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The effect of deep-tillage depths on crop yield: A global meta-analysis

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Abstract: The tillage depth plays a critical role in solving soil compaction – a global problem of soil degradation. However, to date, there are few research reported about tillage depth, and the standard of optimum tillage depth is lacking. Therefore, we conducted a meta-analysis to quantify the effect of tillage depths on crop yield across a global scale, and then to analysis their influence factors such as local climate, soil properties, and managements. Moreover, a global distribution of the optimal tillage depths was estimated by using a random-forest model. Overall, our result demonstrated that crop yield first increased within tillage depths from 25 cm to 35 cm, and then reduced under higher depth of deep tillage compared to conventional tillage, according to 1 109 wheat, maize and soybean (WMS) yield observations from 202 studies and 109 publications. Visibly, 35 cm hence became the optimum tillage depth of WMS across the world, while it varies with different regions. Furthermore, higher crop yields observed in areas with a humid climate, high clay contents, and large bulk density under the optimal depth 40, 35 and 45 cm, respectively. In contrast, a lower yield was observed in areas with arid climates, silty and sandy soils, and lower bulk density within optimal depth of 25, 30 and 25 to 35 cm. Human management efforts, including fertiliser addition, irrigation, straw returning, and changing of cropping system or crop species mostly increased the crop yield under deep tillage. Particularly, our meta-analysis indicated that straw returning needs a greater depth. Finally, we predicted the distributions of optimum depths, which showed that 30 cm and 35 cm were the optimum tillage depths in the temperate and tropical regions, and the total crop yields of global WMS increased by 2 689 million tons per year under the optimal tillage depth, compared with the conventional tillage.

Keywords: conventional tillage; random-forest; best tillage depth; tillage management; subsoiling

Global soil compaction is occurring at an unprecedented rate (Eswaran 2004). Worldwide compaction has degraded an estimated 427 000 km^2 of soil (Sonderegger and Pfister 2021), particularly because of the development of heavy-agricultural machinery and intensification of the cropping system (Stoessel et al. 2018). As one of the main soil degradation types in the world, soil compaction causes high bulk density, poor aeration, low water conductivity, strong strength, and consequently reduces crop growth and yield (Tracy et al. 2011).

Deep tillage is the most effective way to release compacted soil at a global scale, which can decline soil bulk density and increase its pore space by mechanical modification. Therefore, soil water storage, saturated hydraulic conductivity, and air permeability are improved under deep tillage (Drewry et al. 2000). On the other hand, one large profit comes from the

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subsoil nutrient and water resource accessed by propagated plant roots in deep than shallow tillage (Chandra et al. 2017). Soil organic matter also increases within residual straw incorporation due to deep tillage (Chen et al. 2017). Furthermore, crop growth and yield are increased by deep tillage, particularly because of the above-mentioned improvements in soil physiochemical properties (He et al. 2019).

In doing deep tillage practice, tillage depth plays a predominant role. Working/disturbance depth determines the ploughing thickness, net soil displacement and the vertical range of mechanical disruption in the soil profile (Van Muyser et al. 2002), thereby controlling the removal of soil compaction layers and thus influencing other soil properties (Gorucu et al. 2013). For example, the profile distributions of soil organic carbon and nutrients from the above-ground residual plant are controlled by the incorporation depth of the straw. The interaction of soil nitrogen fertilisation and tillage depth was also found by Kahnt (1976), that is, the crop yield increased with tilling depth owing to the increasing mineralisation under deeper ploughing. No matter what, tillage depth was always the first decision that must make for farmers before they plant. In pre-industrial times, tillage depth was usually limited to shallower than 20 cm by the use of only animal-drawn ploughs and manual digging (Eggelsmann 1979). After the second agricultural revolution, tillage depth began increasing with the improvement of plough by ploughwrights (Russell 1956). Between 1850 and 1960, the maximum till-age depth increased up to > 200 cm with the power development of steam and combustion engines (Russell 1956, Eggelsmann 1979). In 1970s, tillage depth declined particularly owing to the farmer concerned about the negative impact of tilling on beneficial soil biota and inconsistent yield response to deep tillage (Kladivko 2001). Nowadays, renew interest in deeper tillage is stimulated by the wide expansion of soil compaction.

However, there is very little to gain from tilling deeper than the compacted layer. Soil tillage erosion belonging to over-deep tillage maybe is the primary risk (Van Oost et al. 2006, Hobbs 2007), and some great wind erosion happens with the decline of soil aggregate stability under the disturbance of deep tilling (Hobbs 2007). Re-compaction phenomenon also severely affects soil structure where a high number of cultivation passes was necessary after deep loosening (Larney 1986, Evans et al. 1996). Moreover, over-deep loosening in sites with high sand topsoil is dangerous for roots to access excessive-infiltration water and fertiliser in the subsoil, because of the poor capacity of the remaining water and nutrient resources (Chaudhary et al. 1985). In addition, the mineralisation of subsoil organic carbon (SOC) would be stimulated by over-deep disturbance, where stored more than 50% of the world's SOC (Feng et al. 2020). Ultimately, the fuel consumption and thereby the fuel costs as well as the CO_2 emissions derived from fuel combustion and subsoil SOC mineralisation process are non-necessary but rapidly increasing within over-deep tillage (Plouffe et al. 1995, Kouwenhoven et al. 2002, Hwang et al. 2019). Because of these, an optimum tillage depth to precisely remove the soil compaction layer, and sustainably manage soil and nutrient resources are urgently needed to avoid further soil degradation.

However, a standard definition for optimum tillage depth globally is lacking, although some studies were set up to determine the best tillage depth for crop growth. In Northern America, optimum tillage depth was reported as 23 cm and 30 cm for maize and sugar beet cultivation by Henderson et al. (2013) and Jabro et al. (2015), respectively, and 40 cm for sugar beet by Mathers et al. (1971), as well as 90 cm for maize and 120 cm for soybean also be reported by Varsa et al. (1997) and Dunker et al. (1995). In Europe, a shallow working depth (5–10 cm) was recommended for wheat and barley by Arvidsson et al. (2013), but 20–25 cm was also suggested for wheat and barley by Arvidsson (1998). Similar inconsistent situations were observed in Asia, Africa, South America, and Australia (Stibbe and Kafkafi 1973, Adeoye 1982, Barbosa et al. 1989, Barber and Díaz 1992, Hammad and Dawelbeit 2001, Kothari et al. 2003, Hemmat 2009, Berhe et al. 2012, Salem et al. 2015, Zeyada et al. 2017, Sun et al. 2019, Shen et al. 2021, Gu et al. 2022), the optimum tillage depth ranges from 10 cm to 50 cm for soybean, wheat, and maize under differential countries. Obviously, the optimum tillage depth was highly scattered in differential research, this is presumably largely due to the strongly site-specific effects of tillage depth on crop yields. However, previous studies were mostly focused on one field with few depth sections due to budget and time constraints, and, to date, no large-scale estimates of the impact of tillage depth on crop growth are available.

Here, we therefore analysis the impact of tillage depth on crop yield and their influencing factors on a global scale and then determine the optimum depth of deep tillage worldwide using a meta-analysis.

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To further understanding the effects of optimum depths on global yield, a machine-learning algorithm (random-forest model) used to predict the relative change of crop yields under individual potential depth, based on local climate, soil properties, and management data. Finally, the global distribution of optimal depths projected onto basic cropland depending on the prediction.

MATERIAL AND METHODS

Data collection

Web of Science Core Collection, Google Scholar, Springer Link, and China Knowledge Resource Integrated Database, were screened using the following Keywords: "sub-soiling", "subsoiling", "deep till*", "deep plough*", "deep rip*", "deep mixing" and their combinations until 2021. 12. 01. We used the following criteria to match literature: (1) papers published in English or Chinese (only collected high scientific quality articles which must include in the Chinese Science Citation Database: CSCD); (2) experiments should be conducted in the field (exclude potting and greenhouse experiments); (3) at least one paired experiment between deep tillage (> 25 cm) and conventional tillage (< 25 cm) with three replications was reported and the depth of differential tilling should be measured and clearly described; (4) studies' precise geographic location (GPS coordinates) needed to be reported or specific city was mentioned; (5) other practices such as residue straw, irrigation, fertiliser and so on should be same between deep tillage and conventional tillage.

After finishing the procedures, 109 publications matched our criteria and 1 109 observations of crop yield collected from 202 studies (Figures 1 and 2). Specifically, for each yield observation, the mean, stand deviation (SD) and replication number were collected directly from tables, or figures using Get Data Graph Digitiser (version 2.26, Moscow, Russia). The SD was calculated as SD = SE × $\sqrt{n}$ if only standard error (SE) was reported and then using Bracken way to estimate in package ("metagear") in R software (version 3.5, Auckland, New Zealand) if it was not reported. Furthermore, other information were compiled such as aridity index (Trabucco 2018), soil texture from 0–20 cm (USDA, Soil Survey Staff 1999), soil tillage (TillageType, TillageDepths and TillageFrequency), soil management (Irrigation, Fertiliser and Straw), soil initial character (soil organic carbon: SOC and soil bulk density in 0–20 cm) and crops (CropSystem and CropSpecies).

Moreover, global cropland information was collected from various sources for predicting crop yield under specific fields, such as local climate, soil properties and management. The global cropland map at 1 km^2 resolution for 2 000 were collected from

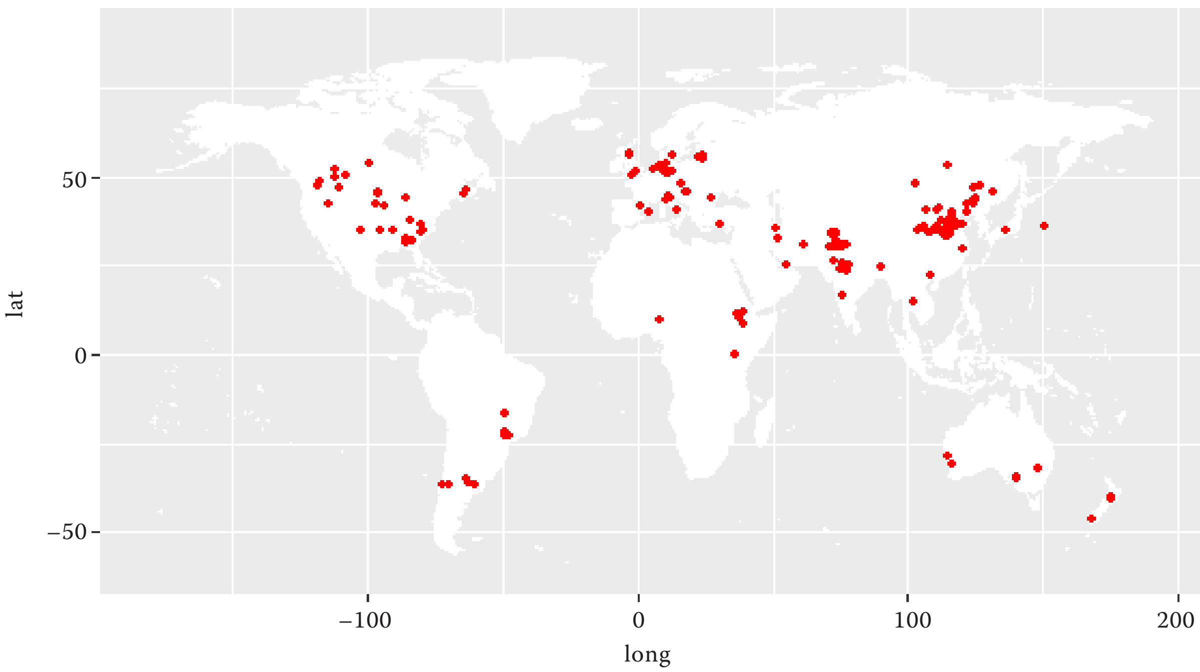

Figure 1. The geographical distribution of the experimental sites included in this meta-analysis

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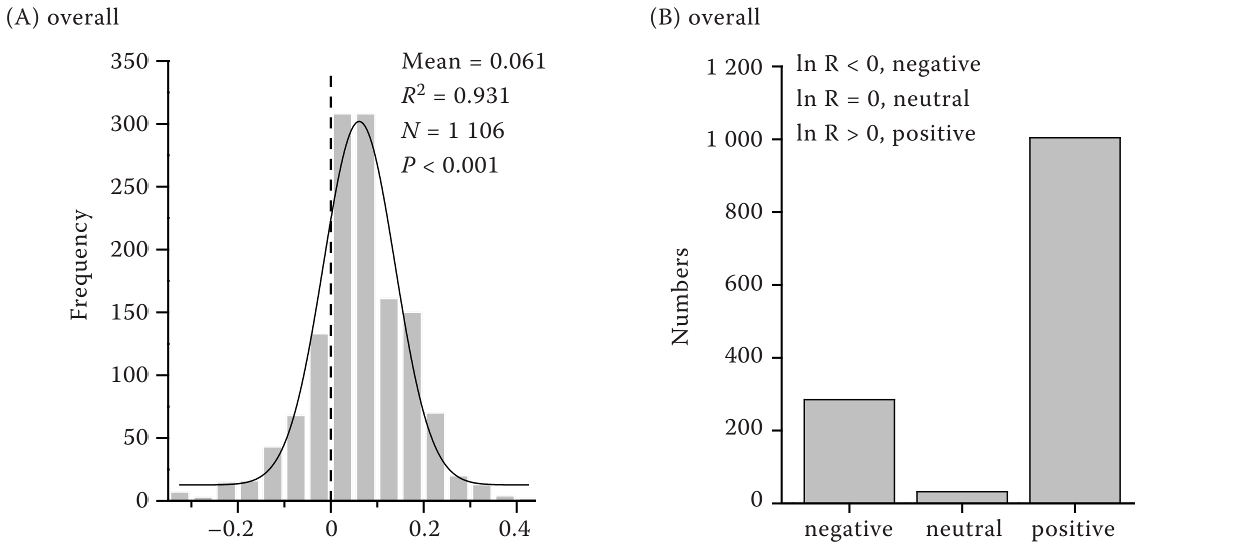

Figure 2. (A) Frequency distributions of effect size i.e. the response ratios (lnR) and (B) numbers of response for global crop yield responses to deep tillage, with data from publications

European Commission (EU 2003). It was the basic spatial GIS database used to integrate other dataset, including the global aridity index for the 1970–2000 period provided by high-resolution (30 arc-seconds) in Consortium for Spatial Information (Trabucco 2019); the global soil texture (sand, clay, silt content), bulk density and soil organic carbon within 30 arc-second raster database came from FAO (Fischer et al. 2008); the average nitrogen fertiliser used for global agriculture in the past decade years (2004–2013) calculated by us from Lu and Tian (2017); the global cropping system, irrigation and species areas extracted from (Yu 2020); and the global crop yield of major crops: maize, wheat, and soybean of decade years (2007–2016) downloaded from Scientific Data (Lizumi 2019).

Meta-analysis

The univariate meta-analysis was performed to determine the impact of tillage depth on crop yield (Figures 2, 3 and 4). The effect size, i.e. the response ratios (RR) of crop yield to tillage depth was calculated as:

$$\text{RR} = \ln\left(\frac{Yield_{Deep}}{Yield_{Control}}\right)$$

Where: $\text{Yield}_{\text{Deep}}$ and $\text{Yield}_{\text{Control}}$ denotes as the mean values of crop yield under deep tillage and conventional tillage, respectively.

The variance of effect size was calculated as:

$$\text{variance} = \frac{Sd_{Deep}^2}{n_{deep}Yield_{Deep}^2} + \frac{Sd_{Control}^2}{n_{Control}Yield_{Control}^2}$$

Where: Sd_{deep} and $\text{Sd}_{\text{Control}}$ represent standard deviation of crop yield in deep and conventional tillage; n_deep and n_control were the replication number of deep tillage and conventional tillage, respectively.

The weighting factor (W_{ij}), weighted mean effect size (MRR), and the standard error of MRR were calculated as below:

$$w_{ij} = \frac{1}{V}$$

$$\text{MRR} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij} R_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}}$$

The standard error of MRR was calculated by:

$$\text{s(MRR)} = \sqrt{\frac{1}{\sum_{i=1}^{m}\sum_{j=1}^{k} w_{ij}}}$$

Where: w – weighting factor defined as the inverse of the pooled variance, *i* and *j* – i^{th} and j^{th} treatments, respectively; m – number of compared groups; and k – number of comparisons in the corresponding groups.

A 95% confidence interval (95% CI) for the MRR was derived by the equation of MRR ± 1.96 × s(MRR). Crop yield in deep tillage was significantly higher (> 0) or lower (< 0) than in conventional tillage, if the 95% CI does not overlap the zero. The relative yield of deep-to-conventional tillage was calculated by using [(exp(ln(R)) – 1) × 100%] for easier understanding. MRR was calculated by R (version 3.5) software using a random-effect model (Adams et al. 1997). We used a nonparametric smooth regression model based on the Gaussian process to fit effect size and tillage depths.

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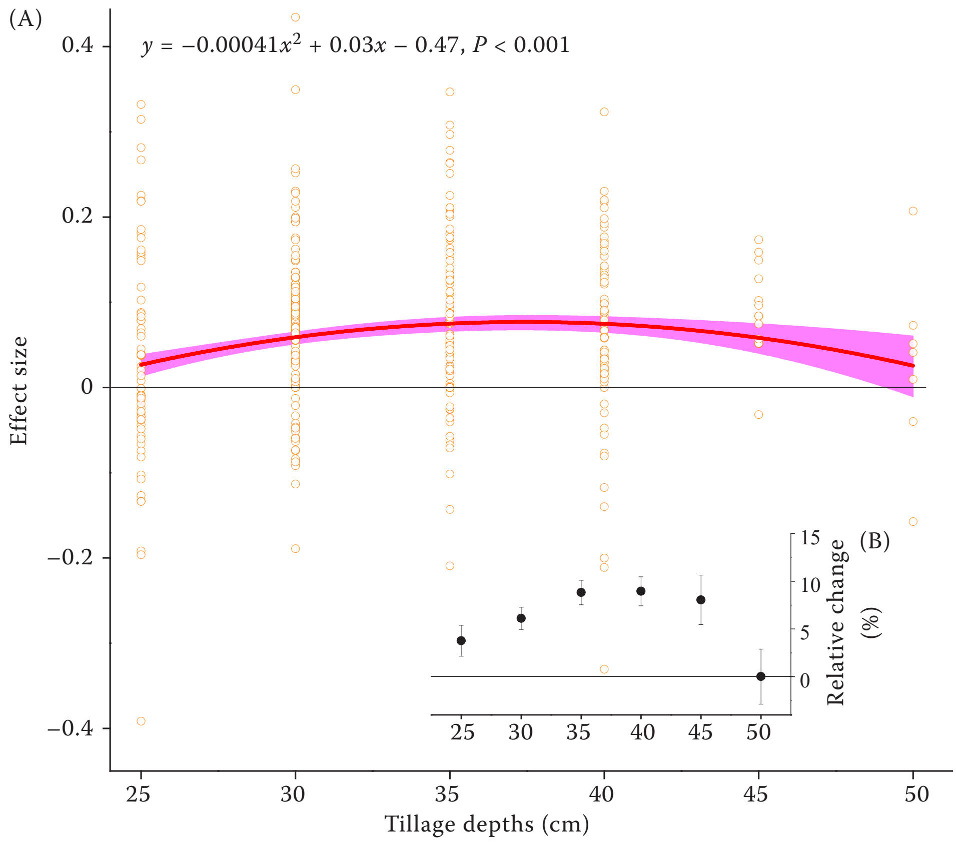

Figure 3. (A) Relationship between effect size of crop yield under different tillage depths and (B) relative changes in crop yield under different tillage depths. Pink area represents the 95% confidence interval (CI). If the CI does not overlap with 0 line, which means significant effects ($P < 0.05$)

Random forest regression modelling

A random-forest (RF) regression model was created for predicting the distribution of optimum tillage depth based on crop yield (Figures 5 and 6) (Prasad et al. 2006). The basic information, including local climate and soil initial properties and managements was incorporated into the RF model by multivariate-statistical regression. Specifically, RF needs first developing and then predicting as the procedures as following showed.

First of all, the effect sizes (RR) and part of the explanation variables selected from dataset 1 depending on relative importance and data availability (including: aridity index (AI), soil sand content, soil silt content, soil clay content, soil organic carbon, soil bulk density and tillage depth) were used to create a RF model, as a training dataset S:

$$S = \{ (X_i, Y_i), i = 1,2, \ldots, N\}$$

Where: X – M-dimensional vector of explanation parameters, and Y – target parameters (RR).

From the training dataset, *n*tree subset Sk (k = 1, 2,..., *n*tree) were randomly selected by using the bootstrap resampling method to generate the regression tree model. For each regression tree, mtry (mtry < M) features were randomly selected at each node, and all split points of these features were traversal for finding the optimal split in minimising the sum square error between the estimated and the real values. For example, consider a split variable j and split point s, and define the pair of half-planes as follows:

$$R_1(j,s) = \{X|X_j \leq s\} \; and \; R_2(j,s) = \{X|X_j > s\}$$

Then, seeking the split variable j and split point s that solve the following:

$$\min(j,s)\left[min_{c1}\sum_{yi \in R_1(j,s)}(yi - c1)^2 + min_{c2}\sum_{yi \in R_2(j,s)}(yi - c2)^2\right]$$

where: c1 – average output value for dataset R_1, and c2 – average output value for dataset R^2.

When finding the optimal split, data was separated into two resulting regions, consequently repeating this splitting process on each of the two sub-nodes,

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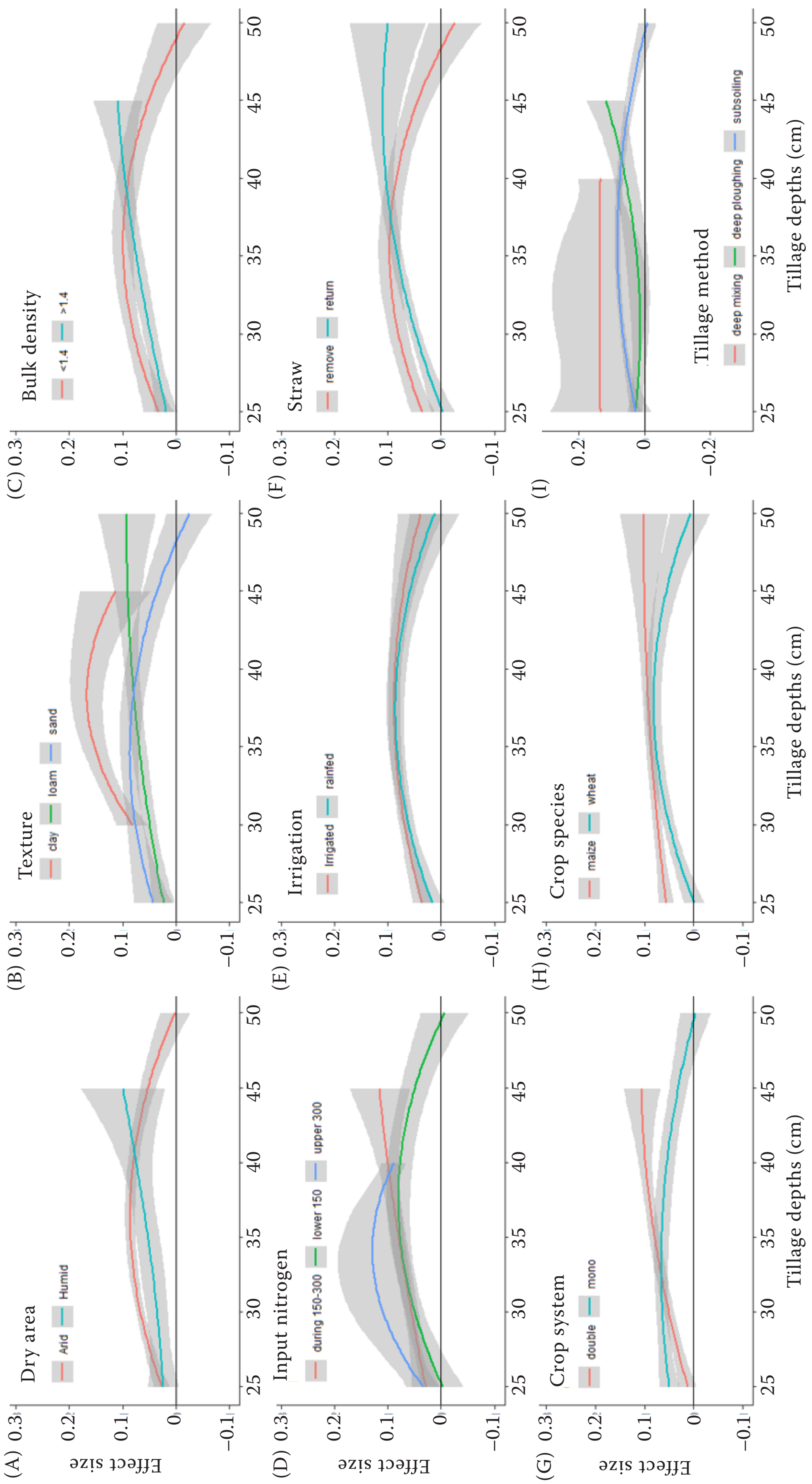

Figure 4. Relationship between effect size (RR) of crop yield under different tillage depths in different factors (A) area; (B) soil texture; (C) bulk density; (D) nitrogen input rate (kg/ha/year); (E) irrigation; (F) straw; (G) cropping system; (H) crops, and (I) tillage method. Grey area represents the 95% confidence interval (CI). If the CI does not overlap with 0 line, which means significant effects ($P < 0.05$)

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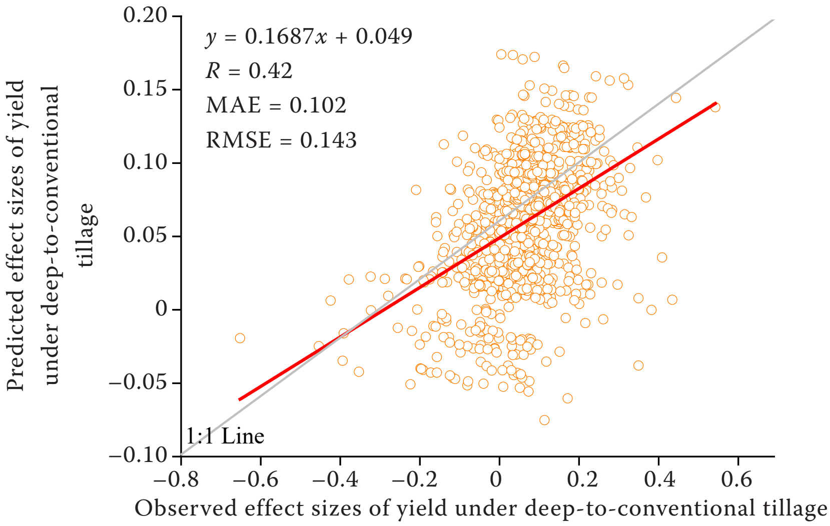

Figure 5. Random forest (RF) model performance evaluated by the correlation between the observed and predicted effect size. The model evaluation follows the framework of "leave-one-out cross validation", that is, one of the nobs observations is held out (test set), which is predicted by the RF model fit on the remaining nobs-1 observations (training set). This procedure is repeated until each observation has served as a test set once and gained a corresponding estimated value. The red line is the one-to-one line

which was stopped if a minimum node (number of observations in a terminal node) was reached.

The ensemble of all the regression trees hi(X), i =1, 2, ..., *n*tree outputs the final prediction (RF) as follows:

$$f(X) = \frac{1}{n_{tree}} \sum_{i=1}^{n_{tree}} hi(X)$$

The general errors of prediction basted on OOB is calculated as:

$$MSE_{OOB} = \frac{1}{n} \sum_{i=1}^{n} (yi - yi^{OOB})^2$$

Where: OBB (out-of-bag data) is approximate 37% of the training data S which un-selected in each bootstrap sample S_k.

After the RF model was created and validated, the global yield potential effect sizes were predicted based on the global cropland information using the RF, and the global distribution of optimum tillage depth depending on crop yield was projected onto a global map (Figure 6).

In the present analysis, we used the package "party" in R (version 3.6.1) software to calculate the RF model and variable importance with the functions of "cforest" and "varimp". Based on the minimised OOB mean squared error, the number of trees to grow in each forest was set at 1 000 (n_{tree}), the number of observations at the terminal nodes of the trees was set at 2, and the number of randomly selected features m_{try} for node splitting was set at 3 for creating the RF model. In doing these, all calculate process running on the super-computer machine from Beijing Super Cloud Computing Centre.

Model accuracy and validation

The "leave-one-out cross validation" framework was used to evaluate the performance of RF model. Keeping one observation out from the nobs first and using the nobs-1 observations to training the RF model, then producing an estimated value. Consequently, repeating this process until every observation has a real value (original data) and an estimated value (prediction data). Furthermore, The R^2 and RMSE measures were calculated to evaluate the accuracy of RF model, as follows:

$$MAE = \frac{\sum_{i=1}^{n} |pi - o|}{n}$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (pi - o)^2}$$

$$R^2 = \frac{\sum_{i-1}^{n} (pi - o)^2}{\sum_{n=1}^{n} (oi - o)^2}$$

where: MAE – mean absolute error; RMSE – root mean square error, R^2 – regression coefficients of determination; P_i – estimated value; O_i – real value, and O – average of the real value.

Finally, the linear-regression relationship between the estimate values and real values was tested to evaluate the model validation (Figure 5).

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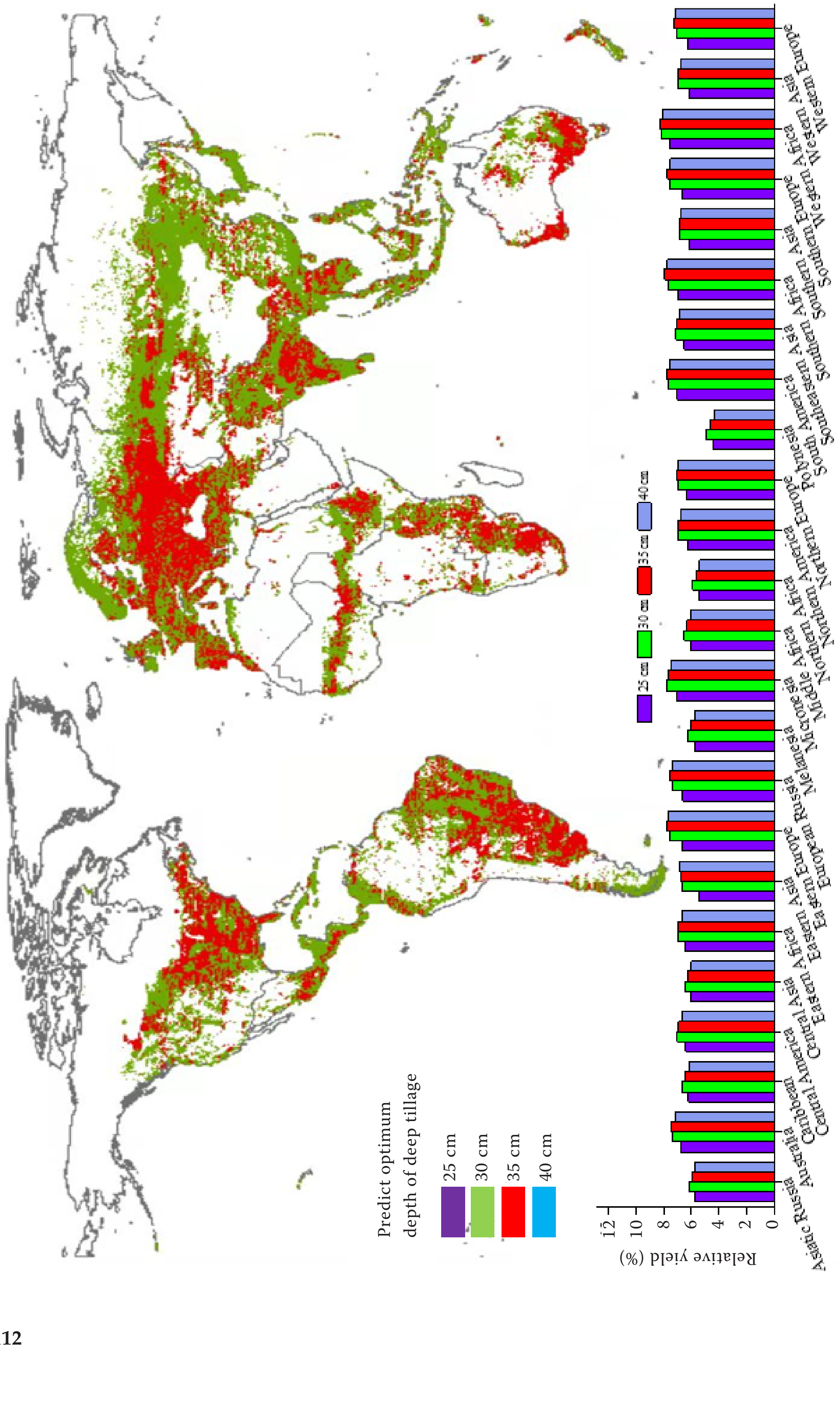

Figure 6. Distribution of optimum depths of deep tillage across global cropland areas. A random-forest regression model was created to calculate the relative predictors of crop yield based on global soil initial properties, climate and crop management, and then collected the optimum tillage depths under each highest crop yield

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RESULTS

Overall impact of deep-tillage depths on crop yield

Our meta-analysis demonstrated that the relative yield of deep tillage compared to conventional tillage were increased from 3.8% [95% confidence interval (95% CI): 2.2%, 5.4%] to 8.8% (95% CI: 7.5%, 10.1%) within tillage depth from 25 cm to 35 cm, and then reduced to 8.7% (7.4%, 10.5%) and 8% (5.5%, 10.7%) within 40 cm and 45 cm, ultimately approximate 0 at depth 50 cm (Figure 3). According to the results, the highest effect size was observed at a depth of 35 cm (average: 0.1; 95% CI: 0.01, 0.02), therefore 35 cm is generally considered to be the optimal depth of deep tillage for global cereals (wheat, maize and soybean), while it varies according to climate regions (Figure 3).

This result was robust to potential publication bias, and statistically significant if estimates of 95% CI did not cover 0 (Figures 2 and 3). However, individual yields were highly scattered under specific depths, for example, the relative yield of deep-to-conventional tillage varied from negative –19% to positive 49% under an optimal depth of 35 cm within differential experiment sites across a global scale (Figure 3). In the following section, we categorised our global dataset into subgroups to estimate and quantify how depth-induced impact varies depending on influence factors such as local climate, soil properties, or human management.

The response of crop yield to deep-tillage depths as affected by different factors

Climate. The arid climate had a higher crop yield than humid areas within depths 25 cm to 40 cm in deep tillage (Figure 4A). In arid climate areas, tillage-depth-induced yield changes were similar performance to the global ones, and the effect sizes first increased within depth 25 cm to 35 cm and then depleted to approximate 0 cm at 50 cm. The 35 cm was still an optimum estimated depth of deep tillage for arid climate areas (Figure 4A). The relative yield of deep-to-conventional tillage was 3.5% (1.7%, 5.4%), 8.4% (7%, 9.8%) and 0% (–4.9%, 4.9%) at depth 25, 35 and 50 cm, respectively, in arid climate areas. For humid climates areas, a positive linear relationship occurred between the effect sizes and tillage depths, the corresponding changes of crop yield in deep-to-conventional tillage were thereby 4.4% (1.1%, 7.6%), 2% (–0.9%, 4.6%), 10.4% (7.2%, 13.7%) and 12% (9.5%, 14.5%) for depth 25, 30, 40 and 45 cm, respectively (Figure 4A). Although 45 cm had a higher crop yield in humid areas, 40 cm was a suggested optimum tillage depth according to the available numbers of observations (46 cm of 40 cm and 2 cm of 45 cm).

Soil properties. The depth-induced yield changes were effectively influenced by soil texture and bulk density (Figure 4B,C). At sites with clay soil (> 30% clay), higher yields were significantly more frequent and stable than at sites with loam or sand soil within deep tillage, and a deeper depth was visibly required by high clay content (Figure 4B). The relative yield in deep-to-conventional tillage was highly increased by 8.5% (6.7%, 10.4%) and by 16.7% (13.6%, 19.8%) at depths 30 cm and 35 cm in clay soil, respectively, although the impact of tillage depths 25, 40, 45 or 50 cm was unable to certainly estimate due to lacking observations (Figure 4B). While effect sizes were increased with tillage depth at loam and sand soil, 25 cm or 30 cm was sufficient for production due to the lower gradient of yield increase (Figure 4B). Moreover, a deeper depth was also required by sites with greater bulk density (> 1.4 g/cm^3), and crop yields were reduced with depth when it was over to 35 cm in low bulk density (< 1.4 g/cm^3) (Figure 4C). Generally, the optimum tillage depths were 25 for loam and sand soil, 35 cm for clay and low bulk density soil, and 45 cm for high bulk density soil across the world.

Soil management practices. Soil management, including fertiliser, irrigation, straw retention, tillage method, and cropping system, was intensely affected on crop yield response to tillage depth (Figure 4). The effect sizes were increased with nitrogen applications under differential depths in deep tillage. Notably, the average effect size was negative (–0.1%, 95%CI: –2%, 1%) at a depth of 50 cm with less 150 kg/ha nitrogen input (Figure 4D). A non-significant difference was observed between irrigated and rainfed regions on a global scale (Figure 4E). In addition, crop yield increased with the depth of straw incorporation, average effect sizes were 7% and 3% for depths over and less than 35 cm, respectively, under straw returning (Figure 4F). Compared with conventional tillage, the mono-cropping system and wheat yields were more sensitive to super-depth of deep tillage; both relative yields were close to 0 at a depth of 50 cm in deep tillage (Figure 4G, H). In general, the optimum depths of deep tillage were similarly 35 cm for most conditions such as medium

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nitrogen input, regions (both irrigated and rainfed), straw removal, mono-cropping system, and wheat planting.

Global performance of deep-tillage-depths on crop yield

Finally, the global distribution of optimal depths was predicted based on crop yield by using a random-forest regression model that incorporated local climate, soil properties, and management data after optimising the model parameter (MAE: 0.102, RMSE: 0.143, R^2: 0.18, Figure 5). Overall, 30 cm and 35 cm were most frequently observed as an optimal tillage depth at on global scale (Figure 4). The predicted yield of deep-to-conventional tillage for wheat, maize and soybean (WMS) was averaged at 7.12% under the optimum tillage depth (Figure 6); that is, the global yields of WMS increased by 2 689 million tons per year. Thus, global wheat, maize, and soybean were increased by 990, 1 395, and 303 million tons per year, respectively (Figure 6). Furthermore, 30 cm was more suitable for the temperate areas such as Western United States, Northern Europe, South Russia and Eastern China, which can achieve an increase in cereal yields (WMS) by 780, 16, 4, and 378 million tons per year, respectively, compared with local cropping system and species and original managements during past decades (Figure 6). Generally, 35 cm was suitable for most tropic regions and part of temperate areas, for example, the Northern and South of America, Europe, Africa, Southern Asia and South of Australia. In these areas, the annual crop yields (WMS) were increased by 778, 445, 364, 291, 167, and 52 million tons under the optimum tillage depth of 35 cm compared to traditional tillage depth (Figure 6).

DISCUSSION

In this paper, we first quantified the global optimum depth of deep tillage using a meta-analysis according to crop yield observations collected from the published paper and then estimated the global distribution of the optimum depth using a random-forest model that considers mainly influence factors.

Overall, 35 cm was observed as an optimum depth of deep tillage at a global scale according to our meta-analysis, which is dependent on strongly site-specific factors, such as local climate, soil management, and initial soil properties (Figures 3 and 4). This work adds a synthesised perspective to earlier inconsistent studies about tillage depth. Furthermore, for the influence factors, a previous large-scale meta-analysis observed that deep tillage can mitigate drought stress partly (Schneider et al. 2017). Similarly, our meta-analysis reveals that deep tillage had a higher yield than conventional tillage in both arid and humid areas (Figure 4A) demonstrating that deep tillage increase the resilience of crops under both drought and waterlogging stress. We further found that yield gaps of deep-to-conventional tillage were higher in arid than humid areas within common depth (25 cm to 40 cm), whereas the humid areas required deeper tillage (Figure 4A). These higher gaps in arid areas in our paper may partly owing to the irrigation, there are 61% of the arid area's sites were irrigated in our dataset. On the other hand, the reduction of soil bulk density and increase of pore abundance in deep tillage can increase the capacity of soils to store plant-available water, increase infiltration rates, and decrease waterlogging and run-off after rain or irrigation, which improved soil water-use efficiency to increase yield (Evans et al. 1996, Drewry et al. 2000, Hou et al. 2012). The second point may also explain the deeper depth required in humid areas, that more deep tillage is associated with more pores to increase infiltration for reducing waterlogging stress on crop growth (Wang et al. 2021).

Ignoring climate, crop growth, and yield under deep tillage are often limited by soil initial properties and improved by soil management in present research according to our data. Deep tillage had a higher yield in clay than sand and silt soils, but the heavy clay soil required a greater tillage depth (Figure 4B). This result is possibly associated with another one that higher soil bulk density needs deeper tillage (Figure 4C). Indeed, the soil with high clay content naturally contains a high strength and is easier to be compacted by agricultural machines (Cho et al. 2015, Sonderegger and Pfister 2021). Conversely, soil management, for instance, adding nitrogen fertiliser, irrigation practices, and changing cropping systems or crop species mostly increase crop yield under deep tillage (Figures 4D, E, G, H). The associated mechanisms have been explained by many researchers (Stibbe and Kafkafi 1973, Barber and Díaz 1992, Zhang et al. 2022). Interestingly, we found that topsoil (< 37 cm) straw incorporation buffered the positive effect of deep tillage on crop yield (Figure 4F), which highlights that straw returning needs a deeper depth to complete decomposition and to avoid affecting seed emergence (Li et al. 2022). For tillage methods,

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both deep mixing and ploughing require more fuel consumption (Sarauskis et al. 2012). Thus, we suggested that subsoiling is the major method of deep tillage at a global scale, although deep ploughing and mixing had a higher yield under some depths (Figure 4I).

Although our meta-analysis revealed that 35 cm is the best tillage depth for crop growth on a global scale (Figure 3), there may need or not be such deep depth in a specific field. Indeed, 30 cm and 35 cm were the most frequently observed as the optimum depth onto the cropland of this world according to our prediction (Figure 6). Furthermore, 30 cm was most suitable for temperate areas and 35 cm fit for both temperate and tropic regions (Figure 6). This result highlights that common tilling depth of 25 cm of deep tillage maybe not satisfied for today's soil environment anymore (Gorucu et al. 2013, Cooper et al. 2016, Feng et al. 2020), owing to the increase of size and load of machines used in agricultural production (Hill and Meza-Montalno 1990). Whereas farmer's presentative feeling that deeper tilling means higher yield also does not work in the real field, a reduction of yield within tillage depth over 40 cm is shown in our data (Figures 3 and 6). Overall, the global crop yield of wheat, maize, and soybean increased by 2 689 million tons per year under optimum tillage depth (30 cm to 35 cm). Which is coincidentally near to the loss rate (–5%) of global yield induced by machines' soil compaction (Sonderegger and Pfister 2021). More specifically, we pointed out the optimum depth has the highest yield (average increase near 8%) in Western and Southern Africa, South America, and Europe, whereas the lowest yield (average 6%) was observed in Polynesia, Northern Africa, and Asiatic Russia and Melanesia.

CONCLUSIONS

This meta-analysis, based on 1 830 yield comparisons of 202 studies conducted globally, demonstrates that crop yield of deep-to-conventional tillage first increases within a tillage depth of 25 cm to 35 cm, and then reduced with tillage depth. Overall, 35 cm has existed as an optimum depth of deep tillage for wheat, maize, and soybean on a global scale, while it depends on areas in different climates. Furthermore, it indicates that humid climate areas required a deeper tillage depth of 40 cm than the arid areas (30 cm), as well as higher clay content and bulk density soil required more tilling. Moreover, human managements including adding nitrogen fertiliser, irrigation, and changing cropping system or crop species often increase crop yield under deep tillage, and the straw incorporation usually needs deeper tillage. Finally, the global distribution of optimum depths was predicted, and 30 cm and 35 cm were estimated as the optimum tillage depth across the temperate and tropical regions.

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