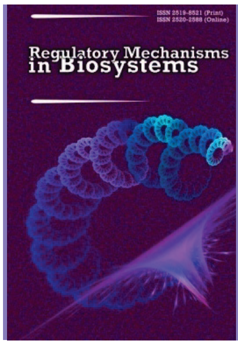

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Biological activity of soils in Ukraine depending on tillage options: A meta-analysis

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Tillage is one of the major factors affecting soil biological activity, resulting in changes in soil organic carbon (SOC) content, providing for carbon sequestration and shifts in carbon dioxide emission from soils. Current climate change and aggravation of global warming through the increased emission of carbon dioxide are main driving forces for global transformation of agricultural practices in the direction of climate-smart agriculture (CSA), which requires the implementation of such crop cultivation practices that result in the minimization of SOC losses and carbon dioxide emissions. The magnitude and direction of different tillage practices affecting soil biological activity are different, therefore, the best tillage options should be chosen for implementation in national CSA systems to ensure achieving the global sustainability goals. This nationwide meta-analysis, conducted for tillage practices utilized in Ukrainian agriculture examines scientifically recorded effects of moldboard tillage depth, flat cutter and no-till options on soil respiration rates and cellulose decomposition intensity in dark-chestnut and chernozem soils of Ukraine. This meta-analysis enrolled 45 studies, which met the stipulated scientific quality criteria. Statistical processing was conducted through the standardized mean difference (SMD) model without subgroups at 95% confidence interval (CI). As a result, it was determined that there is subtle impact of moldboard tillage depth on soil biological activity, which is inconclusive and unclear. The similar results were obtained for the comparison between the tillage and no-till groups, where high heterogeneity of the dataset (I^2 = 82.8%) resulted in low quality of evidence for the benefits of no-till in SOC sequestration. Besides, zero fail-safe numbers support the suggestion of low-quality evidence in favor of shallow plowing advantage over deep plowing, as well as no-till against tillage. As for the difference between the groups of moldboard and flat cutter tillage, it was established that there is strong enough evidence for the advantage of flat cutter tillage in terms of soil respiration rates and cellulose decomposition intensity reduction. Further studies in this direction are required to fill the gaps in current meta-analysis, especially in terms of no-till options and their effect on biological activity of Ukrainian soils in different cropping systems.

Keywords: carbon dioxide; cellulose decomposition; conventional tillage; emission; flat cutter tillage; no-till; tillage depth; subsoil tillage.

Introduction

Climate-smart agriculture (hereafter referred as CSA) is a response to the current climate crisis, connected with global warming, that focuses on technologies and practices that enhance adaptation, reduce greenhouse gas emissions, and contribute to food security (Hellin et al., 2023). This approach is often referred to as the "triple win" strategy and is promoted by the international regulatory bodies such as the World Bank and the Food and Agriculture Organization (FAO) on the global level (Taylor, 2017). Indeed, CSA approaches have proven their benefits on multiple levels in different ways, e.g., food quality improvement, better climate resilience, economic profitability, etc. (Sain et al., 2017). For example, in India, CSA encourages the practices of sustainable agriculture, increasing adaptive capacity and resilience to adverse climatic shocks at multiple levels, while the productivity of croplands remained almost unchanged (Aich et al., 2022). In China it is also believed that rational transfer to scientific CSA systems benefits not only greenhouse gas emission cuts, but also improves health of food products and strengthen national food security (Zhao et al., 2023). Looking at successful experience of other countries, Ukraine is also preparing its national agricultural sector to gradual transfer from an extensive way of manufacturing plant products to the CSA-based environmentally friendly and responsible approaches as this can help save costs, soils, and natural resources (Nikitenko & Averchev, 2021). However, this process in Ukraine is a little bit slower than in the Western-European countries, as most researchers and agricultural practitioners are focused mainly on getting the best crop productivity.Therefore, soil tillage systems in this regard are mainly estimated from the point of view of nutrients accumulation and availability for plants, as well as formation of optimal agrophysical parameters for root growth and moisture uptake, while soil biology remains beyond the scope of scientific interest (Tanchyk et al., 2022). A very small number of Ukrainian studies focus on the features of soil microbiota and fauna to understand its ecological conditions, and an even smaller number of studies are devoted to the establishment of soil biological activity under the impact of modern agricultural practices (Ishchenko & Kozelets, 2021; Langraf et al., 2021).

Modern CSA is an integrated approach that addresses the interconnected challenges of food security and climate change. The key features of modern CSA implementation embrace such agricultural techniques as: cultivation of climate-resilient crop varieties and species; conservation agriculture; development of rational agroforestry measures; involvement of industrialization and digitalization in the context of precision digital agriculture; improved livestock management. Special attention in CSA systems is paid to the task of carbon sequestration, and first of all, carbon-smart farming is focused on sequestering carbon in soils and reduces carbon dioxide emissions connected with crop production practices. Carbon sequestration is a complex and integrative task, which includes such levers of carbon cycle regulation as soil tillage reduction; planting cover crops; rational application of fertilizers; application of special chemical and biological compounds to regulate soil biological activity and respiration rates; rational irrigation. Soil respiration is an important indicator of soil fertility and biological activity, plays a significant role in plant yield, as well as being a factor in the adaptation of agrotechnology to the requirements of CSA. As far as soil biological activity is closely related to crop productivity and reaching the goals of sustainable development in the context of current climate change, great attention is paid to resolving the problem of the beneficial balance between the minimization of soil biological activity and respiration rates under simultaneous preservation of its stability, fertility, and agricultural productivity. In this regard, tillage is believed to be one of the most influential agrotechnological factors affecting soil microbiota activity and health indicators in many ways (Nunes et al., 2020). Previous research explained how different tillage practices impact soil respiration. For example, Rusu et al. (2016) claimed that soil respiration is the highest under deep conventional tillage (averaging to daily CO_2 emissions from 321 to 2480 mmol/m^2 s), while moderate tillage intensity provides a slight decrease in this parameter (daily CO_2 emissions from 318 to 2395 mmol/m^2 s), and no-till practices resulting in the best environmentally friendly outcome (daily CO_2 emissions from 35 to 1914 mmol/m^2s). Therefore, tillage has a significant impact on soil respiration and carbon sequestration.

Reicosky (2008) highlighted the potential for carbon sequestration in conservation agriculture under no-till systems, specifically stressing that the benefits of no-till options are matchless in soil organic carbon preservation. Sundermeier (2011) also supports this point of view, demonstrating the positive impact of continuous no-till on soil biophysical carbon sequestration, as it was found that with no-till farming, crop residues accumulate on the surface, reducing air, water, and energy exchange between the soil surface and the atmosphere. These reductions decrease soil temperature and evaporation, retain soil moisture longer, and thereby reduce soil organic matter (hereafter referred as SOM) loss over time. Moraru & Rusu (2013) also claimed that no-tillage systems generally result in lower soil CO_2 emission than conventional tillage. However, it should be stressed that this pattern is not common for all the soil types and cultivated crops. For example, it was established that the best outcomes of no-till are observed in the arid climates in the soils with low SOM content (Abdalla et al., 2016; Feng et al., 2018).

Besides, it should be noted that no-till is not appropriate in every environmental and agricultural production conditions, e.g., on heavy clay soils, wet climate, heavy weed infestation, and for the cultivation of root crops (Lal, 2017). Notwithstanding the fact of its growing popularity and climate stabilization importance, in some areas agricultural producers should find some balance between conventional moldboard tillage and zero tillage through the implementation of gradual tillage minimization. A considerable amount of scientific research testifies the high importance of rational tillage options selection depending on the soil type and other environmental conditions, so that the best balance between crop productivity and climate change resilience is achieved. For example, Zhang et al. (2009) proved that different tillage systems are significantly different in terms of soil CO_2 emission and have various potential to greenhouse effect reduction. As far as it was mentioned that no-till is not always the best option, Lamptey et al. (2017) established that subsoil tillage provides the best effect on carbon emissions cutting compared to conventional moldboard and zero tillage. Apart from that, subsoiling also benefits rational water use and provides sustainable yielding of crops.

Moreover, it is not correct to concentrate on soil respiration as the only biological marker in CSA systems. It is well-known that cellulose decomposition is another important part of soil biological activity and fertility indicator, which is also strongly related to the efficient soil organic carbon circulation in agroecosystems (Wang et al., 2021). Besides, it is a well-established fact that cellulose decomposition is integral to carbon sequestration and balance in soil ecosystems (Bao et al., 2021). Right understanding of the mechanisms of cellulose decomposition and carbon sequestration in soils is crucial for developing rational strategies to offset CO_2 emissions and prevent climate change aggravation through irrational agricultural activities (Miao et al., 2021). Thus, neglect of cellulose decomposition in soils, frequently measured as the level of linen cloth destruction by soil microbiota during the growing season, can result in incomplete and somewhat distorted knowledge on soil biological activity under various tillage options.

Considering the mentioned results of scientific studies, it is evident that there is no general rule on the benefits of one or another tillage method to achieve CSA goals in terms of carbon dioxide emissions reduction. The best way to establish the true state of facts is by conducting a meta-analysis, based on the results of multiple studies related to the subject. There are several recent meta-analyses conducted, but there is no meta-analysis performed for the soils of Ukraine. It is obvious that different environment, climate, soil types, agrotechnology and crops result in different outcomes, therefore, it is reasonable to carry out the meta-analysis on soil biological activity depending on tillage options on the national level. Thus, the main goal of this study is to perform a meta-analysis of current scientific research, conducted in the croplands of Ukraine, to define whether tillage has a significantly strong effect on soil respiration rates, what is the role of tillage depth in this regard, and what type of tillage (conventional moldboard, flat cutter or zero tillage) provides the best CSA-friendly outcomes in the soils of Ukraine.

Materials and methods

To perform a meta-analysis, scientific literature, published in Ukrainian scientific journals and reports for the studies on soil biological activity conducted within the period 2000–2023, were searched and generalized. The sources of uncertain genesis, with incomplete data sets and results, as well as duplicates and biased studies, were excluded from the meta-analysis. Only the studies which allowed calculation of standard deviations and provided the results of ANOVA were included inthe meta-analysis. The search was performed using Google Scholar search engine, as well as direct search through the specialized agricultural library named after Vernadski. The keywords in the search were: "soil biological activity" or "soil respiration" or "linen cloth decomposition" with "soil tillage" or "no-till" or "zero tillage" or "tillage depth" or "moldboard tillage" or "flat cutter tillage". For inclusion, publications had to meet the following criteria: 1) soil biological activity should be measured in generally accepted units for soil respiration ($mg^{-1}m^{-2}day^{-1}$) and linen cloth decomposition (%); 2) conducted with strong adherence to current methodology requirements; 3) provide an opportunity of data generalization and standard deviation calculation; 4) be conducted in Ukraine. We excluded: 1) duplications; 2) preprints; 3) non-peer reviewed papers; 4) studies presenting results only in graphs rather than in tables; 5) biased studies; 6) studies with incomplete results, which did not allow statistical evaliation of the datasets. In total, 22 studies on CO_2 emission and 23 studies on cellulose decomposition (expressed in the linen cloth decomposition) were selected and subjected to meta-analysis. The studies embraced such types of Ukrainian soils as dark-chestnut soil, southern, ordinary and typical chernozems (black soils), and such major crops as wheat, barley, grain and sweet corn, soybean, lentils, chickpea, sunflower, peas, and vetch-oats mixture. The sources of scientific information were systematized as follows in Table 1 and subdivided into three blocks of studies by soil tillage options, and into two major parts by the way of soil biological activity measurements.

The meta-analysis was performed using the standardized mean difference (SMD) model without subgroups at 95% confidence interval (CI). The average effect size was calculated using the Cohen's distance (h), and also the significance and meaningfulness of the difference between the groups were identified using this parameter (h = 0.20 – small effect size; 0.50 – moderate effect size; 0.80 and higher – large effect size). Fail-safe numbers were computed by Rosenthal to assess the potential impact of publication bias on the meta-analysis results, as well as stability and robustness of the meta-analysis results (the higher fail-safe number is, the stronger the evidence in favor of the meta-analysis results is) (Ellis, 2010; Beheshti et al., 2020; Borenstein et al., 2021). Forest plots for random (with high heterogeneity) and fixed (with high homogeneity) effects models, as well as drapery and funnel plots, were built to visualize the results of the meta-analysis and its reliability. The level of the heterogeneity was estimated by the values of I^2 coefficient.

Results

The meta-analysis of the effects of plowing depth on soil respiration rates provided somewhat inconclusive results. It was determined that the heterogeneity of the study was low (I^2 = 9.4%), with close enough common and random effects models (Table 2, 3). Fail-safe number reached 0, thus, the results of the meta-analysis, notwithstanding the fact of some evidence for the favor of shallower (maximum to 22 cm) plowing comparing to deep (30 cm) plowing, are inconclusive. The random effects model showed no significant difference in favor of either shallow or deep moldboard tillage (Fig. 1). The funnel and drapery plots are presented in Figure 2.

Table 1
The list of scientific studies enrolled in meta-analysis by the subject of soil respiration intensity and cellulose-decomposition ca-pacities (soil biological activity markers)

Blocks of the studies by soil tillage options	Biological acticity of soil measured as	
	respiration (CO_2 emission) intensity	cellulose (linen cloth) decomposition intensity
Plowing depth	Lykhovyd & Lavrenko (2017); Yeshchenko (2011); Lavrenko (2015); Maksymov (2016)	Lykhovyd & Lavrenko (2017); Yeshchenko (2011); Lavrenko (2015)
Moldboard vs Flat cutter tillage	Miroshnichenko et al. (2012); Pavlichenko et al. (2014); Pavli-chenko et al. (2015); Kryhanivskyi & Kostohryz (2010); Tsyli-uryk et al. (2021); Prymak et al. (2019); Bogatyr (2015)	Yurkevich & Voytsekhovskaya (2012); Pavlichenko et al. (2014); Pavlichenko et al. (2015); Sokolov & Marchenko (2009); Tsyliuryk et al. (2017); Pogromska (2019); Medvedev (2018); Datsko & Zakharchenko (2023); Hanhur & Sakhatska (2019); Prymak et al. (2019); Senchuk & Krykunova (2009); Bogatyr (2015)
Tillage vs No-till	Miroshnichenko et al. (2012); Vydynivska (2012); Kryhanivskyi & Kostohryz (2010); Chornyy & Vydynivska (2012); Tsyliuryk et al. (2021); Bogatyr (2015)	Pogromska (2019); Manushkina et al. (2020); Tanchik & Mykolenko (2016); Bo-gatyr (2015)

Table 2
The results of meta-analysis of soil respiration depending on the depth of plowing

Model type	standardized mean difference	95% confidence interval	z|t statistics	P
Common effect model	–0.0763	–0.7533; 0.6007	–0.22	0.8252
Random effects model	–0.0763	–1.2315; 1.0789	–0.21	0.8470

As for the meta-analysis of the impact of plowing depth on the de-composition of linen cloth (cellulose decomposition activity), it was estab-lished that there is a weak evidence for the favor of shallow or deep mold-board tillage in this regard, as fail-safe number reached zero. The meta-analysis was absolutely homogenous (I^2 = 0%); therefore, fixed effects model describes the outcomes best. The results of the meta-analysis are generalized in Table 4, while the fixed and random effects figures are represented in the Figure 3 with the detailed statistics presented in Table 5. Funnel and drapery plots (Fig. 4) also testify the absolute inconclusive nature of the meta-analysis, therefore, it is difficult to tell for sure that moldboard tillage depth has significant and meaningful effect on the cellu-lose decomposition activity and carbon cycle in the soil, notwithstanding the fact that the fixed and random models' plots provide some evidence in favor of shallow plowing. The main reason for the inconclusive results is extremely small number of the studies, included in the meta-analysis.

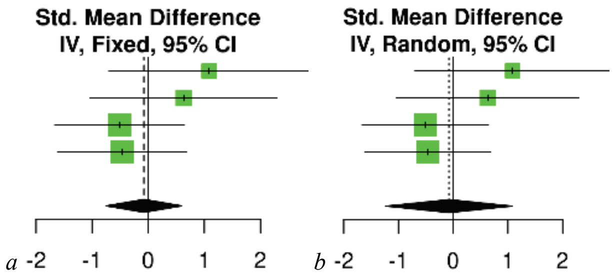

Fig. 1. Fixed (*a*) and random (*b*) effects model of the meta-analysis of soil respiration depending on the depth of plowing

Table 3
Information on the studies, their weight and effects accoding to the results of the meta-analysis of soil respiration depending on the depth of plowing (all the studies enrolled in the analysis were conducted at P < 0.05)

Study	Group 1 (shallow plowing)	Total number	Group 2 (deep plowing)	Total number	Weight, %	Standardized mean difference (fixed)	Standardized mean difference (random)
A	220.9 ± 28.7	3	195.0 ± 17.8	3	14.4	1.08 [–0.70; 2.87]	1.08 [–0.70; 2.87]
B	131.0 ± 7.9	3	126.0 ± 7.9	3	16.5	0.63 [–1.03; 2.30]	0.63 [–1.03; 2.30]
C	129.8 ± 35.2	6	149.7 ± 42.5	6	34.4	–0.51 [–1.66; 0.64]	–0.51 [–1.66; 0.64]
D	149.7 ± 41.6	6	170.8 ± 48.4	6	34.6	–0.47 [–1.62; 0.68]	–0.47 [–1.62; 0.68]
Total (95% confidence interval)		18		18	100	–0.08 [–0.75; 0.60]	–0.08 [–1.23; 1.08]

Note: heterogenity: $tau^2 < 0.0001$; $Chi^2 = 3.31$; df = 3 (P = 0.35); $I^2 = 9.0\%$.

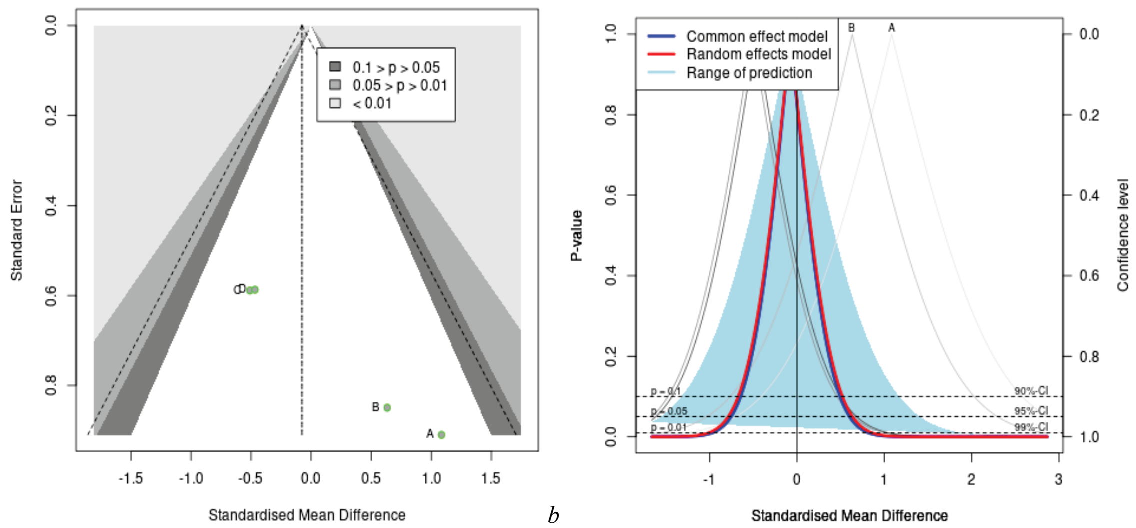

Fig. 2. Funnel (*a*) and drapery (*b*) plots of the meta-analysis of soil respiration depending on the depth of plowing

Table 4
The results of meta-analysis of cellulose decomposition rates in soil depending on the depth of plowing

Model type	Standardized mean difference	95% confidence interval	z|t statistics	P
Common effect model	–0.1288	–0.9301; 0.6726	–0.31	0.7528
Random effects model	–0.1288	–0.2213; –0.0362	–5.99	0.0268

Considering the results of two meta-analyses of the effects of plowing depth on soil biological activity, it could be concluded that further deep studies are required in this direction to provide a robust scientifically sound conclusion on this issue. Current scientific evidence lacks representability to decide whether shallow moldboard tillage provides meaningful benefits for carbon sequestration in the CSA systems in Ukraine.

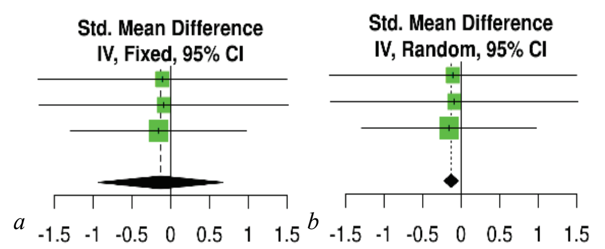

Fig. 3. Fixed (*a*) and random (*b*) effects model of the meta-analysis of cellulose decomposition rates in soil depending on the depth of plowing

Table 5
Information on the studies, their weight and effects accoding to the results of the meta-analysis of cellulose decomposition rates in soil depending on the depth of plowing (all the studies enrolled in the analysis were conducted at P < 0.05)

Study	Group 1 (shallow plowing)	Total number	Group 2 (deep plowing)	Total number	Weight, %	Standardized mean difference (fixed)	Standardized mean difference (random)
A	45.8 ± 12.2	3	47.1 ± 12.1	3	25.0	–0.11 [–1.71;1.50]	–0.11 [–1.71; 1.50]
B	26.1 ± 3.2	3	26.4 ± 3.4	3	25.0	–0.09 [–1.69; 1.51]	–0.09 [–1.69; 1.51]
C	41.9 ± 9.2	6	43.4 ± 9.7	6	50.0	–0.16 [–1.29; 0.98]	–0.16 [–1.29; 0.98]
Total (95% confidence interval)		12		12	100.0	–0.13 [–0.93; 0.67]	–0.13 [–0.22; 0.98]

Note: heterogenity: $tau^2 = 0$; $Chi^2 = 0.01$; df = 2 (P = 1.00); $I^2 = 0\%$.

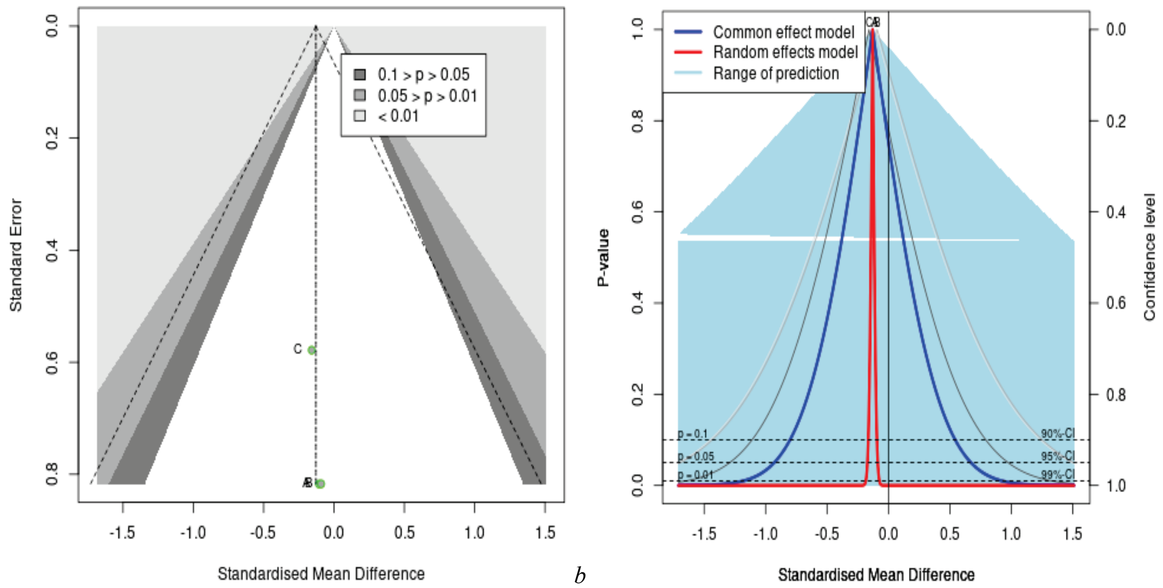

Fig. 4. Funnel (*a*) and drapery (*b*) plots of the meta-analysis of cellulose decomposition rates in soil depending on the depth of plowing

The results of the meta-analysis on the difference between moldboard and flat cutter tillage options are more concrete (Table 6). Fail-safe number reached 4, but the studies, enrolled in the meta-analysis, are still homogenous ($I^2 = 0\%$). Therefore, the attention should be paid more to the fixed effect model rather than to the random effects one (Table 7, Fig. 5), though the outcomes are quite similar in both and testify in favor of the flat cutter tillage option in the reduction of carbon dioxide emission from soil surface. The funnel and drapery plots are presented in Figure 6, providing additional evidence to the homogeneity of the dataset and subtle difference between the random and common fixed effects models. Thus, the results remain somewhat inconclusive in slight favor to flat cutter tillage advantages over the moldboard plowing in terms of regulation of soil respiration rates.

Table 6
The results of meta-analysis of soil respiration rates depending on the type of tillage (moldboard or flat cutter)

Model type	Standardized mean difference	95% confidence interval	z|t statistics	P
Common effect model	0.3309	0.0350; 0.6267	2.19	0.0284
Random effects model	0.3309	0.0517; 0.6100	2.61	0.0243

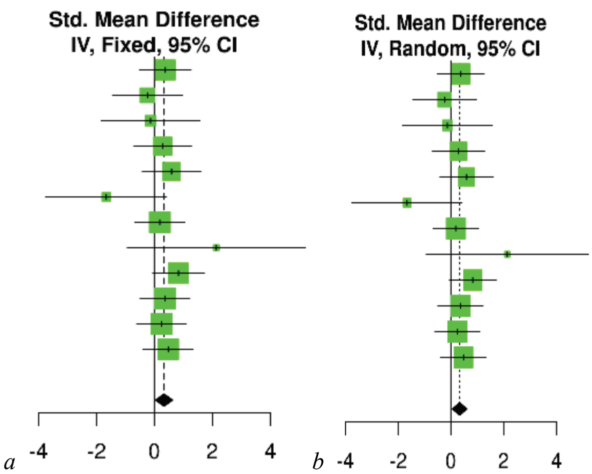

Fig. 5. Fixed (*a*) and random (*b*) effects model of the meta-analysis of soil respiration rates depending on the type of tillage (moldboard or flat cutter)

Table 7
Information on the studies, their weight and effects according to the results of the meta-analysis of soil respiration rates depending on the type of tillage (moldboard or flat cutter) (all the studies enrolled in the analysis were conducted at P < 0.05)

Study	Group 1 (moldboard tillage)	Total number	Group 2 (flat cutter tillage)	Total number	Weight, %	Standardized mean difference (fixed)	Standardized mean difference (random)
A	40.1 ± 7.2	10	37.6 ± 6.1	10	11.2	0.37 [–0.51; 1.26]	0.37 [–0.51; 1.26]
B	159.3 ± 89.0	4	179.1 ± 79.5	8	6.0	–0.24 [–1.45; 0.96]	–0.24 [–1.45; 0.96]
C	201.0 ± 103.2	2	213.3 ± 86.0	4	3.0	–0.14 [–1.84; 1.56]	–0.14 [–1.84; 1.56]
D	8397.9 ± 1443.8	8	7987.1 ± 1411.2	8	9.0	0.29 [–0.70; 1.27]	0.29 [–0.70; 1.27]
E	6362.0 ± 1123.6	8	5739.7 ± 987.3	8	8.7	0.59 [–0.42; 1.59]	0.59 [–0.42; 1.59]
F	19.0 ± 1.0	2	22.0 ± 2.0	4	2.0	–1.66 [–3.75; 0.42]	–1.66 [–3.75; 0.42]
G	3539.6 ± 618.0	8	3424.5 ± 617.6	16	12.1	0.19 [–0.66; 1.04]	0.19 [–0.66; 1.04]
H	12.2 ± 0.5	2	11.1 ± 0.5	2	0.9	2.14 [–0.93; 5.20]	2.14 [–0.93; 5.20]
I	2215.1 ± 119.3	8	2094.5 ± 155.9	16	11.2	0.83 [–0.05; 1.71]	0.83 [–0.05; 1.71]
J	3125.4 ± 561.8	8	2932.0 ± 519.8	16	12.0	0.36 [–0.49; 1.22]	0.36 [–0.49; 1.22]
K	4143.4 ± 721.9	8	3975.7 ± 675.1	16	12.1	0.24 [–0.61; 1.09]	0.24 [–0.61; 1.09]
L	3876.9 ± 588.8	8	3600.9 ± 576.9	16	11.8	0.48 [–0.39; 1.34]	0.48 [–0.39; 1.34]
Total (95% confidence interval)		76		124	100.0	0.33 [0.04; 0.63]	0.33 [0.05; 0.61]

Note: heterogenity: $tau^2 < 0.0001$; $Chi^2 = 7.77$; df = 11 (P = 0.73); $I^2 = 0\%$.

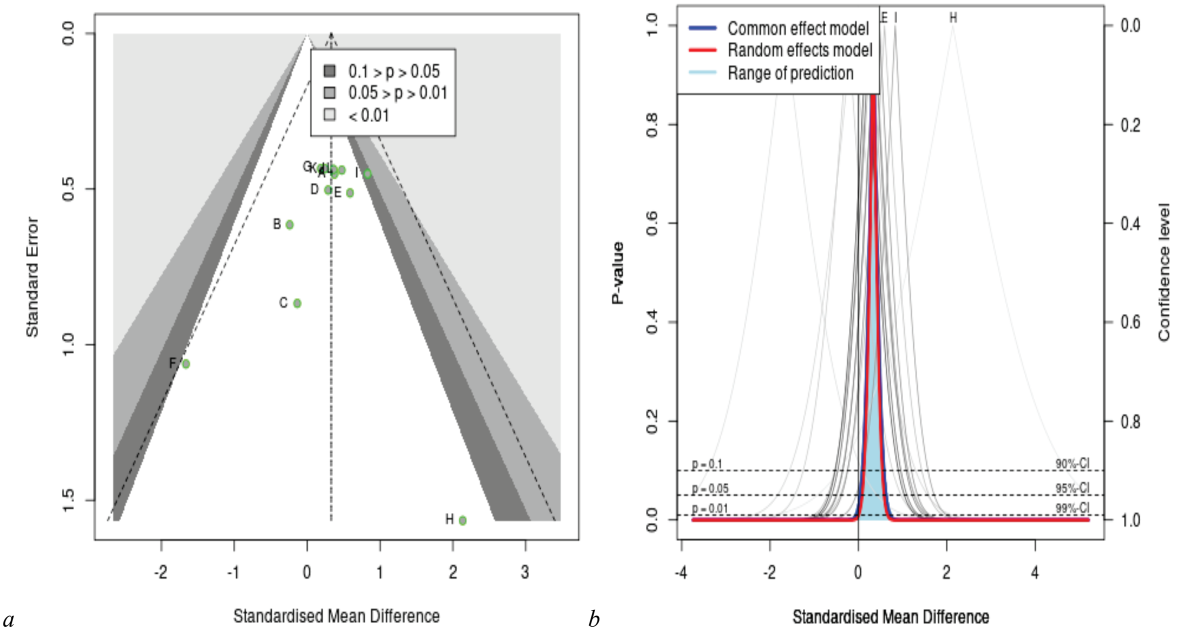

Fig. 6. Funnel (*a*) and drapery (*b*) plots of the meta-analysis of soil respiration rates depending on the type of tillage (moldboard or flat cutter)

The meta-analysis of the same tillage option effects on the cellulose decomposition activity provided much more confident and convincing results (Table 8). The fail-safe number reached 25, while the heterogeneity level was upper-intermediate ($I^2 = 59.0\%$). Both fixed and random effects models testify in favor of flat cutter tillage in terms of reduction in cellulose decomposition activity and following SOC sequestration (Table 9, Fig. 7), but the random effects model is more convincing and provides an evidence for even greater advantage of the flat cutter tillage. The funnel and drapery plots (Fig. 8) provide the evidence for the better reliability of the random effects model in this case. Thus, in the case of cellulose-decomposing microbial activity in soils of Ukraine it is possible to make a statement that flat cutter tillage should be preferred to moldboard tillage in order to better meet the requirements for SOC preservation in the systems of CSA.

Table 8
The results of meta-analysis of cellulose decomposition in soil depending on the type of tillage (moldboard or flat cutter)

Model type	Standardized mean difference	95% confidence interval	z|t statistics	P
Common effect model	0.2827	0.0728; 0.4925	2.64	0.0083
Random effects model	0.2865	–0.1240; 0.6970	1.49	0.1575

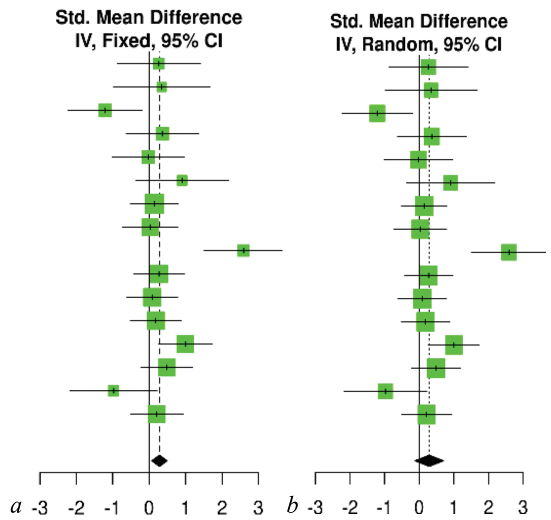

Fig. 7. Fixed (*a*) and random (*b*) effects model of the meta-analysis of cellulose decomposition in soil depending on the type of tillage (moldboard or flat cutter)

Table 9
Information on the studies, their weight and effects according to the results of the meta-analysis of cellulose decomposition in soil depending on the type of tillage (moldboard or flat cutter) (all the studies enrolled in the analysis were conducted at P < 0.05)

Study	Group 1 (moldboard tillage)	Total number	Group 2 (flat cutter tillage)	Total number	Weight, %	Standardized mean difference (fixed)	Standardized mean difference (random)
A	24.6 ± 4.6	6	22.9 ± 7.8	6	3.4	0.27 [–0.87; 1.40]	0.27 [–0.87; 1.40]
B	20.5 ± 4.5	3	18.9 ± 4.7	9	2.5	0.34 [–0.97; 1.66]	0.34 [–0.97; 1.66]
C	16.0 ± 3.8	9	22.3 ± 6.3	9	4.3	–1.21 [–2.23; –0.19]	–1.21 [–2.23; –0.19]
D	30.1 ± 3.3	8	28.1 ± 7.1	8	4.5	0.36 [–0.63; 1.35]	0.36 [–0.63; 1.35]
E	16.2 ± 1.1	8	16.3 ± 5.6	8	4.6	–0.02 [–1.00; 0.96]	–0.02 [–1.00; 0.96]
F	34.3 ± 2.5	4	30.6 ± 4.6	8	2.7	0.91 [–0.36; 2.17]	0.91 [–0.36; 2.17]
G	12.7 ± 3.8	18	12.1 ± 4.8	18	10.3	0.14 [–0.52; 0.79]	0.14 [–0.52; 0.79]
H	7.8 ± 5.3	9	7.7 ± 2.8	27	7.7	0.03 [–0.73; 0.78]	0.03 [–0.73; 0.78]
I	19.9 ± 0.8	9	18.0 ± 0.7	18	3.8	2.59 [1.51; 3.67]	2.59 [1.51; 3.67]
J	24.5 ± 3.1	12	23.0 ± 6.3	24	9.1	0.27 [–0.42; 0.97]	0.27 [–0.42; 0.97]
K	16.3 ± 2.3	12	16.0 ± 3.9	24	9.2	0.09 [–0.61; 0.78]	0.09 [–0.61; 0.78]
L	24.1 ± 1.6	12	23.7 ± 2.5	24	9.1	0.18 [–0.52; 0.87]	0.18 [–0.52; 0.87]
M	27.7 ± 3.3	12	24.4 ± 3.3	24	8.2	1.00 [0.27; 1.73]	1.00 [0.27; 1.73]
N	21.9 ± 1.7	12	19.5 ± 5.9	24	8.9	0.49 [–0.22; 1.19]	0.49 [–0.22; 1.19]
O	6.5 ± 1.4	4	8.5 ± 2.2	12	3.1	–0.97 [–2.16; 0.22]	–0.97 [–2.16; 0.22]
P	41.4 ± 12.5	15	38.8 ± 12.3	15	8.5	0.21 [–0.51; 0.93]	0.21 [–0.51; 0.93]
Total (95% confidence interval)		153		258	100.0	0.28 [0.07; 0.49]	0.29 [–0.12; 0.70]

Note: heterogenity: $tau^2 = 0.31$; $Chi^2 = 36.60$; df = 15 (P < 0.01); $I^2 = 59.0\%$.

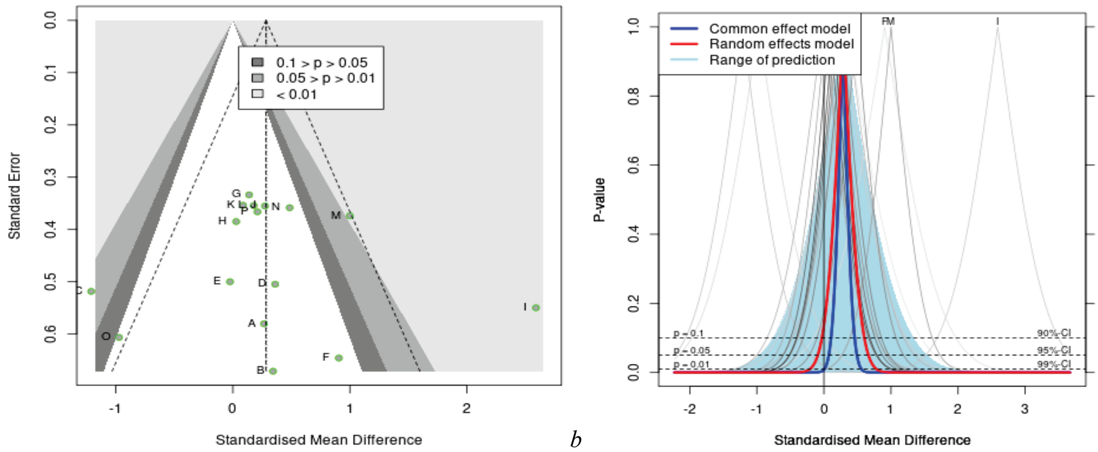

Fig. 8. Funnel (*a*) and drapery (*b*) plots of the meta-analysis of cellulose decomposition in soil depending on the type of tillage (moldboard or flat cutter)

As for the effects of no-till, it was established that there was a slight heterogeneity between the studies in the dataset ($I^2 = 34.7\%$), as well as very low fail-safe number (equal to zero). The meta-analysis provided weak evidence in favor of the no-till option (Table 10). The forest plots both for fixed and random effects models provide slight support for the no-till option in CO_2 emission reduction (Table 11, Fig. 9). Taking into account the low heterogeneity of the dataset, both random and fixed effect models have comparatively similar statistical value, which is additionally demonstrated in the funnel and drapery plots (Fig. 10).

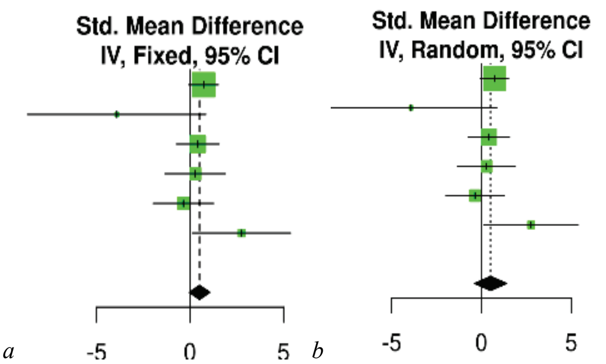

Fig. 9. Fixed (a) and random (b) effects model of the meta-analysis of soil respiration rates depending on the type of tillage (tillage or no-till)

Table 10
The results of meta-analysis of soil respiration rates depending on the type of tillage (tillage or no-till)

Model type	standardized mean difference	95% confidence interval	z|t statistics	P
Common effect model	0.5031	–0.0424; 1.0486	1.81	0.0707
Random effects model	0.5031	–0.3822; 1.3884	1.46	0.2039

Table 11
Information on the studies, their weight and effects accoding to the results of the meta-analysis of soil respiration rates depending on the type of tillage (tillage or no-till) (all the studies enrolled in the analysis were conducted at P < 0.05)

Study	Group 1 (tillage)	Total number	Group 2 (no-till)	Total number	Weight, %	Standardized mean difference (fixed)	Standardized mean difference (random)
A	38.8 ± 6.6	20	34.3 ± 5.4	10	48.6	0.72 [–0.06; 1.50]	0.27 [–0.87; 1.40]
B	4.0 ± 0.4	2	6.0 ± 0.6	2	1.3	–3.92 [–8.68; 0.84]	0.34 [–0.97; 1.66]
C	172.5 ± 79.2	12	139.0 ± 86.6	4	22.8	0.41 [–0.73; 1.56]	–1.21 [–2.23; –0.19]
D	209.2 ± 83.2	6	186.5 ± 84.1	2	11.5	0.27 [–1.34; 1.88]	0.36 [–0.63; 1.35]
E	2.0 ± 0.3	6	21.0 ± 0.1	2	11.4	–0.36 [–1.98; 1.25]	–0.02 [–1.00; 0.96]
F	11.7 ± 0.8	4	9.9 ± 0.2	2	4.3	2.75 [0.13; 5.37]	0.91 [–0.36; 2.17]
Total (95% confidence interval)		50		22	100.0	0.50 [–0.04; 1.05]	0.50 [–0.38; 1.39]

Note: heterogenity: $tau^2 < 0.0001$; $Chi^2 = 7.66$; df = 5 (P = 0.18); $I^2 = 35.0\%$.

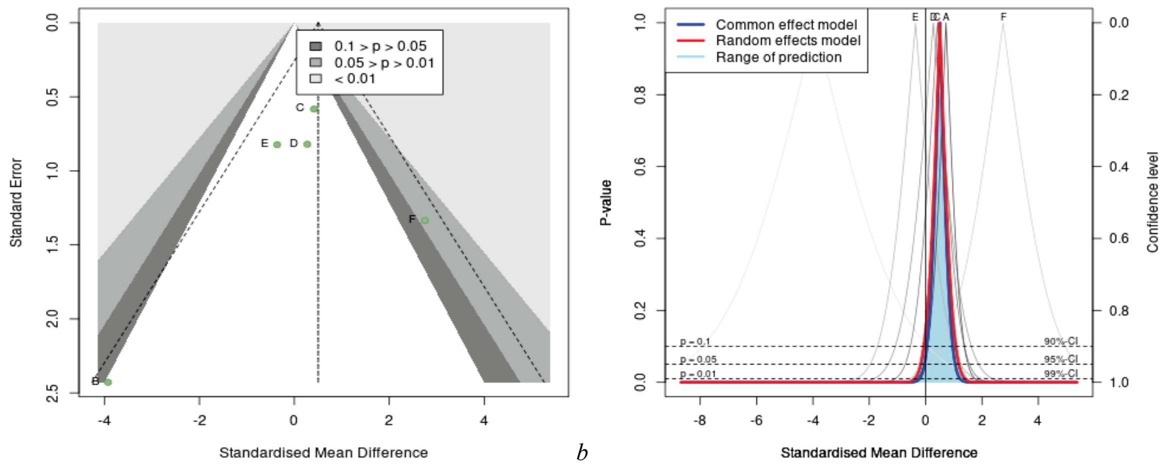

Fig. 10. Funnel (*a*) and drapery (*b*) plots of the meta-analysis of soil respiration rates depending on the type of tillage (tillage or no-till)

A somewhat similar situation is observed for the cellulose decomposition intensity in soils depending on tillage or no-till options. The fail-safe number is also extremely low (zero), but the heterogeneity of the dataset is high enough for one to draw more robust and convincing conclusions ($I^2 = 82.8\%$). General statistics are presented in Table 12. The fixed effects model testifies the clear superiority of the no-till option in lowering cellulose decomposition activity, while the random effects model shows that there is a parity between both options of soil treatment (Table 13, Fig. 11). Analysis of the funnel and drapery plots (Fig. 12) provides us with an idea that the random effects model provides more reliable information on the meta-analysis outcomes, especially considering the higher heterogeneity of the study, thus, it should be concluded that cellulose decomposition is almost not affected by any studied tillage options.

Table 12
The results of meta-analysis of cellulose decomposition in soils depending on the type of tillage (tillage or no-till)

Model type	Standardized mean difference	95% confidence interval	z|t statistics	P
Common effect model	0.6771	0.1552; 1.1991	2.54	0.0110
Random effects model	–0.0462	–3.0793; 2.9869	–0.05	0.9644

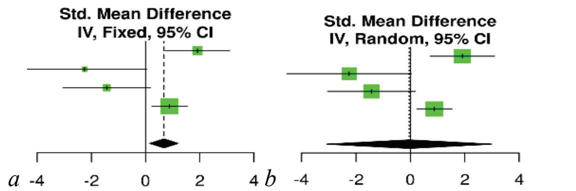

Fig. 11. Fixed (*a*) and random (*b*) effects model of the meta-analysis of cellulose decomposition in soils depending on the type of tillage

To sum up the results of the meta-analysis, it should be stated that in terms of soil respiration rates and decrease in cellulose decomposition rates in the soils of Ukraine:

1) there is weak, inconclusive evidence in favor of shallower moldboard plowing rather than deeper one;

2) there is strong evidence in favor of flat cutter tillage in cellulose decomposition reduction, but slight and inconclusive evidence of its ability to decrease soil respiration rates;

3) there is weak evidence in favor of no-till to reduce carbon dioxide emission from soils, but there is no significant difference between tillage and no-till systems in terms of the regulation of cellulose-decomposing activity of soil microbiota.

Discussion

The meta-analysis, presented in this study, is the first comprehensive and complex attempt to scientifically systematize and estimate the effects of different tillage practices, commonly utilized in Ukrainian agriculture, on soil biological activity in the context of reaching the SDG goals stipulated by FAO within the framework of modern CSA. Of course, the study has numerous limitations. First of all, it should be admitted that the number of qualitative studies on moldboard tillage depth effects on soil microbial activity is extremely small, therefore, the meta-analysis failed to establish a reliable relation between the carbon cycles in soils of Ukraine depending on this agrotechnological parameter. It is an established scientific fact that estimating between-study heterogeneity is difficult in the situation with small datasets. An inaccurate estimation of heterogeneity (high homogeneity in the analyzed data) often results in incorrect or biased effect estimations and narrow confidence intervals (Mathes & Kuss, 2018). Besides, the studies on the plowing depth effects were mainly conducted on the soils of one type (dark-chestnut soil), thus, making them extremely homogenous and making it difficult to create a statistically valuable sample dataset. In addition, some of the studies had significantly greater weight and size effect than the others (e.g., 50% weight for the study C on linen cloth decomposition against 25% weight for the other studies enrolled in the meta-analysis), making the representation of the results unbalanced. Secondly, it is obvious that the current study did not embrace all possible tillage options and their interaction, nor did it account for the crops and the impact of their rotation effects and humidification conditions on the outcomes. Although the mentioned factors are generally believed to have less direct impact on soil biological activity, in some cases they could be crucial in changing the behavior of soil ecosystems (Kladivko, 2001; Emmerling, 2007). However, the debates on the importance of tillage depth have not ceased. As far as most are concerned that tillage depth reduction is beneficial for agroecosystems and can lead to SOC sequestration, Chinese researchers proved the opposite and claimed that deep flat cutter (subsoilling) tillage has advantages over the shallower one in terms of SOC preservation and cutting carbon dioxide emissions (Wang et al., 2023).

The same situation is observed for no-till comparison with different tillage options. There was a great discrepancy in the weights of the studies enrolled in the analysis, in some cases, one study having a 65% weight, that is inappropriate for fair statistical decision. As far as no-till practices in Ukraine are not as comprehensively studied as conventional tillage, there is a great gap between the number of qualitative scientific studies on the subject of no-till effects on soil biological activity. Besides, there are numerous studies lacking adequate presentation of their results making it impossible to enroll them into a meta-analysis. Thus, the results of current meta-analysis on the effects of no-till on SOC cycles in the soils of Ukraine are somewhat inconclusive, but in general, they support the idea that there is no dramatical benefit in no-till practices regarding the reduction of carbon dioxide emission and cellulose decomposition, which has also been claimed in the study, conducted for the Central European site croplands by Gelybó et al. (2022). Some researchers claimed that the level of beneficial effects of no-till depend on soil parameters and cropping systems, and the best advantages could be achieved in arid environments in the soils with low SOC content (Bregaglio et al., 2022). This statement finds support in the work by Huang et al. (2018). In global, Li et al. (2023) proved that no-till decreases CO_2, CH_4, and N_2O emission from soils, but our results cannot provide a strong support to this claim.

Table 13
Information on the studies, their weight and effects according to the results of the meta-analysis of cellulose decomposition in soils depending on the type of tillage (tillage or no-till) (all the studies enrolled in the analysis were conducted at $P < 0.05$)

Study	Group 1 (tillage)	Total number	Group 2 (no-till)	Total number	Weight, %	Standardized mean difference (fixed)	Standardized mean difference (random)
A	23.8 ± 6.1	12	11.9 ± 6.5	6	19.4	1.91 [0.72; 3.10]	0.27 [–0.87;1.40]
B	29.6 ± 5.4	3	45.1 ± 8.1	3	5.2	–2.25 [–4.54; 0.03]	0.34 [–0.97; 1.66]
C	17.7 ± 5.6	4	29.4 ± 10.1	4	10.4	–1.43 [–3.05; 0.18]	–1.21 [–2.23; –0.19]
D	40.1 ± 12.3	30	29.6 ± 11.0	15	65.0	0.88 [0.24; 1.53]	0.36 [–0.63; 1.35]
Total (95% confidence interval)		49	–	28	100.0	0.68 [0.16; 1.20]	–0.05 [–3.08; 2.99]

Note: heterogenity: $tau^2 = 2.953$; $Chi^2 = 17.40$; $df = 3$ ($P < 0.01$); $I^2 = 83.0\%$.

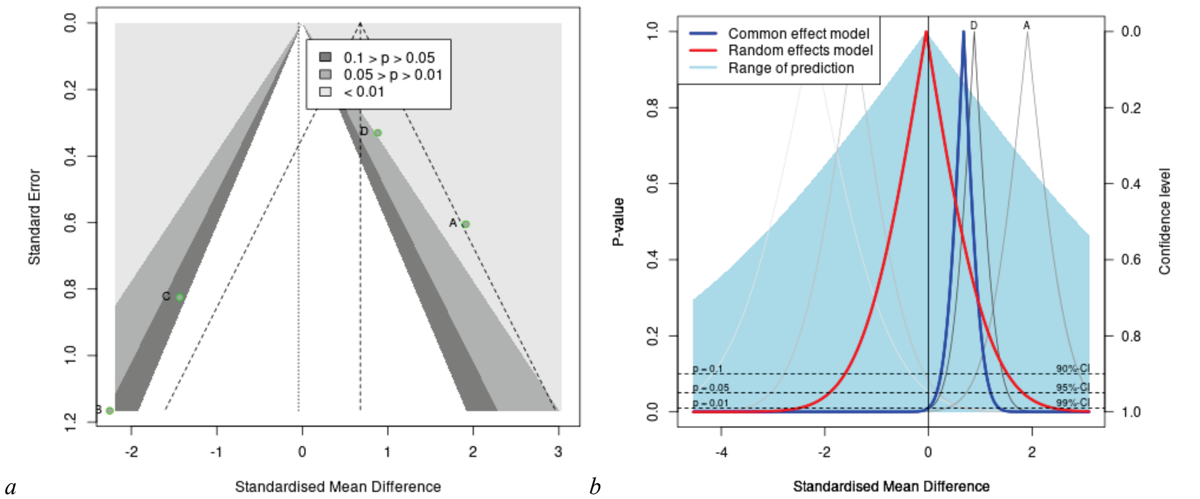

Fig. 12. Funnel (*a*) and drapery (*b*) plots of the meta-analysis of cellulose decomposition in soils depending on the type of tillage (tillage or no-till)

As for the comparison between moldboard and flat cutter tillage options, the results of the meta-analysis provide the best evidence in favor of flat cutter and subsoil tillage to reach the goals of carbon sequestration in the soils of Ukraine. There were enough high-quality studies to allow proceeding with a comprehensive meta-analysis with robust statistical support of its outcomes. The idea that flat cutter tillage has the advantage in terms of SOC sequestration and reduction of tillage impacts on global warming is also supported by numerous studies, conducted in different climatic zones in the soils of different types (Chatskikh et al., 2008; Jiao et al., 2022; Yan et al., 2024). The main difference lays in the field of the depth of flat cutter tillage or subsoiling, which current meta-analysis did not count as a factor of the influence on soil biological activity, and this is another limitation of the presented research.

Furthermore, as it has been claimed above, there is a great difference in CO_2 emission from soils and carbon sequestration in different cropping systems, as plants also have a great impact on the environmental carbon cycles (Ogle et al., 2019). This peculiarity should be accounted in further meta-analysis, performed to establish the features of impacts of agricultural practices on reaching the goals of sustainable development within the framework of modern CSA. In addition, positive effects of tillage reduction are mostly achieved only in strong cooperation with other conservation practices, and not alone, as was proved in the meta-analysis of tillage reduction effects on the soils of the USA (Nunes et al., 2020).

Conclusion

The current study provides the results of first ever meta-analysis of the soil biological activity in Ukraine depending on tillage practices, implemented in the country. The meta-analysis enrolled 45 high-quality scientific studies with robust results on the effects of different tillage options on soil respiration rates (expressed in carbon dioxide emission) and cellulose decomposition intensity (expressed in the percentage of the destroyed linen cloth). Most studies focused on the differences between moldboard tillage and flat cutter subsoiling, while the smaller number of studies embrace the issues of tillage depth and no-till comparison. The meta-analysis results are inconclusive and require further scientific detalization regarding the effects of no-till and moldboard tillage depth, while the confidence of advantages in subsoiling over moldboard tillage found strong statistical support. The results of the meta-analysis in terms of the provision for the achievement of SDG within the framework of CSA in Ukraine could be summarized as follows:

1) shallow moldboard tillage has advantages over deeper one (weak evidence);

2) flat cutter tillage and subsoiling has great advantage over moldboard tillage (strong evidence);

3) no-till has subtle advantages over other tillage options (weak evidence).

Further scientific studies are required to be held in the croplands of Ukraine to provide more robust and scientifically sound recommendations regarding the positive or adverse effects of no-till systems in CSA and SOC sequestration, as well as to adjust the optimal depth of tillage in other cropping systems.

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