Cover crops do not increase soil organic carbon stocks as much as has been claimed: what is the way forward?

Vincent Chaplot [a,b], Pete Smith [c]

[a]*Institut de Recherche pour le Développement (IRD), Laboratoire d'Océanographie et du Climat: Expérimentations et approches numériques, UMR 7159, IRD-CNRS-UPMC-MNHN, 4 place Jussieu, 75252 Paris Cedex 05, France*

[b]*SAEES, University of KwaZulu-Natal, PB X01, Scottsville 3209, Pietermaritzburg, South Africa*

[c]*Institute of Biological and Environmental Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen, AB24 3UU, Scotland, UK*

Abstract

When compared to virgin land (forest and grassland), croplands store significantly lower amounts of organic carbon (OC), mainly as a result of soil tillage, and decreased plant inputs to the soil over the whole year. Doubts have been expressed over how much reduced and zero tillage agriculture can increase OC in soils when the whole soil profile is considered. Consequently, cover-crops that are grown in-between crops instead of leaving soils bare, appears as the "last man standing" in our quest to enhance cropland OC stocks. Despite the claim by numerous meta-analyses of a mean carbon sequestration rate by cover crops to be as high as 0.32±0.08 tonne C ha^{-1} yr^{-1}, the present analysis showed that all of the 37 existing field studies worldwide only sampled to a depth of 30 cm or less and did not compare treatments on the basis of equivalent soil mass. Thirteen studies presented information on OC content only and not on OC stocks, had inappropriate controls (n=14), had durations of 3 years or lower (n=5), considered only one to two data points per treatment (n=4), or used cover crops as cash crops (i.e. grown longer that in-between two crops) instead of catch crops (n=2), which in all cases constitutes shortcomings. Of the remaining 6 trials, 4 showed non-significant trends, one study displayed a negative impact of cover crops, and one a positive impact, resulting in a mean OC storage of 0.03 tonne ha^{-1} yr^{-1}. Models and policies should urgently adapt to such new figure. Finally, more is to be done not only to improve the design of cover-crop studies for reaching sound conclusions but also to understand the underlying reasons of the low efficiency of cover crops for improved carbon sequestration into soils, with possible strategies being suggested.

1. Introduction

Concerns about increasing land degradation and atmospheric CO_2 levels that cause climate change have increased interest during the last decades in the sink potential of soil organic carbon (SOC). Despite the world's soils containing with 1500 Gt of SOC to a depth on 1 metre, a much smaller amount of carbon than the oceans (38,000 Gt of C), they attract attention because they are responsive to shifts in land management. Several initiatives have been launched to increase SOC stocks to compensate for the global emissions of greenhouse gases by anthropogenic sources and to enhance ecosystem sustainability.

Sequestration of atmospheric carbon into soils has been considered as a possible solution to mitigate climate change, as soil stores two to three times more carbon than the atmosphere, and this store has been largely depleted by past agricultural uses. As a consequence, a relatively small increase in SOM stocks could play a significant role in mitigating greenhouse gases emissions. Transferring more carbon into soils is also seen as a means to enhance ecosystem sustainability, as SOM (of which C is the main constituent), is a reservoir of plant nutrients and a source of energy for microorganism, and also improves soil structure, which is key for improving soil infiltration by water, storing and filtering water, and protecting soils from compaction and erosion.

It has long been recognised that agricultural practices deplete organic carbon stocks compared to pristine ecosystems. Long before the modernization of agriculture, Swanson and Latshaw (1919) had demonstrated that cultivation of prairies in Arkansas for decades had depleted SOM content of the 0-20 cm layer by 30% and of the 20-50 cm layer by 6%. Recently, Mazzoncini et al (2011) in central Italy pointed to a current decrease of 0.06 ton ha yr^{-1} for the 0-30 m layer. Several shifts in land management have been suggested to reverse the decline in soil C stocks while ensuring sustained levels of food production and incomes for farmers. Soil fertilization, reduction of the intensity of tillage and introduction of cover crops have been suggested as the most promising (Khan et al., 2007; Poeplau and Don, 2015; Dignac et al. 2017) and numerous *in-situ* investigations and meta-analytical studies seem to support this.

Cropland soils have lost large amount of organic carbon compared to natural ecosystems, because a large fraction of the net primary production (NPP) is harvested and exported from the land while in natural grasslands for instance, most of the plant C goes to the soil for building SOM. Secondly, croplands often have a fallow period after harvest and before the next crop is planted, which means there is no carbon input to the soil for this part of the year. Consequently, increasing NPP through the inclusion of cover crops in agricultural systems, instead of letting soils lay bare for several months, has been suggested as a way to enhance NPP and to input greater amounts of fresh organic matter to soils. Cover crops, also named “catch crops” when used to prevent nitrate leaching, are grown in between two cash crops instead of letting the soil lay bare for several months, such as following the harvest of a winter cereal in summer to the planting of a spring crop in the following spring. The premise is that cover crops, by enhancing the amount of fresh organic carbon inputs to soils, will have a positive impact on C storage (Paustian et al. 2016; Janzen et al., 2022). It has been argued that widespread adoption of cover-crops would result in a soil carbon sequestration rate of 0.24 PgC yr^{-1} in the top 30 cm or 12 PgC over the next 50 years (Kaye and Quemada, 2017). This makes cover-cropping one of the most promising strategies for preventing and reversing land degradation, as carbon is the main constituent of organic matter, the most important determinant of soil quality. This view has now reached general acceptance and numerous governments have started to distribute carbon credits. For instance, the *Build Back Better Bill* in the USA will offer farmers payments of $25 an acre for planting cover crops, and the *Loi bas carbone* in France will offer about $35 per hectare, with millions dollars if not billions dollars at stake, worldwide.

Not long ago, the widely adopted statement that zero tillage (a minimum tillage practice in which the crop is sown directly into soil not tilled since the harvest of the previous crop) increases SOC storage, has been revised. For instance, since Pacala and Socolow (2004) had estimated that conversion of all croplands to conservation tillage would sequester 25 Gt C over 50 years,farmers had received payments through the Chicago Climate Exchange, in return for practicing zero tillage. However, studies since then, including Baker et al (2007) and several other global studies, suggest that the potential of conservation tillage to SOC stock has been overestimated. Despite the general and accepted consensus in favor of cover crops, the objective of this paper is, similarly to what has been previously done for tillage, to offer examine the evidence base and reevaluate the conclusions drawn from the literature.

2. Estimating the impact of land management on soil carbon stocks

The historical method to estimate soil organic carbon (SOC) stocks is based on field sampling at a fixed depth. This methodology, which has been promoted by the Intergovernmental Panel on Climate Change (IPCC) since its first report (IPCC, 1995) presents SOC stocks as the product of soil bulk density, soil depth and SOC concentration. Since then, authors such as Ellert and Bettany (1995), and more recently, Wendt and Hauser (2013), have demonstrated that this methodology yields substantial bias when soil bulk density differs between treatments and/or when it changes over time. This was typically the case for no-till soils for which SOC stocks were systematically overestimated because of a greater soil bulk densities than for tilled soils, thus exaggerating the benefits of tillage abandonment. To avoid any bias, SOC stock comparisons should be thus based on equivalent soil masses. Wendt and Hauser (2013) concluded that “*a considerable body of past research should be re-evaluated*”. These studies should however not be dismissed for that reason.

Further, Baker et al (2007) had pointed out that studies on land management, such as on tillage should consider entire soil profiles instead of to a depth of 0.3 m or less as shallow sampling yielded inaccurate conclusions. Indeed, when sampling is performed deeper than 0.3 m, studies show that the abandonment of tillage do not result in an SOC stock increase but merely a SOC redistribution with higher SOC concentrations building up near the soil surface at the expense of SOC losses deep in profiles. This was further confirmed by Luo et al (2010) using 69 paired till and no-till experiments, Ogle et al (2019) (n=178 worldwide) and Liang et al (2020) (n=52 in Canada).

Studies that don't have deep measurements should not simply be dismissed for that reason but their conclusions should be taken with caution.

Moreover and most likely for any land management practice, experimental trials should be implemented long-term to test the level of significance of the differences because organic carbon inputs to soils and changes in SOC stocks are usually relatively small relative to: (1) total SOC stocks; and (2) errors in estimating SOC stocks. Moreover, longer term there might be a decrease in SOC storage as soils saturate in SOC. A certain number of data points should also be collected to test the level of significance of the differences in SOC stocks between two treatments with optimal sampling strategies minimizing the sample size (Conen et al., 2004). Finally, the selection of a control, i.e. plot replicates that have identical management to the treatment group in all aspects that affect the outcome except the intervention of interest, is a significant criterion for conducting a study in evidence-based research.

3. Cover crop studies

Poeplau and Don (2015) compiled data from 30 experimental sites worldwide and concluded an average increase of soil C stocks by 0.35 ton C ha^{-1} yr^{-1} to a mean soil depth of 22 cm. Several other published meta-studies confirmed these trends such as by McDaniel et al. (2014), who pointed to an average 3.6% increase in soil OC stocks, Blanco-Canqui et al. (2015) (OC stock increase by 0.1 to 1 ton $ha^{-1}yr^{-1}$) and Blanco-Canqui (2022) (average of 0.41 ton C $ha^{-1}yr^{-1}$ in the US), but also Tellatin and Myers (2018), Abdalla et al. (2019), Bolinder et al. (2020), Jian et al. (2020), and Joshi et al. (2023).

. A literature search was conducted on electronic academic databases using search engines such as Google Scholar, Refseek, Science Direct, SciFinder, Scopus, Springer Link and Web of Science. Key words such as carbon storage, carbon stocks, carbon sequestration, cover crops, catch crops, were used to search for further journal articles. Excluding publications not in English, and reports and other publications which were not published in ISI journals, a total of 37 experimental studies were found and were listed in Table 1.

Despite these meta-analytical studies concluding a positive impact of over-crops on SOC stocks, which helped build a positive opinion towards over-crops and policies aiming at their compulsory inclusion into agricultural systems, there are large discrepancies between individual field studies and/or within field studies. For instance, the field study by Constantin et al. (2010) that was included in Poeplau and Don (2015) and several other meta-analytical studies reported a significant increase in SOC stocks at only one of the three French sites under study. In contrast, Thomsen and Christensen (2004) reported a significant negative impact of cover crops from the Askov Experimental Station, Denmark.

For further assessing the evidence base provided by the individual studies, Table 1 informs on best practices for the estimation of the impact of a given land management on OC stocks (e.g. Xiao et al., 2020) such as the use of : (1) soil samples from entire soil profiles, or at least to 1m; (2) soil carbon stocks estimates on the basis of equivalent soil mass (ESM); (3) information on both the OC concentration and the bulk density of a given soil layer, for computing OC stocks; (4) an adequate reference treatment; (5) a sufficient number of data points and duration of trials for the significance of the trends to be tested.

Table 1 (which provides the names of authors, the year of publication and give indications on the duration of the experiment (below or above 3 years), the sampling depth, the use of soil bulk density to estimate SOC stocks, the use of a reference treatment consisting in a bare soil in-between crops, the number of data points used to compare the treatments and the level of the significance of the differences between treatments) shows that 35 out of the 37 studies did not meet one or several of the prerequisites. Surprisingly, none of the studies sampled entire soil profiles (i.e. to a depth of at least 1m) or estimated SOC stocks for equivalent soil masses. The maximum sampling depths ranged from 0.025 m in the study in USA by Hubbard et al (2013) to 0.6 m (Calegari et al., 2008) in Brazil through 0.3 m for instance for Bayer et al. (2000) and Metay et al (2007) in Brazil, Campbell et al. (1991) in Canada, and Mazzoncini et al. (2011) in Italy.

Additionally, none of the studies compared SOC stocks between treatments on the basis of equivalent soil mass. This might have yielded significant bias as compaction changes the depths of limits between soil layers and soil mass layers do not correspond to soil depth layers. Indeed, differences in soils bulk density is likely to have occurred between cover crop treatments and reference treatments because of tilling for weed destruction or chemical weeding.

There were five studies with a duration equivalent or of less than three years, which can be judge too short for changes in soil organic carbon stocks to be detected and for the temporal dynamics of the changes to be assessed, potentially leading to C storage overestimations as rates of sequestration tend to decrease overtime when approaching saturation.Fourteen studies (i.e. 38%) did not have a bare soil as reference treatment. For example, Campbell et al (1991), Kuo et al (1997), Sainju et al (2006) or Arif et al (2021) used grassy fallows as reference treatments instead of a bare soil. Amado et al. (2006) compared cover cropping included in a no-till system to bare soil within a tilled system, which allowed to compare two systems but not specifically the impact of cover crops.

Four studies had a number of samples per treatment equal or below 2, mostly because of the use of composite samples, which did not allow tests of significance to be run.

Out of the 37 studies, 6 trials had a duration over 3 years, investigated simultaneously SOC content and soil bulk density, used a number of data points over 2 and had a bare soil reference treatment, which could all be considered as important requirements. Four of these trials did not point to a significant impact of cover cropping on SOC stocks as pointed out by (1) statistical tests (Constantin et al., 2010 in two of the trials under study; Thomsen and Christensen in one out of two trials) or (2) overlap of interval confidence (case of Balkcom et al., 2013). As shown in Table 1, only two trials yielded significant trends, one in France with a sequestration rate of 0.29 ton C ha^{-1} yr^{-1} and one in Denmark pointing to a loss of 0.23 ton C ha^{-1} yr^{-1}. The mean OC storage rate by cover-crops, which was computed from these two studies showing significant changes, was 0.03 ton ha^{-1} yr^{-1} (Table 1).

The resulting conclusion from the 37 available ISI studies is an absence of a significant impact of cover crops on soil C stocks.

4. On the possible ways forward

First of all, most of the field trials need to be revisited or improved for reaching sound conclusions. We need to make sure that research trials include a proper reference treatment (i.e. a bare fallow for the very same period as the cropping of the cover crop in the corresponding treatment), a sufficient number of plot replicates and sampling data points are set for the level of the significance of the differences between treatments to be tested. Second, the entire soil profile (or at least down to 50 or 60 cm where impacts of land management are mostly detected) should also be considered (or at least sampling well below the plow layer), and OC stocks should be in all cases estimated with data presented by equivalent soil mass. Finally, there is a high level of uncertainty in the current field procedures for evaluation short-term changes in OC stocks since they might not be detectable by classical methods based on soil bulk density estimates and laboratory assessment of OC contents. Scientists should either favor long-term field trials and/or seek alternative methods to estimate OC changes, such as those based on carbon isotopes (e.g. Balesdent et al. 1990; Kuzyakov and Domanski, 2000).

Overall, and based on the 6 trials meeting the most basic requirements for reaching sound conclusions, cover-crops did not lead to a significant increase in C stocks. The low efficiency of cover crops confirms that significantly increasing soil C inputs, as by adding cover-crops into cropping systems, does not necessary translate into greater soil C storage as previously show by Dignac et al. (2017). Indeed, fresh C inputs to soils can stimulate the decomposition of the old and stable soil organic matter through “priming” for bacteria to acquire key nutrients for their development (e.g. Fontaine et al. 2004, 2007; Blagodatskaya and Kuzyakov 2008) rather than building OC stocks. Such an absence of cover crop impact on soil C stocks puts into question the “Photosynthetic limits on carbon sequestration in croplands” suggested by Janzen et al (2022), thus calling for other limiting factors.

As Kirby et al. (2013, 2014) and Poeplau et al. (2016) have shown, supplementing crop residues with nutrients could increase organic matter formation from fresh inputs by up to 3 fold, so soil fertilization thus appears as the “last man standing” in our quest to enhance soil carbon stocks. Kirby et al. (2014) revealed that post-harvest fertilization might increase the conversion of wheat straw into stable organic matter from 7% (control) to 29% when adding 10 kg N, 4 kg P and 2.6 kg S per ton of straw. The increase in fresh residue conversion to organic matter was further confirmed in field trials by Poeplau et al. (2016), thus pointing to nutrient deficiencies as a main limiting factor of organic matter formation in croplands. Nutrient deficiency, whose origin in croplands is likely to be due to the staggering amounts of nutrients exported by grains and other agricultural products and the need of nutrients by decomposers that are not accounted for in fertilization programs, thus leads to low humification rates and organic matter destruction (e.g. Chaplot and Smith, 2023; Zeng et al., in press). More work must be done on investigating the dual increase of C and nutrient inputs by agricultural practices to soils for enhancing their long term C stocks for sustainable agriculture and a series of environmental benefits, while balancing the climate change and other environmental risks of adding more nutrients to the soil. The significant increase in OC stocks found by Constantin et al. (2010) at a former cattle farm shows that in a nutrient rich environment, using cover-crops to add C-rich fresh organic material might yield significant sequestration.

5. Conclusions

There are many good reasons to introduce cover crops in agricultural systems, such as to reduce soil erosion and nutrient leaching to water tables, to increase soil infiltration by water, and to increase biodiversity, and this paper should not be construed as a defence of bare soils. While these benefits have been well documented, and are in themselves sufficient to justify the promotion of cover cropping, we challenge the widespread assumption that cover crops will increase soil OC levels. We show that the apparent evidence may simply be an artefact, as most current studies do not allow significant trends to be concluded. Further research from long-term trials with adequate sampling methodology and/or investigating the combined impact of nutrient supply might clarify this issue. Until then, it is premature for the scientific community to communicate figures on the C sequestration rate of cover crops to policy makers. It is not only a question of potentially wasting public money, as millions of dollars are distributed worldwide as carbon credits, but also a question of credibility for the scientific community.

Overestimations of the impact of cover crops will need to be urgently considered by models, future science and policy.

References

Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., ... & Smith, P. (2019). A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. *Global change biology*, *25*(8), 2530-2543.

Abdollahi, L., & Munkholm, L. J. (2014). Tillage system and cover crop effects on soil quality: I. Chemical, mechanical, and biological properties. *Soil Science Society of America Journal*, *78*(1), 262-270.

Amado, T. J. C., Bayer, C., Conceição, P. C., Spagnollo, E., de Campos, B. H. C., & Da Veiga, M. (2006). Potential of carbon accumulation in no-till soils with intensive use and cover crops in southern Brazil. *Journal of environmental quality*, *35*(4), 1599-1607.

Arif, M., Jan, T., Riaz, M., Akhtar, K., Ali, S., Shah, S. & Wang, H. (2021). Biochar and leguminous cover crops as an alternative to summer fallowing for soil organic carbon and nutrient management in the wheat-maize-wheat cropping system under semiarid climate. *Journal of Soils and Sediments*, *21*, 1395-1407.

Astier, M., Maass, J. M., Etchevers-Barra, J. D., Pena, J. J., & de León González, F. (2006). Short-term green manure and tillage management effects on maize yield and soil quality in an Andisol. *Soil and Tillage Research*, *88*(1-2), 153-159.

Balkcom, K. S., Duzy, L. M., Kornecki, T. S., & Price, A. J. (2015). Timing of cover crop termination: Management considerations for the Southeast. *Crop, Forage & Turfgrass Management*, *1*(1), 1-7.

Bawa, A., MacDowell, R., Bansal, S., McMaine, J., Sexton, P., & Kumar, S. (2021). Responses of leached nitrogen concentrations and soil health to winter rye cover crop under no-till corn–soybean rotation in the northern Great Plains. *Journal of Environmental Quality*.

Bayer, C., Mielniczuk, J., Amado, T. J., Martin-Neto, L., & Fernandes, S. V. (2000). Organic matter storage in a sandy clay loam Acrisol affected by tillage and cropping systems in southern Brazil. *Soil and tillage research*, *54*(1-2), 101-109.

Blanco-Canqui, H., Mikha, M. M., Presley, D. R., & Claassen, M. M. (2011). Addition of cover crops enhances no-till potential for improving soil physical properties. *Soil Science Society of America Journal*, *75*(4), 1471-1482.

Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C. A., Hergert, G.W., 2015. Cover crops and ecosystem services: insights from studies in temperate soils. Agronomy Journal 107, 2449–2474. https://doi.org/10.2134/agronj15.0086.

Blanco-Canqui, H. 2022 . Cover crops and carbon sequestration: Lessons from US studies. *Soil Science Society of America Journal*, 86, 501-519.

Bolinder, M. A., Crotty, F., Elsen, A., Frac, M., Kismányoky, T., Lipiec, J., ... & Kätterer, T. (2020). The effect of crop residues, cover crops, manures and nitrogen fertilization on soil organic carbon changes in agroecosystems: A synthesis of reviews. *Mitigation and Adaptation Strategies for Global Change*, *25*, 929-952.

Calegari, A., Hargrove, W. L., Rheinheimer, D. D. S., Ralisch, R., Tessier, D., de Tourdonnet, S., & de Fatima Guimarães, M. (2008). Impact of long-term no-tillage and cropping system management on soil organic carbon in an Oxisol: A model for sustainability. *Agronomy Journal*, *100*(4), 1013-1019.

Campbell, C. A., Biederbeck, V. O., Zentner, R. P., & Lafond, G. P. (1991). Effect of crop rotations and cultural practices on soil organic matter, microbial biomass and respiration in a thin Black Chernozem. *Canadian Journal of Soil Science*, *71*(3), 363-376.

Chander, K., Goyal, S., Mundra, M. C., & Kapoor, K. K. (1997). Organic matter, microbial biomass and enzyme activity of soils under different crop rotations in the tropics. *Biology and fertility of soils*, *24*, 306-310.

Conen, F., Zerva, A., Arrouays, D., Jolivet, C., Jarvis, P. G., Grace, J., & Mencuccini, M. (2004). The carbon balance of forest soils: detectability of changes in soil carbon stocks in temperate and boreal forests. In *The carbon balance of forest biomes* (pp. 235-249). Taylor & Francis.

Constantin, J., Mary, B., Laurent, F., Aubrion, G., Fontaine, A., Kerveillant, P., & Beaudoin, N. (2010). Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. *Agriculture, ecosystems & environment*, *135*(4), 268-278.

Curtin, D., Wang, H., Selles, F., Zentner, R. P., Biederbeck, V. O., & Campbell, C. A. (2000). Legume green manure as partial fallow replacement in semiarid Saskatchewan: Effect on carbon fluxes. *Canadian Journal of Soil Science*, *80*(3), 499-505.

Dozier, I. A., Behnke, G. D., Davis, A. S., Nafziger, E. D., & Villamil, M. B. (2017). Tillage and cover cropping effects on soil properties and crop production in Illinois. *Agronomy Journal*, *109*(4), 1261-1270.

Dube, E., Chiduza, C., Muchaonyerwa, P., Fanadzo, M., & Mthoko, T. S. (2012). Winter cover crops and fertiliser effects on the weed seed bank in a low-input maize-based conservation agriculture system. *South African Journal of Plant and Soil*, *29*(3-4), 195-197.

Eckert, D. J. (1991). Chemical attributes of soils subjected to no-till cropping with rye cover crops. *Soil Science Society of America Journal*, *55*(2), 405-409.

Dignac, M. F., Derrien, D., Barré, P., Barot, S., Cécillon, L., Chenu, C., & Basile-Doelsch, I. (2017). Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. *Agronomy for sustainable development*, *37*, 1-27.

Ellert, B.H. and Bettany, J.R. (1995). Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Canadian Journal of Soil Science, 75, 529-538.

Fronning, B. E., Thelen, K. D., & Min, D. H. (2008). Use of manure, compost, and cover crops to supplant crop residue carbon in corn stover removed cropping systems. *Agronomy journal*, *100*(6), 1703-1710.

Hermawan, B., & Bomke, A. A. (1997). Effects of winter cover crops and successive spring tillage on soil aggregation. *Soil and Tillage Research*, *44*(1-2), 109-120.

Hubbard, R. K., Strickland, T. C., & Phatak, S. (2013). Effects of cover crop systems on soil physical properties and carbon/nitrogen relationships in the coastal plain of southeastern USA. *Soil and Tillage Research*, *126*, 276-283.

Janzen, H. H., van Groenigen, K. J., Powlson, D. S., Schwinghamer, T., & van Groenigen, J. W. (2022). Photosynthetic limits on carbon sequestration in croplands. *Geoderma*, *416*, 115810.

Jian, J., Du, X., Reiter, M. S., & Stewart, R. D. (2020). A meta-analysis of global cropland soil carbon changes due to cover cropping. *Soil Biology and Biochemistry*, *143*, 107735.

Joshi DR, Sieverding HL, Xu H, Kwon H, Wang M, Clay SA, Johnson JM, Thapa R, Westhoff S, Clay DE. 2023. A global meta-analysis of cover crop response on soil carbon storage within a corn production system. *Agronomy Journal*.

Khan, S. A., Mulvaney, R. L., Ellsworth, T. R., & Boast, C. W. (2007). The myth of nitrogen fertilization for soil carbon sequestration. *Journal of environmental quality*, *36*(6), 1821-1832.

Kuo, S., Sainju, U. M., & Jellum, E. J. (1997). Winter cover cropping influence on nitrogen in soil. *Soil Science Society of America Journal*, *61*(5), 1392-1399.

Liang, B. C., VandenBygaart, A. J., MacDonald, J. D., Cerkowniak, D., McConkey, B. G., Desjardins, R. L., & Angers, D. A. (2020). Revisiting no-till's impact on soil organic carbon storage in Canada. *Soil and Tillage Research*, *198*, 104529.Luo, Z., Wang, E., & Sun, O. J. (2010). Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. *Agriculture, ecosystems & environment*, *139*(1-2), 224-231.Mandal, U. K., Singh, G., Victor, U. S., & Sharma, K. L. (2003). Green manuring: its effect on soil properties and crop growth under rice–wheat cropping system. *European Journal of Agronomy*, *19*(2), 225-237.

Mazzoncini, M., Sapkota, T. B., Barberi, P., Antichi, D., & Risaliti, R. (2011). Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. *Soil and tillage research*, *114*(2), 165-174.

McDaniel M, Tiemann L, Grandy AS (2014) Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. Ecol Appl 24:560–570. doi:10.1890/13- 0616.1

Metay, A., Moreira, J. A. A., Bernoux, M., Boyer, T., Douzet, J. M., Feigl, B., ... & Scopel, E. (2007). Storage and forms of organic carbon in a no-tillage under cover crops system on clayey Oxisol in dryland rice production (Cerrados, Brazil). *Soil and Tillage Research*, *94*(1), 122-132.

Moore, E. B., Wiedenhoeft, M. H., Kaspar, T. C., & Cambardella, C. A. (2014). Rye cover crop effects on soil quality in no-till corn silage–soybean cropping systems. *Soil Science Society of America Journal*, *78*(3), 968-976.

N'Dayegamiye, A., & Tran, T. S. (2001). Effects of green manures on soil organic matter and wheat yields and N nutrition. *Canadian Journal of Soil Science, 81*(4), 371-382.

Ogle, S. M., Alsaker, C., Baldock, J., Bernoux, M., Breidt, F. J., McConkey, B., and Vazquez-Amabile, G.G. (2019). Climate and soil characteristics determine where no-till management can store carbon in soils and mitigate greenhouse gas emissions. *Scientific reports*, *9*(1), 11665.Olson, K., Ebelhar, S. A., & Lang, J. M. (2014). Long-term effects of cover crops on crop yields, soil organic carbon stocks and sequestration. *Open Journal of Soil Science*, *2014*.

Paustian, K., Lehmann, J., Ogle, S., Reay, D., Robertson, G. P., & Smith, P. (2016). Climate-smart soils. *Nature*, *532*(7597), 49-57.

Poeplau, C., & Don, A. (2015). Carbon sequestration in agricultural soils via cultivation of cover crops–A meta-analysis. *Agriculture, Ecosystems & Environment*, *200*, 33-41.

Poeplau C, Bolinder MA, Kirchmann H, Kätterer T (2016) Phosphorus fertilisation under nitrogen limitation can deplete soil carbon stocks: evidence from Swedish meta-replicated long-term field experiments. Biogeosciences 13:1119–1127. doi:10.5194/bg-13-1119-2016

Sainju, U. M., Singh, B. P., & Whitehead, W. F. (2002). Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. *Soil and Tillage Research*, *63*(3-4), 167-179.

Sainju, U. M., Singh, B. P., Whitehead, W. F., & Wang, S. (2006). Carbon supply and storage in tilled and nontilled soils as influenced by cover crops and nitrogen fertilization. *Journal of environmental quality*, *35*(4), 1507-1517.

Tellatin, S., Myers, R.L., 2018. Cover crop impacts on US cropland carbon sequestration. Journal of Soil and Water Conservation 73, 117A–121A. https://doi.org/10.2489/jswc.73.5.117A.

Thomsen, I. K., & Christensen, B. T. (2004). Yields of wheat and soil carbon and nitrogen contents following long-term incorporation of barley straw and ryegrass catch crops. *Soil Use and Management*, *20*(4), 432-438.

Utomo, M., Frye, W. W., & Blevins, R. L. (1990). Sustaining soil nitrogen for corn using hairy vetch cover crop. *Agronomy Journal*, *82*(5), 979-983.

Vieira, F. C. B., Bayer, C., Zanatta, J. A., Mielniczuk, J., & Six, J. (2009). Building up organic matter in a subtropical Paleudult under legume cover-crop-based rotations. *Soil Science Society of America Journal*, *73*(5), 1699-1706.

Xiao, L., Zhou, S., Zhao, R., Greenwood, P., & Kuhn, N. J. (2020). Evaluating soil organic carbon stock changes induced by no-tillage based on fixed depth and equivalent soil mass approaches. *Agriculture, Ecosystems & Environment*, *300*, 106982.

Swanson C. O. and W. L. Latshaw. 1919. Effect of alfalfa on the fertility elements of the soil 'in comparison with grain crops. Soil Science Vol 8, (1) 1-39.

Wendt, J. W., & Hauser, S. (2013). An equivalent soil mass procedure for monitoring soil organic carbon in multiple soil layers. *European Journal of Soil Science*, *64*(1), 58-65.

Zeng W.; Wang Z.; Chen X.; Yao X.; Ma Z.; Wang W. 2023. Nitrogen deficiency accelerates soil organic carbon decomposition in temperate degraded grasslands STOTEN. In press.