harvesting	mm	± to (from reference)$^{-1}$	
					mm	%				mm	%
Mouldboard variable-depth,10–30 cm	0–40	108	68	88	–	–	96	63	80	–	–
	0–100	200	84	142	–	–	172	90	131	–	–
Subsurface blade, variable-depth, 10–30 cm	0–40	100	48	74	–14	–16	82	71	77	–3	–4
	0–100	178	62	120	–22	–16	153	103	128	–3	–2
Adaptive, 10–45 cm	0–40	97	65	81	–7	–8	98	73	85	6	7
	0–100	180	90	135	–7	–5	179	108	143	12	9
Shallow disk, 10–12 cm	0–40	89	65	77	–11	–12	70	60	65	–15	–19
	0–100	162	70	116	–26	–19	135	90	112	–19	–14
Surface disk, 6–8 cm	0–40	91	45	68	–20	–23	77	64	70	–9	–12
	0–100	168	62	115	–27	–19	156	93	125	–6	–5

Note: against background of using by-products in crop rotation at mean amount of 6.5–7.0 t·ha^{-1} + $N_{70}P_{58}K_{68}$.

can be explained by the strong July rains (2017–2018) as well as the insignificant water consumption by the plants at the end of their growth, when the water was well preserved under the cover of the plant mulch produced by the ripening haulm stand of the crop.

In the case of the adaptive soil tillage system, the conditional mean accretion of water stock in the 1 m soil layer in the course of the growth period (143 mm) was greater by 3–9 mm or 9–28%, than in any of the alternative cases. The water accumulation potential of deep chiselling (43–45 cm) was obviously fulfilled in the grain maize field, where the weighted mean available water stock in the 0–100 cm layer was equal to 189 mm, which was greater by 13–34% (12–48 mm) than the respective figures of the plough, subsurface blade and disk tillage of the soil.

The excessive dehumification of agronomic soils indicates that the mineralisation processes aimed at developing the productivity of agrocenoses prevail over the compensation of the organic matter loss by means of adequately returning the unmarketable part of the harvest into the soil. Although the supply of organic carbon rises in this case by a factor of 1.5–3.0 relative to the classic organic fertilizers, until now, no valid replacement for the latter has been found [FAO. 2014].

It has been proven by special pilot studies that the localised embedding of litter manure, crop husbandry by-products, mineral fertilisers and chemical amendments into the zone of relatively stable hydrothermal conditions (8–13 cm layer) or at least into the upper half (0–15 cm) of the arable layer is a suboptimal model for their use. In effect, the described approach implies some kind of composting the soil-and-fertiliser mixture with an aim of adjusting the processes of the destruction-synthesis-release-assimilation of fertiliser elements contained in different-quality organic and mineral components.

At the end of the four-field crop rotation period, the distinct non-uniformity of the soil profile with regard to the humus content was recorded (Fig. 3). At the same time, the total stock of humus (0–40 cm) in the case of mouldboard (reference) and combined soil tillage systems turned out to be identical for practical purposes (64.6–66.0 t·ha^{-1}), while the non-mouldboard tillage resulted in the decrease of the figure by 6.0–6.9%.

The conclusion is that the rational agronomic technology solutions provide for the non-deficit, but only simple reproduction of C_{org} in grey forest soils, taking into account the genetic limitations for its accumulation and the equality of the microbiologic transformation processes that both the organic matter in the soil and the plant biomass undergo. There is an alarming fact of the significant deterioration observed in the humification that takes place in the 20–40 cm soil layer against the background of alternative non-mouldboard tillage systems (–10.3–16.4%).

It has been proven that the use of by-products has a positive effect not only on the physical properties of the soil, but also improves the nutrient conditions in it to a considerable extent. The average return into the soil with aftermath residues per annum per ha of land in crop rotation: 103–116 kg of nitrogen, 31–37 kg of P_2O_5 and 81–96 kg of K_2O. The maximum enrichment

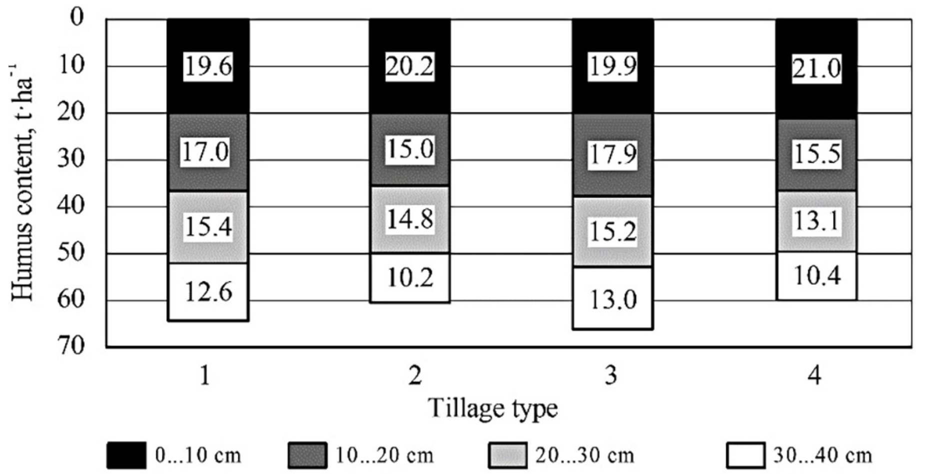

Figure 3. Layer-by-layer differentiation of humus reserve [t·ha^{-1}] in different soil tillage systems used in crop rotation (as of August 2020), against background of by-product use in crop rotation at 6.5–7.0 t·ha^{-1} + $N_{70}P_{58}K_{68}$: 1 – mouldboard ploughing; 2 – subsurface blade tillage; 3 – adaptive tillage; 4 – shallow disk tillage

of the soil with nutrients was observed in the case of the mouldboard and adaptive tillage systems – 238–249 kg•ha^{-1} of NPK. In the case of subsurface blade tillage of the soil their amount decreased by 4.7–8.9%, after long-term shallow and surface disk tillage – by 7.6–11.7% and 10.6–14.0%, respectively.

The annual debit of nitrogen in crop rotation due to the entered by-products amounted to 432 kg•ha^{-1}, phosphorus – 136 and potassium – 356 kg•ha^{-1}. The following input of each crop in the recirculation of the soil nutrient pool seems to have been present, in ascending order: soybean 5.6–16.0%, spring barley – 21.4–24.4%, winter wheat –15.2–21.1% and grain maize – 40.6–54.8% (Fig. 4).

Once again, it should be noted that the soil profile features abnormal (excessive) layer-by-layer differentiation with regard to the contents of nitrogen, available phosphorus and exchange potassium against monotype (long-term) disk tillage backgrounds with disking to depths of 6 to 12 cm. On the face of it, it is good that the fertility of the 0–15 cm surface layer theoretically increases. However, the 20–40 cm layer, quite the reverse, is continuously becoming poorer and the regression from this phenomenon is noticeable, because the artificial contraction of the humus-accumulated horizon brings about the depression in the development of root systems, the dependence of the soil and plants on the instantaneous weather conditions increases, which results in the decline of the potential and effective soil fertility and the overall productivity of the experimental agrocenoses.

The calculated balance of mineral elements in the four-field grain crop rotation cycle (Table 4) indicate the equally slightly deficient provision of plants with nitrogen (–14 kg•ha^{-1}) in the case of both the traditional and adaptive tillage systems and a trend of its deterioration (–16–21 kg•ha^{-1}) after using non-mouldboard tillage systems, first of all, surface and shallow loosening with the use of disk implements. The intensity of balance of the key organogenic element (N) is equal to 88 and 81–86%, respectively.

The surficial concentration of mineral fertilisers, grain cenosis by-products and soil microbiota in the case of the absent soil layer overturning allegedly brings about favourable conditions for the phosphorus and potassium contents in the soil and plants, as proven by the data on their balance intensity (181–187% P_2O_5 and 138–143% K_2O). These figures exceed the ones observed in the case of the conventional mouldboard and advanced combined soil tillage systems by 26–32 and 14–19%, respectively. In reality, the mobile compounds of phosphorus and potassium are apparently assimilated

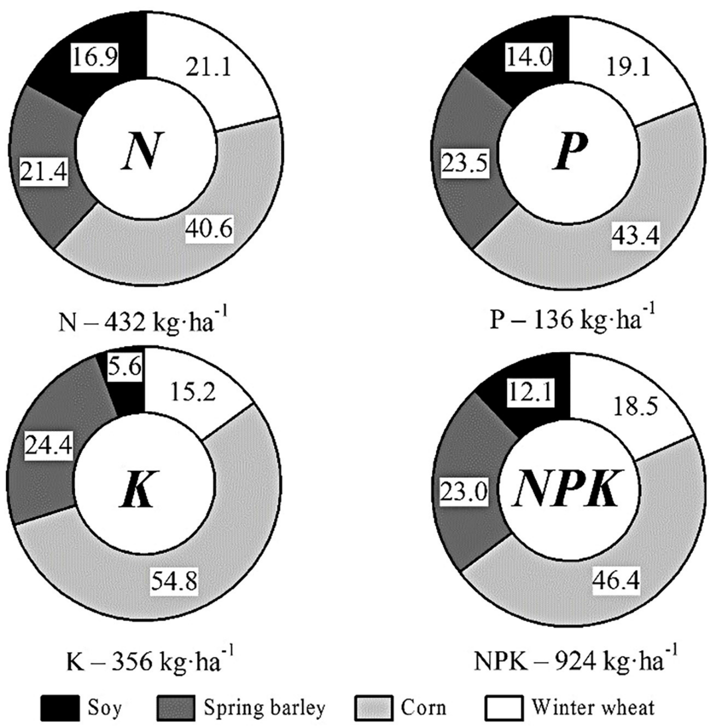

Figure 4. Structure of mineral element recirculation with by-products of crops in grain crop rotation [%], 2016–2020 (against background of by-products used in crop rotation at mean amount of 6.5–7.0 t•ha^{-1} + $N_{70}P_{58}K_{68}$)

Table 4. Balance of mineral elements in grain crop rotation with different soil tillage systems, kg·ha^{-1}, 2016–2020

System of soil tillage in crop rotation	Nitrogen		Intensity of balance [%]	Phosphorus		Intensity of balance [%]	Potassium		Intensity of balance [%]
	Input	Consumption		Input	Consumption		Input	Consumption	
Mouldboard variable-depth, 10–30 cm (reference)	102	116	88	60	38	158	42	31	135
Subsurface blade variable-depth, 10–30 cm	96	112	86	58	32	181	42	30	140
Adaptive, 10–45 cm	104	118	88	62	40	155	41	33	124
Shallow disk, 10–12 cm	92	112	82	56	30	187	40	29	138
Surface disk, 6–8 cm	91	112	81	55	30	183	40	28	143

Note: against background of by-products used in crop rotation at mean amount of 6.5–7.0 t·ha^{-1} + $N_{70}P_{58}K_{68}$.

to a lesser extent in the first case because of the more strained hydrothermal conditions in the root habitable layer, while in the second case the above-mentioned major nutrient elements are taken up more intensively for the build-up of vigorous biomass, resulting in higher grain productivity of the crops under investigation.

The long-term application of non-mouldboard, in particular, surface and shallow primary soil tillage techniques strains to a considerable extent the herbological situation, first of all in the plantings of crops with low weed resistance – maize and soybean. In the experiment, the actual amount of grass species was as follows: barn grass varied across the range of models within the range of 8–120 pcs·m^{-2}, yellow-foxtail grass 4–42 pcs·m^{-2}; separate beds of couch grass – 1–4 pcs·m^{-2}. The occurrence of dicotyledonous weeds (wild radish, lamb's quarters, galinsoga parviflora, black nightshade, red-root amaranth) did not exceed 5–24 pcs·m^{-2}. In both the agrocenoses, a few-year, mostly grass-type weediness developed. The share of the grass synusia decreased from 93% (without fertilisers) to 65% (organic and mineral fertiliser system) with the adequate replacement (from 7 to 35%) by the annual dicotyledonous component. The first waves of weed seedlings were eradicated by means of cultivation before sowing the crop, in the post-emergence period – by chemical weeding with the use of herbicides admitted for application and corresponding to the structure of eradicate weeds. Their technical effectiveness reached 90–95%.

The research results have proven that, in the case the productive atmospheric precipitation occurs in the second half of the growth period, the quantity of weeds growing in the plantings of the above-mentioned crops against inalterably non-mouldboard tilled backgrounds is greater by 6–88%, than in the case of either the conventional mouldboard or combined soil tillage in crop rotation. The harmful effect of weeds in the reproductive organ formation period is proven by the averaged data on the accumulation of weed dry weight in the pre-harvesting period (Fig. 5). In turn, the minimum level of it (216 g·m^{-2}) was reached after differentiated tillage, after subsurface blade tillage it rose to 260 g·m^{-2} (+20.4%), the rise was especially strong against the background of surface and shallow disk tillage – to 299–378 g·m^{-2} or by 38.4–75.0%. It is indicative that, due to the powerful plant habit of maize and soybean against the organic and mineral fertiliser background and the weed shading effect, the weed load on the average for the soil tillage systems was equal to 183 g·m^{-2}, which was 1.4–2.0 times lower, than in the case of fertilising solely with the by-products of the predecessor or controlling (without fertilisation), respectively.

No distinct alternative-specific preference for the development and propagation of fungal diseases (blister smut, rust, Septoria blight, Cercospora blight) and insect pests (sod webworm, corn-worm, wheat thrips, red spider) has been found in the experimental grain and bean agrocenoses. Moreover, the spread and intensity of the attack on the crops by hazardous organisms did not exceed the standard economic harmfulness limits, that is, no additional measures were needed for controlling them.

The yield capacity of the crops under investigation as the defining economic effectiveness

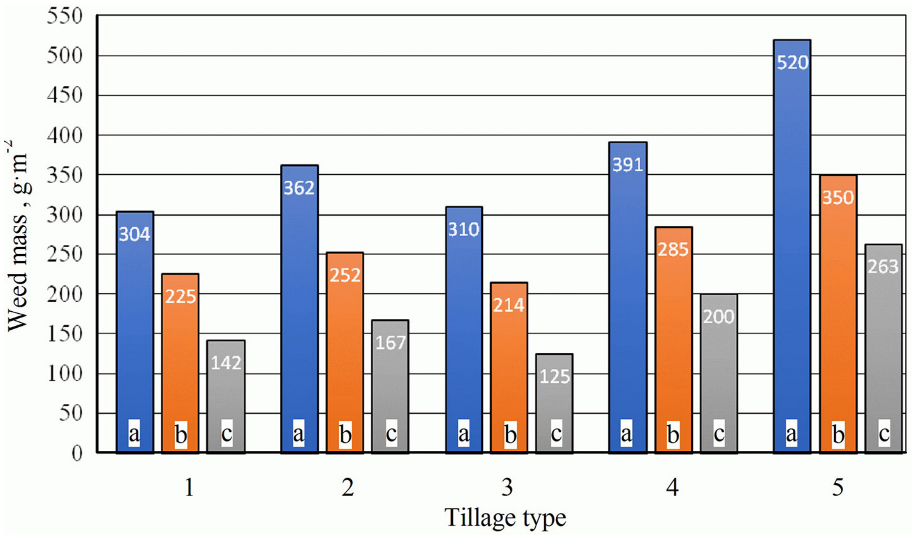

Figure 5. Average dry weight of weeds prior to harvesting maize and soybean in the case of different tillage and fertilisation systems [g m^{-2}], 2016–2020. Tillage system: 1 – mouldboard, variable-depth; 2 – subsurface blade, variable-depth; 3 – adaptive, variable-depth; 4 – shallow disk; 5 – surface disk. Fertilisation system: a – no fertilisation; b – by-products; c – by-products + NPK

criterion increased in proportion to the intensity of the agronomic background: natural fertility > fertilisation with by-products at 6.5–7.0 t·ha^{-1} > the same + $N_{70}P_{58}K_{68}$ in all soil tillage systems (Table 5).

The statistical analysis of the crop yield indices has proven that each of them had certain variation range and coefficient of variation. The yield of winter wheat had a medium coefficient of variation (V = 16.4%). The other crops featured significant variability, as indicated by the respective coefficients of variation (V = 24.7–34.2%).

In particular, the highest mean yield of winter wheat (5.0 t·ha^{-1}) was achieved with the use of the agronomic technology model based on shallow disk tillage (10–12 cm) within the framework of the system of adaptive tillage and organic and mineral fertilisation in crop rotation. The statistically equal grain productivity of the crop was provided by the mouldboard tillage system. In its turn, ploughing, first of all, against a balanced agronomic background, was significantly superior to the every-year shallow disk tillage (10%), variable-depth subsurface blade tillage (12.3%) and, especially, surface disk tillage (by 21.5% or 0.87 t·ha^{-1}).

Comparing to the reference case without fertilisation, fertilisation with by-products increases the crop yield capacity after ploughing by 30%, after surface and shallow disk tillage by 23.4–25.6% and after subsurface blade tillage – by 18%. Due to the additional application of $N_{80}P_{60}K_{80}$, the total increase in the winter wheat yield rose to 44.4%, 35.9–44.3% and 34.4%, respectively. However, the yield increase due to the additional application of solid mineral fertilisers did not exceed 11.0–13.8%.

Grain maize and soybean are less sensitive to the layer-by-layer differentiation of the soil fertility in view of the rather high grain crop yield, but that is true only subject to meeting the key requirement – to ensure the depth (22–45 cm) of the autumn ploughing that is biologically necessary for them with the use of a usual plough, a subsurface blade cultivator or a chisel deep tiller.

The maximum yield of both the crops (maize 8.89 t·ha^{-1} and soybean 3.17 t·ha^{-1}) on the average for 2016–2020 was obtained in the case of the alternatives with differentiated primary soil tillage (chisel tillage 43–45 cm and ploughing 22–24 cm, respectively) against the background of the organic and mineral fertilisation system and the input of soil-applied and postemergence herbicides. Despite their technological identity, the single-type shallow and especially surface disk loosening resulted in the substantial decline in the yield capacity of both grain maize (11–19%) and soybean – by 16–20%.

Special consideration is to be given to the fact that the chemical weed control in the plantings of grain cenoses is highly effective, as it enhances the performance of the other production methods in crop growing, in particular, in the case of maize

Table 5. Crop yield capacity and grain crop rotation productivity in relation to tillage and fertilisation system, 2016–2020

System of soil tillage in crop rotation (factor A)	Fertiliser (factor B)	Yield [t·ha⁻¹]					Productivity of crop rotation t ha⁻¹ grain units	± to (from reference)⁻¹		
		Winter wheat	Grain maize	Spring barley	Soybean	Mean		a	b	c
Mouldboard variable-depth, 10–30 cm (reference)	a*	3.40	4.69	2.13	1.52	2.94	3.04	–	–24.8	–44.6
	b*	4.42	5.96	2.81	2.17	3.84	4.04	32.9	–	–26.4
	c*	4.91	8.50	4.32	2.96	5.17	5.49	80.6	35.9	–
Subsurface blade variable-depth, 10–30 cm	a	3.25	4.87	2.20	1.35	2.92	3.00	–1.1	–25.7	–45.4
	b	3.84	6.14	2.37	1.87	3.56	3.72	22.4	–7.9	–32.2
	c	4.37	8.15	4.14	2.81	4.87	5.18	70.4	74.3	–5.6
Adaptive, 10–45 cm	a	3.63	5.02	2.55	1.54	3.19	3.28	7.9	–18.8	–40.7
	b	4.49	6.36	2.93	2.06	3.96	4.12	35.5	2.0	–25.0
	c	5.00	8.89	4.45	3.17	5.38	5.72	88.2	41.6	4.2
Shallow disk, 10–12 cm	a	3.28	4.75	2.07	1.22	2.83	2.92	–3.9	–27.7	–46.8
	b	4.12	5.68	2.57	1.69	3.52	3.65	20.1	–9.7	–33.5
	c	4.46	7.94	3.99	2.67	4.77	5.06	66.4	25.2	–7.8
Surface disk, 6–8 cm	a	2.80	4.16	1.78	1.02	2.44	2.56	–15.8	–36.6	–53.4
	b	3.47	5.31	2.23	1.44	3.11	3.28	7.9	–18.8	–40.3
	c	4.04	7.22	3.44	2.53	4.31	4.60	51.3	13.9	–16.2
$\bar{X} \pm S\bar{x}$		3.97 ±0.17	6.24 ±0.40	2.93 ±0.23	2.00 ±0.18	3.79 ±0.24	3.98 ±0.26	–	–	–
V, %		16.4	24.7	30.8	34.2	24.5	25.6	–	–	–
S		0.65	1.54	0.90	0.68	0.93	1.02	–	–	–

Note: *a – without fertilisers; b – by-products; c – by-products + NPK. Mean input over crop rotation cycle: by-products 6.5–7.0 t·ha⁻¹ + $N_{70}P_{58}K_{68}$.

by 26–30%, while in the case of soybean – by a factor of 1.9–2.3. The conclusion is that no-herbicide technology of growing the latter is just economically inadvisable.

Spring barley positively responds to the concentration of the physical, agrochemical and biological components of fertility in the upper part of the tilled topsoil. That is the exact cause of the fact that the maximum yield of the crop (4.45 t·ha⁻¹) was achieved after carrying out one-time disking to a depth of 10–12 cm with the aftereffect of the deep chisel ripping that had been done for the preceding maize. The only exception was the invariable surface soil tillage in crop rotation, in which case even with the organic and mineral fertilisation system the shortfall in the grain harvest was at a level of almost 24%. Alongside the bundle of problems stipulated by the sharp differentiation in the fertility of the humus horizon, the difficulties have also been noted in the performance of high quality sowing with the use of a standard grain seeder caused by the presence of great amounts of plant residues in the near-surface soil layer.

The effectiveness and complementarity of the agronomic engineering measures applied in the experiment has been proven by the wide range of variation in the actual crop yield (2016–2020): winter wheat 2.80–5.05 t·ha⁻¹ (mean value $\bar{X}$ 3.96 t·ha⁻¹), grain maize 4.1–8.89 t·ha⁻¹ ($\bar{X}$ 7.22 t·ha⁻¹), spring barley 1.78–4.45 t·ha⁻¹ ($\bar{X}$ 3.44 t·ha⁻¹) and soybean 1.02–3.17 t·ha⁻¹ ($\bar{X}$ 2.0 t·ha⁻¹). That is, depending on the resource and engineering support, under the conditions of Right Bank Forest Steppe, credible possibilities exist for the further improvement of productivity of main grain crops.

The average grain crop yield in crop rotation against the agronomic background of no fertilisation is equal to 2.8 t·ha⁻¹, with the input of 6.5–7.0 t·ha⁻¹ of plant residues from the predecessor – 3.6 t·ha⁻¹ (126%) and in case of their application in combination with $N_{70}P_{58}K_{68}$ – 4.90 t·ha⁻¹ (171%).

Almost 25% increase in the productivity, when the best model of combined soil tillage (5.38 t·ha⁻¹) is compared to the relatively worst one – surface disk tillage (4.31 t·ha⁻¹), even when correct organic and mineral nutrition is provided for the plants, convinces that exactly adaptive (dynamic) primary tillage technologies are the ones to be chosen for application.

In the weighted mean amount of the harvested marketable grain equal to 15.1 t•ha^{-1} per annum, the share of winter wheat is equal to 26.7%, maize – 41.2%, spring barley – 19.1% and soybean – 12.9%. Such breakdown among crops is also typical for the tested soil tillage models, in accordance with the actual yield capacity: maize – 38.8–43.2%, winter wheat – 22.4–29.3%, spring barley 16.7–21.3%, soybean 10.5–14.7%.

The productivity of the crop rotation system under investigation correlates with the dynamics of the yield capacities of individual crops in the tested alternatives, but with 10–15% surplus above the estimate rated parameters: when using the natural fertility (without fertilisers) – 2.96 t•ha^{-1} of grain units; against the background of biologic fertilisers (use of by-products) – 3.76 t•ha^{-1} of grain units (+27.1%); against the organic and mineral fertilisation background on the average for the five alternative soil tillage systems – 5.21 t•ha^{-1} of grain units (+76.1%).

Thus, the consolidation of natural and anthropogenic factors activated by mechanical soil cultivation facilitates (in accordance with the agronomic background) improving the initial biologic potential of a hectare of plough land by a factor of 1.3–1.8.

The minimum productivity of the crop rotation cycle within the range of fertilisation backgrounds (2.56–4.60 t•ha^{-1} of grain units) has been recorded for the most simplified continuous disk tillage to a depth of 6–8 cm, the maximum one (3.28–5.72 t•ha^{-1} of grain units) – in the case of clear differentiation of both the techniques and depths of soil tillage in accordance with the distinctive agrobiological features of each crop: disk tillage (10–12 cm) for winter wheat; strip chisel tillage (43–45 cm) for grain maize; disk tillage (10–12 cm) for spring barley and mouldboard ploughing (20–24 cm) for soybean, subject to indispensable rationalisation of the fertilisation system and protection of plantings against hazardous organisms.

The mean productivity of the crop rotation cycle in the case of such primary tillage differentiation is equal to 4.37 t•ha^{-1} of grain units, which exceeds the level of the conventional variable-depth ploughing by 4.0%. At the same time, the long-term variable-step minimisation – application of the variable-depth subsurface blade, shallow and especially surface disk tillage systems – results in a substantial decrease (by 0.54–1.12 t•ha^{-1} of grain units or 10.4–24.3%) in the productivity of the crop rotation cycle. The priority in the updated model of adaptive soil tillage is given to the multiple-vector remediation of old arable edaphotopes and the agrobiological production processes towards self-reproduction (homoeostasis), ecophilia, efficiency, resource and energy conservation in agronomic technologies. That is supported by the results of the earlier research performed by other authors in 2012–2018 (Kravchuk et al., 2019).

The expert appraisal of the economic efficiency achieved with the use of the experimental agronomic technologies mostly coincides with the theoretic indices obtained for the yield capacities of individual crops and the productivity of the overall crop rotation cycle in the tested alternatives. The scope of this paper is limited to the thesis accents on the performance of the alternative tillage and fertilisation systems in monetary terms.

The analysis of data on the economic efficiency has revealed (Table 6) that the mean grain production cost for the four crops in crop rotation (117 €•t^{-1}) is kind of the median value for the anthropogenic load and the actual biological productivity present in the discussed agronomic technology alternatives.

On the basis of the above, the minimum estimated cost value (107 €•t^{-1}) is typical for the purely organic fertilisation system due to the combination of high productivity and moderate process costs. In contrast, the technologies with no fertilisation or combining organic and mineral components, on account of upsetting that balance, cause the corresponding increase in the grain cost value – by 17 and 14 €•t^{-1} or by 15.8 and 13.1%, respectively.

The nominal earning power of one hectare in the crop rotation field closely correlates with the grain productivity: background “a” (reference) – 390 €, background “b” – 545 € (140%), background “c” – 652 € (167%). The average revenues from the use of the conventional mouldboard and subsurface blade tillage systems are by 6.7–14.1% (42–87 €•ha^{-1}) lower, than in the case of the adaptive model (617 €•ha^{-1}). The every-year shallow and surface disk tillage systems are significantly inferior to the best alternative (–17.1–33.6%).

In the structure of the total net revenue from the crop rotation cycle (2.114 €•ha^{-1} per annum) winter wheat accounts for 27.8%, grain maize – 35.1%, spring barley – 13.5% and soybean – 23.6%.

It has been established that in the total financial expenses connected with the implementation

Table 6. Economic efficiency of different soil tillage and fertilisation systems in grain crop rotation, 2016–2020

System of soil tillage in crop rotation (factor A)	Fertiliser (factor B)	Grain production cost [t·ha⁻¹]	Income [€·ha⁻¹]	± to (from reference)⁻¹			Level of profitability [%]
				a	b	c	
Mouldboard variable-depth, 10–30 cm (reference)	a*	3.577	406	–	-32.8	-43.3	128
	b*	2.979	604	81.1	–	-15.7	170
	c*	3.464	716	76.4	18.6	–	130
Subsurface blade variable-depth, 10–30 cm	a	3.560	407	0.2	-32.6	-43.2	133
	b	3.179	539	32.8	-10.8	-24.8	157
	c	3.607	644	58.8	6.7	-10.0	120
Adaptive, 10–45 cm	a	3.280	464	14.3	-23.1	-35.2	147
	b	2.941	624	53.9	3.4	-12.8	177
	c	3.398	761	87.6	26.1	6.3	139
Shallow disk, 10–12 cm	a	3.764	384	-5.4	-36.4	-43.4	126
	b	3.247	528	30.1	-12.5	-26.2	157
	c	3.679	622	53.3	3.1	-13.1	116
Surface disk, 6–8 cm	a	4.445	272	-33.0	-55.0	-62.0	93
	b	3.735	427	5.3	29.2	-40.3	127
	c	4.040	514	26.7	-14.8	-28.2	96

Note: *a – no fertilisation; b – by-products; c – by-products at 6.5–7.0 t·ha⁻¹ + $N_{70}P_{58}K_{68}$.

of the tested agronomic technologies the fertilisers account for 41%, pesticides – 26%, machinery and fuels and lubricants – 14%, seeds – 11%, electric power and manual labour – 8%.

The level of profitability of grain farming in the case of fertilisation with by-products amounts to 158%, while in the absence of fertilisers (low productivity) and against the organic and mineral background (excessive costs) its reduction by 20–25% at a mean crop rotation cycle parameter of 134% has been proven.

Due to the optimisation of the agrochemical components, the differentiated tillage system delivered the maximum (154%) technical and economic payback in the researched crop rotation system. On average, this value is greater by 11%, than in the case of the reference alternative (mouldboard ploughing) and by 17–49% – in comparison to continuous non-mouldboard tillage techniques.

Accordingly, it is obvious that the economic feasibility of growing grain in the edaphic and ecologic conditions of the Right Bank Forest Steppe region with regard to the discussed crops is as follows, in descending order: grain maize (163%) < winter wheat (146%) < soybean (132%) < barley (97%).

In the completed research, comprehensive original scientific factual data have been obtained on the transformation of the physical, agrochemical and biological condition and the effective and potential fertility of grey forest light loam soil within a crop rotation cycle (2016–2020). The research included an experiment with the following design: in the four-year grain crop rotation cycle, five alternative soil tillage systems with different techniques and tillage depths were applied against three alternative agrochemical backgrounds, which included the use of crop husbandry by-products as a fertiliser and moderate amounts of mineral fertilisers $N_{70}P_{58}K_{68}$.

The differentiation in the topsoil has been revealed with regard to its fertility criteria (distribution of after-harvest crop residues, bulk density, hardness, microbiological activity, humus content and reserve, potential weed infestation, availability of assimilable forms of NPK and balance of major nutrient elements) in the case of continuous non-mouldboard tillage, especially superficial and shallow disking.

The initial hypothesis that the priority is to be given to the evolutionary implementation of agricultural technological innovations has been confirmed. The evolutionary approach has to be based on the rational combination (depending on the crop rotation design and the cultivated crops) of adaptive tillage (with a variable depth of 10–45 cm), traditional ploughing, subsurface blade tillage, strip chisel primary tillage and disking, in conjunction with the optimal organic and mineral fertilisation system, an essential component of which is the utilisation of by-products after their composting and controlled biological destruction.

The agronomical technology optimisation ensures, depending on the agrochemical load, a 1.3–1.8 times increase in the mean productivity of the experimental crop rotation from 2.96 to 5.21 t•ha^{-1} of grain units with a variation range of 5.72–4.60 t•ha^{-1} of grain units after adaptive tillage (to depths 10–45 cm) and every-year superficial disking (6–8 cm), respectively, against balanced organic and mineral fertilisation backgrounds.

The technical and economic efficiency (cost effectiveness) of growing different grain crops is as follows: grain maize 163%, winter wheat – 146%, soybean – 132%, barley – 97%.

The results of the comprehensive research give evidence of the environmental, agrobiological and socioeconomic efficiency of applying adaptive (flexible) resource-saving soil tillage and fertilisation technologies in regional crop rotation systems, subject to the adequate technical, informational and navigational support throughout the complete crop production cycle.

Among the relevant publications on the discussed topic, the following are to be pointed out: Medvedev (2013) and Marandola et al. (2019).

In the studies by the scientists of the National Scientific Centre "O.N. Sokolovsky Institute of Soil Science and Agrochemistry Research under the National Academy of Agrarian Sciences of Ukraine" (Medvedev, 2013 and 2015), significant attention has been paid to the physical and physical-and-technological criteria of the advisable minimization in the tillage of soils of different origin (mostly chernozem soils). At the same time, they do not contain any data on the effectiveness (practical validation of the theoretical imperatives in the soil tillage rationalisation methods). Moreover, the extent of the possible introduction of the no-till technology is clearly overestimated. That said, the scientists of this scientific institution advocate the application of exclusively adaptive (combined) soil tillage systems (technologies) with due account for the whole set of edaphic-ecologic and socioeconomic conditions. Such an approach is in line with the main provisions of this paper.

Despite the certain informational boom around the innovative no-till technology, the Italian scientists have also expressed only reserved optimism with regard to the trend towards non-mouldboard tillage as an agrotechnological panacea. That is supported by the official statistics: as of April 2019, the no-till technology was applied throughout the world in an area of 156 mln•ha. That means just 11% of the world's cultivated land after half a century of the implementation of the supposedly revolutionary scientific concept.

A distinctive feature of this study is the long-term stationary experimental research that evolves in accordance with the socioeconomic needs of society and the concurrent situation.

The further theoretical and practical development of arable farming will most likely take place in the form of the efficient utilisation of the existing resources and facilities in the existing agricultural businesses, the gradual re-equipment of the agricultural industry with up-to-date machinery and the further rational implementation of the controlled transformation (biodestruction) technologies in order to make use of the crop husbandry by-products as a most important (in fact, the dominant) form of organic fertilisers with an aim of raising the soil fertility and utilising in full the biological potentials of agrocenoses.

CONCLUSIONS

1. The progress and direction of the mobilisation and regeneration edaphic and production processes in grain agrocenoses under stochastic unfavourable changes of the climate are determined by the specific interaction of the following factors: tillage-fertilisation-crop.
2. The near-surface concentration of mineral fertilisers, crop husbandry by-products, microbiota and weed seeds (in excess of 65%) in the case of long-term subsurface blade tillage and, especially, surface and shallow disk tillage in crop rotation results in the excessive layer-by-layer differentiation of the grey forest light loam soil with regard to its fertility ("enriched" 0–15 cm, "emaciated" 18–40 cm soil layers).
3. The adaptive (combined) and purely mouldboard soil tillage systems against a balanced organic and mineral fertilisation background are superior to the non-mouldboard alternatives as regards the total stock of humus and the intensity of balance of mineral nitrogen (88% and 81–86%, respectively). However, in the absence of mouldboard ploughing, the phosphorous and potassium conditions in the soil improve (up to 26 kg•ha^{-1} and up to 12 kg•ha^{-1}, respectively) with the corresponding improvement of the intensity of their balance (by 29% and 17%, respectively).

4. Uniform disk tillage, in view of its higher "provocative" capacity, strains the herbological situation, in particular, in the plantings of grain maize and soybean. Comparing to every-year ploughing and combined soil tillage, the number of weeds in the case of shallow and surface disk tillage is increased even in the pre-harvesting period by 6–88%, their mass – by 12–91%.
5. During the rotation cycle (2016–2020), the biological potential of the four-field grain crop rotation on the average for the five alternative soil tillage systems increases in proportion to the agrochemical load by a factor of 1.3–1.8: natural fertility – 2.96 t·ha^{-1} of grain units; fertilisation with by-products at 6.5–7.0 t·ha^{-1} – 3.76 t·ha^{-1} of grain units; the same + $N_{70}P_{58}K_{68}$ – 5.21 t·ha^{-1} of grain units.
6. The minimum productivity of the experimental crop rotation cycle (2.56–4.60 t·ha^{-1} of grain units, depending on the agronomic background) has been recorded in the case of continuous surface disk tillage (6–8 cm), its maximum level (3.28–5.72 t·ha^{-1} of grain units) – in the case of the adaptive soil tillage system: disk tillage (10–12 cm) for winter wheat; strip chisel tillage (43–45 cm) for grain maize; disk tillage (10–12 cm) for spring barley; ploughing (22–24 cm) for soybean.
7. The mean grain production cost in advanced agronomic technologies based on adaptive primary soil tillage techniques and organic and mineral fertilisation systems applied to the crops in rotation is equal to 113 €·t^{-1}, earning capacity – 761 €·ha^{-1} per annum, level of profitability – 139%, while in the case of the other tested alternatives, these indices are lower by 3–21 €·t^{-1}, 45–110 €·ha^{-1} per annum and 9–23%, respectively. The economic feasibility (payback) of growing grain crops in the edaphic and ecologic conditions of the Right Bank Forest Steppe region is as follows, in descending order: grain maize (163%) < winter wheat (146%) < soybean (132%) < barley (97%).
8. The results of the completed comprehensive research give evidence of the environmental, agrobiological and socioeconomic efficiency of using exclusively adaptive (flexible) resource saving soil tillage technologies in the crop rotation systems of the Forest Steppe region with the state-of-the-art technical and technological, information and navigation support throughout the whole crop husbandry production cycle.

REFERENCES

1. Baig, M.N., Gamache P.M. 2009. The Economic, Agronomic and Environmental Impact of No-Till on the Canadian Prairies. Alberta Reduced Tillage Linkages. Canada, 135.
2. Baker, J.C., Saxton, E.K., Ritchie, R.W., Chamen, T.C.W., Reicosky, C.D., Ribeiro, F., Justice, S.E., Hobbs, P.R. 2007. No-tillage seeding in conservation agriculture, 2nd Edition, Edited by Baker JC, Saxton EK, Typeset by AMA DataSet Ltd, Preston, UK, 326. Link: https://bit.ly/3fMw2y7
3. Borys, N., Küüt, A. 2016. The influence of basic soil tillage methods and weather conditions on the yield of spring barley in forest-steppe conditions. Agronomy Research, 14(2), 317−326.
4. Daponte, P., De Vito, L., Glielmo, L., Iannelli, L., Liuzza, D., Picariello F., Silano, G. 2019. A review on the use of drones for precision agriculture. – IOP Conference Series: Earth and Environmental Science, 275, 012022. DOI: 10.1088/1755-1315/275/1/012022.
5. Derpsch, R., Friedrich, T. 2009. Global Overview of Conservation Agriculture Adoption. Proceedings, Lead Paper, 4th World Congress on Conservation Agriculture,. 4–7 February 2009, New Delhi, India, 429–438.
6. FAO. 2014. The three principles of conservation agriculture. http://www.fao.org/assets/infographics/CA-principles-infographic.pdf.
7. FAO. 2015. Status of the World´s Soil Resources: Main Report. ITPS, Global Soil Partnership, Rome, Italy, 650.
8. Farooq, M., Siddique, K.H.M. (Eds). 2014. Conservation Agriculture. Springer International Publishing, Switzerland, 665. DOI: 10.1007/978-3-319-11620-4
9. Friedrich, T., Kassam, A.H. 2009. Adaption of Conservation Agriculture Technologies: Constraints and Opportunities. IV.
10. Glinski, J., Horabik, J., Lipiec, J. 2013. Agrophysics – physics in agriculture and environment. Soil Science Annual, 64(2), 67–80. DOI: 10.2478/ssa-2013-0012
11. Gonzalez-Sanchez, E.J., Veroz-Gonzalez, O., Blanco-Roldan, G.L., Marquez-Garsia, F., Carbonell-Bojollo, R. 2015. A renewed view of conservation agriculture and its evolution over the last decade in Spain. Soil & Tillage Research 146, 204–212. DOI: 10.1016/j.still.2014.10.016
12. Jury, W.A., Horton, R. 2004. Soil Physics, 6th Edition. Wiley, 384.
13. Kaminskyi, V., Gadzalo, J.M., Saiko, V.F., Kornichuk, M.S. 2015. Farming in the 21st century – problems and solutions. Edelweiss, 272. (in Ukrainian)
14. Kaminskyi, V., Kolomiiets, L., Bulgakov, V., Olt, J. 2021. An investigation into the state of agricultural

lands under water erosion conditions. Agronomy Research, 19(2), 458‒471. DOI: 10.15159/AR.21.029

15. Kassam A., Friedrich T., Derpsch R., Kienzle J. 2015 Overview of the worldwide spread of agriculture. Field Actions Science Reports 8, 1–11. htpps://jornals.openedition.org/facts.reports/3966
16. Kolomiiets, L.P., Shevchenko, I.P., Tereshchenko, O.M. 2019. Agroecological effectiveness of soil protection technologies in the system of contour-reclamation organization of land use. Bulletin of Agricultural Science 12, 5–12. (in Ukrainian) DOI: 10.31073/agrovisnyk201912-01
17. Kravchuk, V.I., Novohatsky, M.L., Gusar, V.G. 2019. Synthesis of technical and technological decisions for opening and use of resources of agrarian biosphere. Proceedings of UkrNDIPVT, 24(38), 193-2001. (in Ukrainian). DOI: 10.31473/2305-59-87-2019-1-24
18. Larocque, G.R. 2020. Ecological Forest Management handbook. 1st Ed. CRC Press, 624.
19. Lindwall, C.W., Sonntag, B. (Eds). 2010. Landscape Transformed: The History of Conservation Tillage and Direct Seeding. Knowledge Impact in Society. Saskatoon: University of Saskatchewan, 220.
20. Marandola D., Belligiano A., Romagnoli L., Ievoli C. 2019. The spread of no-till in conservation agriculture systems in Italy: indicators for rural development policy-making. Agricultural and Food Economics, 7. DOI: 10.1186/S40100-019-0126-8
21. Marshall, T.J., Holmes, J.W., Rose, C.W. 1996. Soil Physics. 3dr Edition. Cambridge University Press, UK, 472.
22. Medvedev, V.V. 2013. Agro- and ecophysics. Harkov, Polesataya Publishing, 312. (in Russian)
23. Morgan, R.P.C. 2005. Soil Erosion and Conservation. Oxford: Blackwell Publishing, 304.
24. Morgan, R.P.C. 2006. Managing sediment in the landscape: Current practices and future vision. Soil erosion and Sediment Redistribution in River Catchments: Measurement, Modelling and Management, 287–295.
25. Shukla, M.K. 2014. Soil Physics. An Introduction. CRC Press, 478.
26. Souza, R., Hartzell, S., Ferraz, A.P.F., Almeida, A.Q., Lima, J.R.S.L., Antonino, A.C.D., Souza, E.S. 2021. Dynamics of soil penetration resistance in water-controlled environments. Soil and Tillage Research, 205, 104768, DOI: 10.1016/j.still.2020.104768
27. Stanojevic, A.B. 2021. Conservation agriculture and its principles. Annals of Environmental Science and Toxicology 5(1), 018.022. DOI: 10.17352/aest.00031
28. Tarariko, O.H., Ilienko, T.V., Kuchma, T.L., Novakovska, I.O. 2019. Satellite agroecological monitoring within the system of sustainable environmental management. Agricultural Science and Practice 6(1), 18–27.