RESPONSE LETTER TO REVIEWER #1

Dear Reviewer,

Thank you for your highly constructive feedback. We explain in detail below how we addressed your comments. The reviewer's comments are in black, and our responses are in blue.

Reviewer #1

This paper does a great job bridging academic science and agricultural practice. They did a considerable amount of work, collected interesting and useful data, and reached insightful findings that deserve to be highlighted.

General comments

"Digging deeper: assessing soil quality in a diversity of Conservation Agriculture Practices" presents novel data and understanding of the effects of conservation agricultural practices on several metrics of soil quality. Twenty-eight farms using Conservation Agriculture in Wallonia, Belgium, are sampled and surveyed to document the agricultural practices used and fifteen soil quality outcomes. The agricultural practices and soil properties outcomes are conceptualized within the framework of previous work by the same authors (Ferdinand and Baret, 2024). Correlations are calculated between farming practice and soil quality, indicating that the rotation of temporary grassland substantially improves soil organic carbon content and soil stability. The co-dependence of multiple conservation practices is highlighted, particularly in the case of reduced tillage, which is observed to not be strongly beneficial without other concurrent conservation practices.

Overall, the manuscript is interesting and very high quality. The study is well-conceptualized, the data collection is comprehensive and valuable, and the results are well-presented. The primary strength of the study is the comprehensive dataset which characterizes practices at 28 conservation agriculture farms. The data is clearly carefully collected and has insights to offer. The analysis and discussion effectively address the topic of additive benefits of multiple practices, rather than dichotomous classification based on single practices.

The manuscript could be strengthened by adding further analysis and discussion on the context-dependent success of various strategies. This important topic is noted in the introduction and the conclusions, but not addressed substantively. The farms included in this study span a climactic gradient and range from permanent cropland to pasture rotation – it would be compelling to understand how practices and outcomes covary with the context in which they are applied.

Thank you for your encouraging feedback, which is highly appreciated. We agree with your comment about the strong dependency between soil and climatic conditions, farming systems (e.g., arable cropping *vs* systems strongly connected to animal husbandry), and the performance of the three pillars of CA (e.g. permanent soil cover is much easier in arable-ley rotations than in arable cropping systems). The strong link between CA-types and the specificity of farming systems is now explained specifically in the introduction when describing the CA-types investigated; in the methods the link between soil and climatic conditions and the typology of farming systems is clearly established; Several elements in the discussion already put forward the strong interdependence between farming systems, agricultural practices soil, and climatic conditions. According to your advice, we propose emphasizing this point in each point of the discussion: e.g.

4.1. "*Our dataset includes crop-livestock mixed farming systems with ley-arable rotation. In such systems, soil cover indicators have very high values and organic matter inputs from ley and farmyard manure favor soil organic matter storage, which improves the overall resilience and stability of soil structure (in line with an increase in the SOC:clay ratio).*"

4.2. "*Our results support the view that maintaining or achieving high SOC stocks is challenging in arable farming systems disconnected from animal husbandry. Indeed, in such systems temporary grassland is generally absent, crop succession has a high proportion of spring crops and access to cattle manure may be limited.*"

4.3. "*In order to assess the covariation between CA-type and climate conditions, a balanced sampling protocol would have been necessary. However, the GEM type appears more prevalent in southern Wallonia, while the CIN type predominantly occupies the northern part. In some respects, we are faced with a circularity as some practices are only present in certain soil types, and those soil types constrain the practices that can be implemented and affect the outcomes of these practices.*";

The second paragraph of the conclusions contributes to summarize this challenge: "*These findings highlight the need to move beyond simplistic dichotomies when evaluating the agronomic and environmental performance of CA systems, whose response depends on local soil, crop and climatic conditions and the specific combination of practices implemented. Our study also revealed that the most important factors for the control of soil quality (e.g., tillage, C inputs, occurrence of temporary grassland, tillage-intensive crops) are intimately linked to (i) the productive orientation of the farm and (ii) the organic certification. These two elements were also dominant in the definition of CA-types by Ferdinand and Baret (2024). This is not surprising because both factors largely influence crop rotations, the choice of cultivars and associated soil management practices, which in turn control soil quality. To refine the results of this work, a comparison between CA versus conventional farms from the same productive orientation and within the same soil and climatic region would be appropriate to assess the specific benefits of CA.*"

1. Specific comments

1.1. The methods section is extremely thorough, but the detailed description of the soil chemical analysis could be edited for brevity or moved partially to the supplement. Additionally, several analyses are introduced that are not discussed – perhaps these could be moved to the supplement as well.

Thank you for your feedback. We propose shortening the section to improve clarity and brevity, and adding a new supplementary data section dedicated to additional soil chemical analyses. In particular, the description of POXC measurement is currently too detailed compared to the other methods. We propose to make it more concise:

"Permanganate oxidizable carbon (POXC) constitutes a labile sub-pool of SOC, defined as the carbon oxidized by 0.02 M potassium permanganate (KMnO4) (Huang et al., 2021). POXC was measured following Culman et al. (2012): 2.5 g of soil were incubated in 20 ml of 0.02 M KMnO4 for 10 minutes, and POXC was calculated from the remaining MnO4- concentration, determined by spectrophotometry at 550 nm. The labile SOC fraction was expressed as the ratio of POXC to SOC contents (POXC:SOC) and used as an indicator of nutrient cycling, soil structure, and microbial activity associated with soil degradation or restoration (Bongiorno et al., 2019; Weil et al., 2003)."

Permanganate oxidizable carbon is used to measure the labile carbon pool, but this metric is known to be sensitive to soil type to some extent – this should be addressed in the methods or the discussion.

Thank you for your comment. Indeed, as Culman et al. (2012) point out, the POXC measurement is sensitive to soil conditions. However, our data span over a relatively narrow range of soil type and properties (pH, texture), suggesting that soil conditions have limited impact on POXC results compared to agricultural practices. Accordingly, we did not observe any significant correlation between POXC and pH and texture variables (see supplementary data S4), which support the view that POXC results are not biased by soil type. We propose to add a paragraph in the section 3.3.2.: "*Although POXC is known to be partially sensitive to soil type (Culman et al., 2012), this effect appeared minimal in our dataset. The soils included in this study covered a relatively narrow range of textural classes, with clay content ranging from 11.6% to 21.5%. No significant correlation was found between POXC and pH or granulometry fractions (see Supplementary Data S4), which support the view that soil type interfered poorly with POXC response to CA-types.*"

1.2. CA type is used heavily throughout the manuscript, but the motivation is not specifically addressed. Further discussion could help clarify the utility of this classification.

Thank you for your comment. We propose adding a sentence to explain our motivation in the Introduction: *"The categorization of CA-types highlights the diversity of cropping systems on CA farms, and helps to understand the relationship between a farm's productive orientation, the extent to which CA practices are implemented, and soil quality metrics."*

1.3. It is not clear what happened to the seven field not assigned to any CA type. Why were those fields not classified? Were those fields included in the analysis of correlation between practices and outcomes? It seems they would have information about the breadth of CA practices actually in use, and for the analysis in table 2 and figure 3, as well as further analysis of context.

Thank you for your comment. Although archetypal analysis offers a better identification of distinct practices, it results in a high percentage of unclassified practices (e.g., 35% in Tittonell et al. (2020) and 43% in Tessier et al. (2021)). Combining it with hierarchical clustering reduces this number by creating intermediate groups (Ig1 and Ig2).

We propose to explain this more clearly : "*Seven fields were not assigned to any CA-type, as archetypal analysis—while improving the identification of distinct practices—typically leaves a substantial share of practices unclassified, even when complemented by hierarchical clustering to reduce this proportion (Ferdinand and Baret, 2024)*."

Although removing the seven unclassified fields from any CA-type reduces the data, we decided to exclude them from the analysis because our goal is to use CA-types as an entry point to assess the impact of CA on specific soil quality indicators.

We added this explanation in section 2.4. : "Data analysis focuses only on fields falling within one of the CA-types (excluding the seven unclassified fields), as our goal is to use CA-types as an entry point to assess the impact of CA on specific soil quality indicators."

1.4. Gradients in soil and climate are introduced but not used for the analysis or discussion. To interpret the results, it would be useful at minimum to understand the covariation of CA type and climate/geology. This could shed light on to what extent practice or underlying factors are responsible for the observed differences in outcome.

Thank you for your comment. To understand the covariation of CA-type and climate/geology, a balanced sampling protocol with sufficient numbers of fields per CA-type and agricultural region would have been necessary, requiring sample size calculations and classification of CA-types prior to field sampling. However, the CA-types, i.e., the implementation of the three pillars, are linked to the characteristics of the farms, which are dependent on the terroir (climate, soil, cultural practices, etc.). Therefore, we doubt that all Walloon CA-types are present in each agricultural region; for instance, the GEM-type appears more prevalent in southern Wallonia, while the CIN-type predominantly occupies the northern part. This is a constraint that cannot be influenced.

We propose to add this explanation in section 4.3. "*In order to assess the covariation between CA-type and climate conditions, a balanced sampling protocol would have been necessary. However, the GEM type appears more prevalent in southern Wallonia, while the CIN type predominantly occupies the northern part. In some respects, we are faced with a circularity as some practices are only present in certain soil types, and those soil types constrain the practices that can be implemented and affect the outcomes of these practices.*"

It should also be noted that the last line of the paper also addresses this issue: "*To refine the results of this work, a comparison between CA versus conventional farms from the same productive orientation and within the same soil and climatic region would be appropriate to assess the specific benefits of CA.*"

2. Technical comments

The manuscript is well written and edited, with only a few confusing word choices:

2.1. 38: should be "and also to unsustainable …"

Thank you for your comment. We have reworded the sentence accordingly: "This is due to increased pressure on the land to support human infrastructures and activities, and also to unsustainable farming practices (Mason et al., 2023)."

2.2. 47-49: "on the one hand"/"on the other hand" indicates conflicting ideas – different transition words here would make more sense

Thank you for your comment. We have replaced these terms with "First" and "Additionally": "First, OM increases the stability of soil aggregates, […]. Additionally, the increase in OM in topsoil horizons may affect positively soil fertility, […]."

2.3. 2.3.153: change "combined to a" to "combined with a"

Thank you for your comment. We have made the change: "Briefly, the method classifies CA practices by an archetypal analysis combined with a hierarchical clustering analysis (Ferdinand and Baret, 2024)."

2.4. 3.166: Pie roll = rolling pin?

Thank you for your comment. For the sake of clarity and conciseness (to respond to your first specific comment), we have rewritten the sentence: "All samples were dried at room temperature for at least one week, then gently ground and sieved to 2 mm."

2.5. 3.3.30: "average per CA type" is not clear what was done

Thank you for your comment. We have removed this element from the sentence to avoid any confusion: "The fields were classified according to threshold values of SOC:Clay ratios (1:13, 1:10, and 1:8) proposed by Johannes et al. (2017), corresponding to expected levels of soil structural (in)stability (Figure 4)."

2.6. 2.80: "enrich" => "enriching"

Thank you for your comment. We have reworded the sentence accordingly: "These C inputs from the rhizosphere increase the labile, N-rich SOC fraction, which gradually contributes to enriching stable SOC stocks, dominated by mineral-associated SOC (Liang et al., 2017; van Wesemael et al., 2019)."

REFERENCES

Johannes, Alice, Adrien Matter, Rainer Schulin, Peter Weisskopf, Philippe C. Baveye, et Pascal Boivin. 2017. « Optimal Organic Carbon Values for Soil Structure Quality of Arable Soils. Does Clay Content Matter? » *Geoderma* 302 (septembre): 14-21. https://doi.org/10.1016/j.geoderma.2017.04.021.

Prout, Jonah M., Keith D. Shepherd, Steve P. McGrath, Guy J. D. Kirk, et Stephan M. Haefele. 2020. « What Is a Good Level of Soil Organic Matter? An Index Based on Organic Carbon to Clay Ratio ». *European Journal of Soil Science* 72 (6): 2493-503. https://doi.org/10.1111/ejss.13012.

Tessier, Louis, Jo Bijttebier, Fleur Marchand, et Philippe V. Baret. 2021. « Identifying the Farming Models Underlying Flemish Beef Farmers' Practices from an Agroecological Perspective with Archetypal Analysis ». *Agricultural Systems* 187 (février): 103013. https://doi.org/10.1016/j.agsy.2020.103013.

Tittonell, P., O. Bruzzone, A. Solano-Hernández, S. López-Ridaura, et M. H. Easdale. 2020. « Functional Farm Household Typologies through Archetypal Responses to Disturbances ». *Agricultural Systems* 178 (février): 102714. https://doi.org/10.1016/j.agsy.2019.102714.