

### Comprehensive tools for ecological restoration of soils foster sustainable use and resilience of agricultural land.

Corresponding Author: Dr Lena Neuenkamp

**This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.**

**Attachments originally included by the reviewers as part of their assessment can be found at the end of this file.**

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

In this qualitative review, Neuenkamp and colleagues aim to explore recent developments in restoration science in order to improve sustainability of agricultural soils. This is a noble endeavour, particularly given the substantial amount of work on sustainability of soils in the agricultural sphere.

At the outset, I found it extremely difficult to understand exactly where the authors were leading with this manuscript for two main reasons. First, the exact meaning of a lot of the text is unclear, mainly because of the length of the sentences and the way that they are constructed. The text is extremely verbose and could be written in substantially fewer words. This will improve the readability and allow the authors to focus on the truly novel parts of the manuscript. I honestly believe that the way forward for this manuscript is that it should be reviewed by a competent editor whose native language is English. This is critical in order to make sure that many of the sentences, which are quite convoluted, make absolute sense to the reader. There are many examples throughout the manuscript, for example "ecosystem restoration by the Society of ecological restoration that is due to the lack of data...", "Ecosystem degradation among scientists...". My point is not to criticise what has been written, but unless the text is logical, then it's impossible for the reader to understand exactly what you mean.

The second thing that is needed is more signposting, where you tell the reader something about the preceding section, what is important, and how it improves our understanding of restoration of agricultural systems. An example of this would be the five sections beginning on L176. An appropriate heading, something like 'Five goals of soil restoration' will then guide the reader to the important material and allow them to understand where the manuscript is heading.

Third, more could be made of the excellent depiction of conflicts and goals for soil restoration presented in Figure 2. It wasn't clear to me whether this is an original figure that has been designed by the authors, or it comes from another publication, but structured discussion about the meaning of this figure, how it helps us to understand soil restoration in agricultural environments, and feedbacks and trade-offs would be a very useful addition to the paper and would provide the novelty. There is a lot of proceeding text about general impacts of restoration on soils microbial communities. This is interesting, but is not particularly novel. Incorporating this type of information in the description of your model in figure 2 would be a great way to contribute to the science of soil restoration.

Reviewer #2

(Remarks to the Author)

Great paper! Please find my suggestions attached in a MS Word document.

Reviewer #3

(Remarks to the Author)

The authors present an interesting manuscript, with important information on ecological restoration of agro/ecosystems and emphasizing on soils. They suggest including the restoration of agricultural soils to improve their productive performance and yield.

Overall, they have done a good job on bringing the literature together on the topic. The subject is generally well covered but too general in the approach. It lacks depth on several subjects. Nor do they consider important aspects that can affect a restoration program, for example, how do these processes and recommendations vary along climatic gradients? How does this vary with type or intensity of agricultural disturbance?

Using the same general framework, I would recommend the author to develop the text and make it more practical and useful. I suggest including a monitoring section.

Adding, throughout the text there are several problems in contextualization. One of them, for example, is to generalize soils when referring to agricultural soils; There are also statements with deficient or without any support in bibliographical references.

I would appreciate it if the authors included a discussion or a comparative analysis between the actions to achieve success in a restoration of agricultural soils and good agricultural practices (agroecology or ecological agriculture, organic agriculture, conservation agriculture and others).

The authors propose five restoration goals for soil restoration and some indicators. But,

- All goals must be reformulated, emphasizing on agricultural soils (then, it is correct to refer later to the challenges of this type of restoration). Ideas must be clear and well developed. The content is very general, without any connection to put it into practice or reference that allows viewing it. It must be greatly improved.
- Indicators need to be developed. These should provide a practical means of evaluating the progression and success of a restoration. There is nothing in the content related to this.

An Implications and Future Research section is included, but it is very underdeveloped. The implications may be worth an entire section, while Future research could be included in a more reflexive manner.

In the last paragraph of the manuscript, the authors write as a conclusion, the importance of integrating the social dimension. But this is not developed in the manuscript and is just mentioned superficially. I believe that the role of knowledge and the interests of farmers and other stakeholders involved in the target agro-system of restoration should be considered and developed. Because these stakeholders are a dynamic/drive (or halt) agent in any process that affects their main (sometimes exclusive) economic activity.

While it is a well-written paper, there are a few spots where a dedicate review could help with excess words in one's sentences.

Additionally, I suggest the following changes:

Page 2. Line 34. I suggest changing ">" to, for example, "more than..."

Page 3. Line 73-76. Please be more concise. Clearly summarize the idea that you want to transmit.

Page 3. Line 76-78. I consider this statement to be incorrect nowadays. I can find several articles, works, theses, reports, and others, where the importance of soil in the recovery of ecosystems (ecological restoration) is highlighted. I suggest changing the idea to, for example, "Therefore, soils are increasingly considered in restoration programs..."

Page 4. Line 83-84. Ecological restoration is only one of the ways (and after the damage), it is also very important to change agricultural management, making it more ecological, and other aspects. Please don't reduce it.

Page 4. Line 90-92. Please be more concise. Clearly summarize the idea that you want to transmit.

Page 4. Line 93. I suggest remove "missing". You should be more careful with these types of statements.

Page 4. Line 95. "agricultural land impacts"? Do you mean "impacts of poor agricultural practices on soils"?

Page 5. Line 98-100. I suggest being more concise or splitting this sentence into two.

Page 5. Line 115. You are repeating fertilizers and pesticides. I suggest changing those two to "contamination"

Page 5. Line 116. What about soil biodiversity?

Page 5. Line 119. It seems to me that you are being repetitive. However, if you are going to keep this sentence, you should add reference(s).

Page 7. Line 153-155. Ecological restoration must consider all the main components of the ecosystem. If a restoration excludes or minimizes the soil dimension, this restoration is not ecological. Please re-paraphrase this statement. I suggest review Morales-Márquez and Meloni. 2023. DOI 10.1111/rec.13686.

Page 8. Line 176. The proposal in this restoration objective is very similar (or the same) to what is suggested to be done from agroecological practices or in conservation agriculture. I don't understand why it's included here as a new idea or restoration goal.

Page 8. Line 191. "...human health"? Do you mean "human society" or "human well-being"? You are limiting a lot and being very reductionist. This paragraph needs to be rephrased. It's confusing. This objective should be developed further and clearly.

Page 11. Line 242-243. This figure seems interesting, but it must be explained/developed in the text, not in supplementary material.

Page 11. Line 246. I consider that this section could be built into bullet points or listing the challenges for easier visualization and understanding. Regarding part of its content, generalized statements call my attention, for example: it is generalized that

maximizing the quality of the soil and its function is contrary to agricultural production and yields. This is a fact that depends on the management of the agrosystem and environmental conditions (see DOI: 10.1016/S2095-6339(15)30010-1). You must be careful when you generalize situations.

Page 13. Line 273-274. For Figure 2, please apply the same as for Figure 1. Additionally, I believe that statements such as “ ‘Better water management’ has a negative impact on ‘Resource use efficiency’ ” must be reviewed. In most cases, this is partially or completely incorrect. Please review and support these statements very well.

Page 13. Line 279-280, and 284. I don't understand why you put "human health"... do you mean "human well-being"? Why only health?... what about the other socio-environmental aspects?

Page 14. Line 340. I suggest review Sarmiento et al. 2002. “Balancing Conservation of Biodiversity and Economic Profit in the High Venezuelan Andes: Is Fallow Agriculture an Alternative?”. DOI: 10.4324/9780429342585-24. Here link.

Page 19. Line 422. I suggest review Hernández-Hernández, R. M. et al. 2011. The integration of local and scientific knowledge in the sustainable management of soils in savanna agroecosystems. *Interciencia* 36, 104–112 (2011). Here link.

Page 19. Line 423. Please change "Actual" to "Current".

Furthermore, it is not the current rates of ecosystem degradation that are boosting development and research, but rather the search for solutions to this problem. Please rephrase.

Page 19. Line 428. What program or object from the FAO Global Soil Partnership?

Page 19. Line 441-444. This sentence is very long and confusing, please rephrase.

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

Please see attached MS Word document.

Reviewer #3

(Remarks to the Author)

I am happy with improvements done in the paper during review which in my opinion substantially improve overall quality of the ms.

Version 2:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

The authors have worked diligently to illuminate a challenging topic direly needed in our time, bring all the scientific literature and restoration logic to task, and provide a useful and understandable article and scenarios. The result is a novel summary of literature and implementation of the science that is timely and helpful. Thank you for the thoughtful implementation of prior comments and hard work refining the manuscript. I recommend the article for publication.

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*Line-by-line response to the reviewers' comments (in blue and italics); referenced line numbers are highlighted in yellow in the manuscript.*

Reviewers' comments:

**Reviewer #1 (Remarks to the Author):**

In this qualitative review, Neuenkamp and colleagues aim to explore recent developments in restoration science in order to improve sustainability of agricultural soils. This is a noble endeavour, particularly given the substantial amount of work on sustainability of soils in the agricultural sphere.

At the outset, I found it extremely difficult to understand exactly where the authors were leading with this manuscript for two main reasons. First, the exact meaning of a lot of the text is unclear, mainly because of the length of the sentences and the way that they are constructed. The text is extremely verbose and could be written in substantially fewer words. This will improve the readability and allow the authors to focus on the truly novel parts of the manuscript. I honestly believe that the way forward for this manuscript is that it should be reviewed by a competent editor whose native language is English. This is critical in order to make sure that many of the sentences, which are quite convoluted, make absolute sense to the reader. There are many examples throughout the manuscript, for example "ecosystem restoration by the Society of ecological restoration that is due to the lack of data...", "Ecosystem degradation among scientists...". My point is not to criticise what has been written, but unless the text is logical, then it's impossible for the reader to understand exactly what you mean.

The second thing that is needed is more signposting, where you tell the reader something about the preceding section, what is important, and how it improves our understanding of restoration of agricultural systems. An example of this would be the five sections beginning on L176. An appropriate heading, something like 'Five goals of soil restoration' will then guide the reader to the important material and allow them to understand where the manuscript is heading.

*Response:*

*Thank you for pointing out the lack of clarity in some sentences. During writing one becomes a bit blind to such aspects. We have gone through the whole text and shortened long sentences.*

*We also added more signposting.*

*As an example, we now introduce the logical structure of the restoration goal section better, by mentioning "five restoration goals" directly in the subheading. We believe that with this clearer subheading and the preceding sentence to the description of the five goals: "To foster holistic ecosystem restoration strategies that can be applied to agricultural soils, we propose the following five soil restoration goals." (l130)*

*We did the same with structuring the challenge section better into subsections ordered by restoration goals (l1213-340).*

*"Thus, in the following lines we explore our current understanding and possibilities for synergies and trade-offs between soil restoration and agricultural production goals and associated actions (Fig. 1, Supplementary Table S1)." (l1237-239)*

Third, more could be made of the excellent depiction of conflicts and goals for soil restoration presented in Figure 2. It wasn't clear to me whether this is an original figure that has been designed by the authors, or it comes from another publication, but structured discussion about the meaning of this figure, how it helps us to understand soil restoration in agricultural environments, and feedbacks and trade-offs would be a very useful addition to the paper and would provide the novelty. There is a lot of proceeding text about general impacts of restoration on soils microbial communities. This is interesting, but is not particularly novel. Incorporating this type of information in the description of your model in figure 2 would be a great way to contribute to the science of soil restoration.

*Response:*

*We agree and now introduce Figure 2 and a new Figure 3 better in the text. They are all self-made by the authors. We also explain the relationships detailed in the Figures in the text and add effect sizes to the Figures where appropriate. While we kept the direction of intended effects in the restoration actions (Fig.2, now Fig.1) we following the reviewer's suggestion by linking actions to soil properties and those to agricultural goals. We do this by highlighting the general link to the figures in the beginning of the respective section in the text and then mentioning the elements detailed in the figure one-by-one. We feel this way effects are better to grasp.*

*Figure1 has been deleted from the manuscript. Figure 2 (now Figure1) is introduced in section "Aligning soil restoration with agricultural production goals" (ll213-340), new Figure 2 in section "Implication for restoration of agricultural soils" (ll359-458).*

#### **Reviewer #2 (Remarks to the Author):**

Great paper! Please find my suggestions attached in a MS Word document. (*Comments copied below*).

#### **Summary:**

This study adds to crucial scientific knowledge about agro ecology regarding the need for considering soil communities. This review is unique in providing clear outlines of how different actions may affect both ecological goals and agricultural goals positively and/or negatively, and by providing clear examples of ways to balance both goals.

#### **Overall Impression:**

This review is highly needed. It is a crucial addition to the discussion of how ecological restoration applies to lands with multiple uses and/or that are recognized as areas where "pristine" conditions or maximum ecological functioning may not return, and how on these lands we can (and should) still support the maximum ecological functioning possible.

*Response:*

*We thank the reviewer for this positive response!*

## Suggestions

- Line 135: Recommend including Pankova et al. (2018) and Helander et al (2018).

*Response: We thank the reviewer for suggesting them and included them in the early version of our revision. Yet, finally, for increasing the conciseness of the manuscript and its focus on the most novel parts (soil restoration) we only mention agricultural impacts on soil in general without going into detail. So, the mentioned section was deleted and the references thus not included. If the reviewer feels we should include them in another section of the manuscript we are happy to do so.*

- Overall, and for the goals starting on p 176: Suggest that goals could apply to areas that have multiple and/or competing uses or where it has been recognized that the ultimate restoration goal is not a pristine condition. For example, heavy machinery is also used to log forests, and/or thin forests in the US to prepare them for the return of fire (see Gibson et al. 2023, for example), which has negative effects on soil compaction/structure and soil biology.

*Response:*

*We agree with the reviewer and highlight this aspect in the text and now clearer in Fig1 – foremost with regard to topsoil removal, which has the most contradictory effects compared to the other restoration goals. Including soil properties and how they mediate restoration action effects on agricultural goals hopefully further makes the multiple uses of restoration goals visible.*

- Lines 226-227, and overall: Recommend language be revised to more specifically recommend against the use of foreign/mass produced soil material/inoculants and recommend for the use of locally or regionally appropriate sources that support the full range of native soil biodiversity to the maximum extent possible. For example, see literature on potential spread of mycorrhizal or other invasives, (e.g. Hayward et al. 2015a and 2015b) as well as the ability of foreign mycorrhizae to preclude colonization by local mycorrhizae and spread at the site (e.g. Janouskova et al. 2013). Doing so would also minimize the risk of introducing a pathogen or having other unintended consequences (e.g. lines 374-375). There are also two papers that I'm aware of that are currently in review/prep, and that show that mis-matching soil biodiversity with plant biodiversity can result in meaningful reductions in outcomes such as drought resilience and plant survival. The approach of using local/native soil inoculum also has the advantage of being aligned with the goals, ethics, and standards of ecological restoration (Gann et al. 2019) even if a site is acknowledged as a location that may not ever reach "pristine" status, and being consistent with United Nations' Principles for Ecosystem Restoration (FAO et al. 2021).

*Response:*

*We agree with the reviewer that this is an important aspect that we have not addressed sufficiently so far. We now stressed the importance of inoculum quality/nativity in the section of restoration implications. 1st, in our new section about restoration-yield trade-offs:*

*"Though quite promising as a new possibility for agricultural-restoration in active systems, the side effects of this recently implemented practice are not yet fully clear (Trivedi et al. 2017), e.g., amendments with foreign, mass-produced microorganisms can change the local microbial community and associated soil functions (Hart et al. 2018, Jack et al. 2021)." (l1282-286)*

*And 2nd in the paragraph where we are giving our recommendations for integration of soil restoration into agricultural systems:*

*"Inoculations with microbes are a fast way to see benefits but this potentially has only short-term effects and can negatively affect native soil biodiversity (Neuenkamp et al. 2018b). Especially the use of foreign or mass-produced inoculum might bear the risks of suppressing local microbial communities, their associated benefits, and introducing unwanted invasive or pathogenic microbial taxa (Hart et al. 2018, Jack et al. 2021). To mediate between time-contrasted solutions, native inoculum containing the local biodiversity and matching the environmental conditions should be preferred, which is also in alignment with current standards of ecological restoration (Gann et al. 2019)." (l1407-414)*

- **Figures:** The Figures really form the backbone of how scientists and agricultural specialists will utilize and refer to this paper, so I would love to see the figures come across very clearly. Thus, while they are beautiful figures, I would like to see more time spent making them extremely clear for readers. For example, I found the arrows representing positive and negative effects a little confusing to consider alongside the icons representing effects. I suggest it might be easier for readers if the icons represented a concept/value (e.g. soil organic matter) rather than a concept plus a direction (e.g. soil organic matter loss), and if the arrows were instead plus signs or minus signs (e.g. "+" or "-") to represent whether something helps or hurts those concepts / values? I think the arrows could still be used in the figures where arrows pointing at something are still needed and could just be colour coded the same as the plus and minus signs.

*Response: We agree and now detail the relationships detailed in the Figures in the text and add effect sizes to the Figures where appropriate. We included effect sizes in the figure about trade-offs indirectly (Fig1), by linking actions to soil properties and those to agricultural goals. In this detailed manner all effects are approximately equally important, yet differentiation in links between soil properties and agricultural goals highlight which restoration actions have a strong effect (i.e., through many and/or very relevant soil properties). We followed the reviewer's suggestion, however, directly by differentiating effect sizes with arrow line type in the new Figure 2 linking existing sustainable agricultural practices to soil threats and restoration goals.*

- **Overall:** I suggest that a few of the examples of potential conflicts between agricultural goals and ecological goals could be described individually in the text and/or in figures in more detail. Effect sizes and/or percent changes seen could be discussed, and examples given on things to think about as one tries to navigate balancing both. For example, one that comes to mind for me is the use of fertilizer and/or compost for crops and their effects on mycorrhizae. I think taking one or two concrete examples and walking the readers through the known advantages and disadvantages, their effect sizes, and what might be good to consider to arrive at a decision about what is best to do (e.g. long-term effects, short term effects, costs,



etc.) could be really helpful and informative. This could be in the paper itself, or in the SI, but I think it would really attract readers.

*Response: We agree and now detail the relationships detailed in the Figures in the text and add effect sizes to the Figures where appropriate. For example, we add the time-scale of effects to Figure 1 and walk the reader through the Figure items.*

*Figure1 has been deleted from the manuscript. Figure 2 (now Figure1) is introduced in section "Aligning soil restoration with agricultural production goals" (ll213-340), new Figure 2 in section "Implication for restoration of agricultural soils" (ll359-458).*

- Lines 378-379: Living labs and lighthouse farms would also offer opportunities to test the utility of using local / native mycorrhizae and soil inoculations for the crop species in question.

*Response:*

*Indeed, thank you for the suggestion. We added this aspect to the text:*

*"We further stress that all agricultural restoration measures should be tested for their feasibility and on their effects also on yield together with local communities including farmers. The establishment of 'living labs' and 'lighthouse farms' where farmers co-create together with scientist solutions to improving the soils, are a way forward (Gamache et al. 2020)." (ll417-421)*

- Lines 390-405: The use of hedgerows or flower strips might also have significance with improving soil conditions – for example, these could be the locations for reintroducing soil inoculum that are native and support those native pollinator plant species.

*Response:*

*Exactly, we now highlight this in the text.*

*"As direct soil restoration practice, soil inoculation with native soil from the surroundings could be applied to enhance soil diversity steering hedgerows and other matrix elements towards the favourable conditions that can then allow them to increase crop yield and pollination (Neuenkamp et al. 2018b)." (ll447-450)*

- Abstract: I suggest that at least two or three of the most specific, and novel findings from the paper be specifically reiterated/re-stated in the abstract. For example, if there are actions that contribute to both ecological and agricultural goals, that could be highlighted. If there are activities where there are specific tradeoffs, that could be highlighted, along with a statement about how the authors recommend proceeding or balancing the tradeoffs.

*Response:*

*We changed the abstract accordingly and added the most important results:*

*"Calls for reductions in provisioning services, i.e., yield production, from ecological restoration practices conflict most directly with wider soil-ecosystem-service-focused restoration actions, including also supporting and regulating*

*services. Holistic restoration actions harnessing the interdependence of multiple soil properties, including contribution to vegetative yield, appear to be most efficient, such as recent evidence showing that restoring soil biodiversity leads to multiple benefits through its link with soil functioning. Also acknowledging spatial dependencies in the landscape is a promising soil restoration goal due to spill off effects from high quality soil in the surroundings of agricultural sites, which can lead to soil improvement while minimizing restoration impacts on the agricultural site.” (ll 21-29)*

- **Figures and SI:** These summaries should be really helpful for scientists and agricultural specialists. I would suggest including some examples of effect sizes and/or percent changes where they might be available, to remind folks how crucial each of these aims/impacts are. This might also be something to highlight in the abstract.

*Response:*

*We agree and are happy to read that the reviewer finds these figures useful. This was also our idea behind them. We now added a new Fig 2 to even more summarize the synergies between agricultural approaches and restoration goals, and there we visualized effect sizes for the relationships highlighted in Fig3. These effect sizes are based on how directly or strongly the measures affect a certain soil characteristic. To avoid too much complexity, we divided effects into two groups only (weaker, stronger) highlighted by dashed and solid lines in the Figures and not-bold and bold text in the respective Supplementary Tables. We also highlight the main results now more obviously in the abstract. As for the changed version of Fig. 1 (former Fig.2) we now detail effects more by linking them restoration actions to their respective effects on soil properties, we feel no weighing is needed. As all relationships shown are relevant. The relevance is visible by the number of soil properties affected by a restoration action and its effect on ecosystem services (agricultural goals).*

## **Literature Cited**

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Hayward, Jeremy, et al. "A single ectomycorrhizal fungal species can enable a Pinus invasion." Ecology 96.5 (2015): 1438-1444.

Hayward, Jeremy, Thomas R. Horton, and Martin A. Nuñez. "Ectomycorrhizal fungal communities coinvasive with Pinaceae host plants in Argentina: Glomeromycetes bajo el bosque." *New Phytologist* 208.2 (2015): 497-506.

Helander M, Saloniemi I, Omacini M, Druille M, Salminen J-P, Saikkonen K (2018) Glyphosate decreases mycorrhizal colonization and affects plant-soil feedback. *Science of the Total Environment* 642:285–291. <https://doi.org/10.1016/j.scitotenv.2018.05.377>

Janoušková, Martina, et al. "Effects of inoculum additions in the presence of a preestablished arbuscular mycorrhizal fungal community." *Applied and environmental microbiology* 79.20 (2013): 6507-6515.

### **Reviewer #3 (Remarks to the Author):**

The authors present an interesting manuscript, with important information on ecological restoration of agro/ecosystems and emphasizing on soils. They suggest including the restoration of agricultural soils to improve their productive performance and yield.

Overall, they have done a good job on bringing the literature together on the topic. The subject is generally well covered but too general in the approach. It lacks depth on several subjects. Nor do they consider important aspects that can affect a restoration program, for example, how do these processes and recommendations vary along climatic gradients? How does this vary with type or intensity of agricultural disturbance?

#### *Response:*

*The authors thank the reviewer for the positive view on the manuscript and the constructive comments. While we agree that context-dependency is a relevant point shaping restoration success and needs to be included into restoration planning, the aim of this review was more targeted to give a general overview on potential soil restoration implication possibilities and conflicts in agricultural systems. Thus, we did not add a section on context dependency yet highlight it, where appropriate.*

#### *For example:*

*"To mediate between time-contrasted solutions, native inoculum containing the local biodiversity and matching the environmental conditions should be preferred, which is also in alignment with current standards of ecological restoration (Gann et al. 2019)." (ll411-414)*

Using the same general framework, I would recommend the author to develop the text and make it more practical and useful. I suggest including a monitoring section.

#### *Response:*

*The aspect of monitoring is indeed important and we now embedded the aspect within the restoration goals by linking each goal to an indicator (ll130-214). We further use these indicators to highlight potential synergies and trade-offs between restoration and production goals (Figure 1).*

*We also intended to order goals, trade-offs and implications better within one framework to highlight its applicability better. This we did by embedding everything into the ecosystem service framework which we now detail*

*in the rewritten section on soils need for restoration (ll87-127), pinpointing also to the need of indicators (l106). We hope that these changes enhance the applicability of our ideas.*

Adding, throughout the text there are several problems in contextualization. One of them, for example, is to generalize soils when referring to agricultural soils; There are also statements with deficient or without any support in bibliographical references.

*Response:*

*We now revised the text for clarity and contextualisation.*

I would appreciate it if the authors included a discussion or a comparative analysis between the actions to achieve success in a restoration of agricultural soils and good agricultural practices (agroecology or ecological agriculture, organic agriculture, conservation agriculture and others).

*Response:*

*This seems useful, indeed, so we now amended the text and added an illustration accordingly (Fig.2, and text introducing Fig. 2 in the implication section, ll359-458).*

The authors propose five restoration goals for soil restoration and some indicators. But,

- All goals must be reformulated, emphasizing on agricultural soils (then, it is correct to refer later to the challenges of this type of restoration). Ideas must be clear and well developed. The content is very general, without any connection to put it into practice or reference that allows viewing it. It must be greatly improved.

*Response:*

*The idea of this section was to start proposing soil restoration goals, from the point of soil health and functioning and in the light of agricultural intensification. And to introduce the synergies and trade-offs between both of them as well as solutions. (Fig. 1 and 2). This way we approach the topic from the two sites, can clearly introduce the problems and goals of the restoration and agriculture site to then merging them in the end. Thus, we prefer to not add more agricultural links at this stage.*

*In any case, we streamlined the two parts to enhance the focus on agriculture, e.g. by toning down the focus on potential soil and vegetation restoration conflicts. Further, we make the linkage to agricultural practices stronger in the implications section where we group actions also in the light of already applied agricultural practices.*

- Indicators need to be developed. These should provide a practical means of evaluating the progression and success of a restoration. There is nothing in the content related to this.

*Response:*

*We now more clearly linked each restoration goal to a potential indicator just below each restoration goal. We also use these indicators (soil properties) to explain the trade-offs and synergies between restoration and agricultural goals in Fig 1 (former Fig. 2).*

*"Restoration strategies also require indicators of the degree of soil degradation and restoration success (Prach et al. 2019, Marchand et al. 2021). Soil quality and its associated soil properties might serve well here (Grifith et al. 2016)." (ll 109-111)*

An Implications and Future Research section is included, but it is very underdeveloped. The implications may be worth an entire section, while Future research could be included in a more reflexive manner.

*Response:*

*We agree with the reviewer. Thinking about this comment we realized that the section before on how to integrate soil restoration techniques into agriculture fulfils the function of the implication section. So, we renamed this section to " Implications for restoration of agricultural soils"(ll 359-464). We accordingly renamed the Implications&Future Research section to "Future Research". The latter now only contains the ideas/reflexions on future research (ll 464-503).*

In the last paragraph of the manuscript, the authors write as a conclusion, the importance of integrating the social dimension. But this is not developed in the manuscript and is just mentioned superficially. I believe that the role of knowledge and the interests of farmers and other stakeholders involved in the target agro-system of restoration should be considered and developed. Because these stakeholders are a dynamic/drive (or halt) agent in any process that affects their main (sometimes exclusive) economic activity.

*Response:*

*We agree with the reviewer but think that including this aspect in the core of the review would exceed the scope of a mini-review, which covers already many aspects only focussing on the non-human aspects. But we agree that the social dimension is important and thus to be mentioned in the future research section. would exceed the goal of this review. We highlight this fact now more clearly in the text.*

*" Finally, an aspect that has not been explicitly focused on in this review but that we emphasized as important to consider in the introduction, is the social aspect of ecological restoration, i.e., the inclusion of diverse stakeholders and diverse sources of knowledge, including traditional ecological knowledge, into restoration projects. This is not a new idea; it has been put forward as a strategy to enhance restoration success and acceptance of restoration projects within the populations most closely affected by these very measures (Elias et al. 2022, Ladouceur et al. 2022)." (ll497-503)*

While it is a well-written paper, there are a few spots where a dedicate review could help with excess words in one's sentences.

*Response:*

*We are pleased about the overall positive impression of our manuscript. We went through the text and shortened overlong sentences and rephrased where necessary to improve clarity. The latter meant also a moderate change of the order of argument in the text. Now we embed the relationship between agricultural goals and restoration goals in the framework of ecosystem services as this enabled a better logical flow of our arguments and thus likely also the applicability of our ideas (ll87-127).*

Additionally, I suggest the following changes:

Page 2. Line 34. I suggest changing ">" to, for example, "more than..."

*Response:*

*The text has been shortened and the comparative statement has been removed:*

*"Human activities including land use expansion and intensification have degraded ecosystems worldwide. This has threatened their biodiversity and supply of ecosystem services (Gibbs et al. 2015, IPBES 2019)." (ll32-34)*

Page 3. Line 73-76. Please be more concise. Clearly summarize the idea that you want to transmit.

*Response:*

*We made the section more concise, deleting the sentence in question.*

Page 3. Line 76-78. I consider this statement to be incorrect nowadays. I can find several articles, works, theses, reports, and others, where the importance of soil in the recovery of ecosystems (ecological restoration) is highlighted. I suggest changing the idea to, for example, "Therefore, soils are increasingly considered in restoration programs...".

*Response: Thank you for pointing this out. We changed the sentence accordingly:*

*"Soils are therefore increasingly included into restoration programs, but a standardized approach based on ecological theory is still largely missing (Baer et al. 2012). While ecological theory is increasingly incorporated into restoration thinking (Wainwright et al. 2020), these ideas mostly focus on vegetation and leave consideration of other parts of the ecosystem, including soils, largely absent (e.g., Baer et al. 2012, Török et al. 2021)." (ll 63-68)*

Page 4. Line 83-84. Ecological restoration is only one of the ways (and after the damage), it is also very important to change agricultural management, making it more ecological, and other aspects. Please don't reduce it.

*Response: We agree and highlight this point in our implication section where we name the practices of sustainable agriculture as potential restoration measures that can be applied on the production site.*

Page 4. Line 90-92. Please be more concise. Clearly summarize the idea that you want to transmit.

*Response:*

*We improved clarity of the whole introduction the sentence highlighting the need for soil restoration and it's alignment with agricultural production reads now like that:*

*"There is thus a need to develop ecological restoration practices customized to agricultural soils, especially if we are to simultaneously meet the UN Sustainable Development Goals of zero hunger, clean water and sanitation, climate action, and life on land (Bach et al. 2020, Nolan et al. 2021, OECD FAO 2022)." (ll72-75)*

Page 4. Line 93. I suggest remove "missing". You should be more careful with these types of statements.

*Response:*

*Changed accordingly and we also checked the text for similar statements:*

*"In this article we aim to provide an overview of ecological-theory-informed restoration actions can be effectively applied in agricultural systems." (ll79-80)*

Page 4. Line 95. "agricultural land impacts"? Do you mean "impacts of poor agricultural practices on soils"?

*Response:*

*Yes, and we changed the phrasing accordingly "agricultural impacts on soil". The sentence in question was deleted but we use this phrasing in the following section:*

*"We suggest that concurrently identifying agricultural impacts on soils and soil restoration goals within the ecosystem service framework may be useful here, as it allows us to find synergies and trade-offs between food production and other ecosystem services provided by agricultural soils (Baer et al. 2012)." (ll101-103)*

Page 5. Line 98-100. I suggest being more concise or splitting this sentence into two.

*Response:*

*Thank you for the suggestion. We changed the phrasing for soil health, which is now introduced as this:*

*„ The concept of soil health is also closely related to that of soil multifunctionality (i.e., the simultaneous functioning of multiple soil functions at high levels, or the supply of multiple soil services at different hierarchical scales); one aspect of soil health, for example, is ecological processes of which many are mediated by soil microbial communities (e.g., organic matter decomposition or nutrient cycling). Restoration measures of soil health can and should thus capture biotic aspects of soil quality, despite their increased complexity, including soil microbial community characteristics (diversity, composition) and microbially-mediated ecosystem process rates and trophic interactions (Griffith et al. 2016, Creamer et al. 2022). (ll 115-122)*

Page 5. Line 115. You are repeating fertilizers and pesticides. I suggest changing those two to "contamination"

*Response: True, indeed. Changed accordingly.*

Page 5. Line 116. What about soil biodiversity?

*Response:*

*Soil biodiversity is included in the term biological soil quality and made this clearer now with naming the three aspects of soil quality now (physical, chemical and biological). We noted that we did not make this connection very clear and introduced it at the beginning of the section (llxxx)*

*„The concept of soil health is also closely related to that of soil multifunctionality (i.e. the simultaneous functioning of multiple soil functions at high levels, or the supply of multiple soil services at high levels) as one aspect of soil health is ecological processes (e.g. organic matter decomposition or nutrient cycling). Restoration measures of soil health should therefore capture aspects of biotic soil quality including soil microbial community characteristics (diversity, composition) and microbially-mediated ecosystem process rates and trophic interactions (Griffith et al. 2016, Creamer et al. 2022). (ll xxx)*

Page 5. Line 119. It seems to me that you are being repetitive. However, if you are going to keep this sentence, you should add reference(s).

*Response:*

*We agree and change/shortened the entire "The need for soil restoration in agricultural systems" section deleting the sentence.*

Page 7. Line 153-155. Ecological restoration must consider all the main components of the ecosystem. If a restoration excludes or minimizes the soil dimension, this restoration is not ecological. Please re-paraphrase this statement.

I suggest review Morales-Márquez and Meloni. 2023. DOI 10.1111/rec.13686.

*Response:*

*We agree with the reviewer that restoration should holistically address all ecosystem components including soil. This is what we wanted to highlight as our motivation to call for a soil restoration strategy as complementary to the*

existing strategies. We changed the text of the paragraph that the reviewer commented on, but made this same point now clearer already in the introduction:

*"Here, we propose that a holistic set of restoration goals should include the following aspects: 1) consideration of both ecosystem processes (i.e., ecosystem functions) and community properties (e.g., species composition and diversity; Bullock et al. 2021, Tian et al. 2022), 2) inclusion of multitrophic community properties (Neuenkamp et al. 2018a), and 3) acknowledgement of socio-cultural values (human economy and traditional knowledge) and the related ecosystem services that are demanded from restored systems (Aronson et al. 2020, Bardgett et al. 2021, Cárdenas Pardo et al. 2023)." (ll53-59)*

*And: "Soils constitute the backbone of all terrestrial ecosystems, and so underpin their biodiversity and ecosystem service supply (Montanarella et al. 2015, Guerra et al. 2021); making them a vital component of any holistic ecological restoration program (Heneghan et. al 2008, Kardol & Wardle 2010, Farrell et al. 2020)." (ll60-63)*

Page 8. Line 176. The proposal in this restoration objective is very similar (or the same) to what is suggested to be done from agroecological practices or in conservation agriculture. I don't understand why it's included here as a new idea or restoration goal.

*Response:*

*We raise this here as a separate restoration goal not because it is new, but in the attempt to compile the existing/important aspects that should be included into soil restoration strategies.*

*From formalizing it as a soil restoration strategy it's importance is highlighted. Now this goal can be filled with existing techniques e.g. from sustainable agriculture. We therefore highlight these synergies now more clearly in the new Figure 2 and the Implication section.*

Page 8. Line 191. "...human health"? Do you mean "human society" or "human well-being"? You are limiting a lot and being very reductionist. This paragraph needs to be rephrased. It's confusing. This objective should be developed further and clearly.

*Response:*

*We deleted this aspect in the current version of our manuscript, as indeed this topic was not focus of our paper.*

Page 11. Line 242-243. This figure seems interesting, but it must be explained/developed in the text, not in supplementary material.

*Response:*

*We agree and applied this suggestion to Figure 1 and 2. While streamlining the paper, we decided however, to shorten the vegetation-focused section and to leave the figure out of the revised version of the paper. The essential point we wanted to make was that foremost topsoil removal can be a restoration measure harmful to soils, which we now visualize in Figure 2 and mention in the text.*

*"Top-soil removal aims to diminish contamination through removal of the active soil layer and has been successfully applied to restore oligotrophic vegetation (Török et al. 2021). Yet, this also causes problems like soil erosion (Klaus 2023, Bardgett et al. 2021), i.e., reduced soil organic carbon content and microbial diversity, which contradicts other soil restoration goals (Fig. 1; Griscom et al. 2017, Morrien et al. 2017, Neuenkamp et al. 2018b, Cotrufo et al. 2022)." (ll 271-276)*

Page 11. Line 246. I consider that this section could be built into bullet points or listing the challenges for easier visualization and understanding. Regarding part of its content, generalized statements call my attention, for example: it is generalized that maximizing the quality of the soil and its function is



contrary to agricultural production and yields. This is a fact that depends on the management of the agrosystem and environmental conditions (see DOI: 10.1016/S2095-6339(15)30010-1). You must be careful when you generalize situations.

*Response:*

*We now structure this section into subsections to ease reader guidance and adapted Figure 2 (now Figure 1) to aid this, too (ll 215-357). Here we link restoration actions to soil properties and those to agricultural goals. This way the reason for some positive and negative effects become clear, which we also differentiate in the accompanying text.*

Page 13. Line 273-274. For Figure 2, please apply the same as for Figure 1. Additionally, I believe that statements such as “ ‘Better water management’ has a negative impact on ‘Resource use efficiency’ ” must be reviewed. In most cases, this is partially or completely incorrect. Please review and support these statements very well.

*Response:*

*We agree and now detail the relationships detailed in the Figures in the text.*

*Figure1 has been deleted from the manuscript. Figure 2 (now Figure1) is introduced in section “Aligning soil restoration with agricultural production goals” (ll213-340), new Figure 2 in section “Implication for restoration of agricultural soils” (ll359-458).*

*We also revised all statements.*

Page 13. Line 279-280, and 284. I don't understand why you put "human health"... do you mean "human well-being"? Why only health?... what about the other socio-environmental aspects?

*Response:*

*We deleted this aspect in the current version of our manuscript, as indeed this topic was not focus of our paper.*

Page 14. Line 340. I suggest review Sarmiento et al. 2002. “Balancing Conservation of Biodiversity and Economic Profit in the High Venezuelan Andes: Is Fallow Agriculture an Alternative?”. DOI: 10.4324/9780429342585-24. Here link.

*Response:*

*Thank you! We now added the reference to the text:*

*“Regenerative agriculture follows a similar approach than organic farming to conserve the soil but puts soil conservation more holistically into focus, i.e., beyond reduction of artificial. external inputs. The approach of regenerative agriculture entails various adaptive, resource-conserving agricultural practices aiming to minimize soil disturbance, keep soils covered and leave living roots inside the soil, encourage diversity, and integrate livestock (Fig. 2; Sarmiento et al. 2002, Khangura et al. 2023).” (ll382-387)*

Page 19. Line 422. I suggest review Hernández-Hernández, R. M. et al. 2011. The integration of local and scientific knowledge in the sustainable management of soils in savanna agroecosystems. Interciencia 36, 104–112 (2011). Here link.

*Response:*

*Thank you! We now added the reference to the text:*

*"From an agricultural point of view, that means enabling food security while combining profitable production with sustainability, ideally while also integrating local and scientific knowledge (Hernández-Hernández et al. 2011). Considering this, soil's immense potential in supporting this task is at the centre of attention (e.g., Soils and the SDGs by FAO's Global Soil Partnership)." (ll467-472)*

Page 19. Line 423. Please change "Actual" to "Current".

Furthermore, it is not the current rates of ecosystem degradation that are boosting development and research, but rather the search for solutions to this problem. Please rephrase.

*Response: Changed accordingly.*

*"Current rates of ecosystem degradation, ongoing climate-change have boosted research and development to find strategies combating these trends." (ll 464-465)*

Page 19. Line 428. What program or object from the FAO Global Soil Partnership?

*Response:*

*We now clarify that we mostly refer to the awareness rising campaign for example to the infographics linking soil to the SDGs. We added a hyperlink now to this infographic. (llxxx)*

*"Considering this, soil's immense potential in supporting this task is at the centre of attention (e.g., Soils and the SDGs by FAO's Global Soil Partnership)." (ll470-472)*

Page 19. Line 441-444. This sentence is very long and confusing, please rephrase.

*Response:*

*We agree and feel it is not needed in the text anymore so deleted it.*

Reviewed: Neuenkamp et al., Ecological restoration of soils to foster sustainable use and resilience of agricultural land

Summary: This study adds to crucial scientific knowledge about agro ecology regarding the need for considering soil communities. This review is unique in providing clear outlines of how different actions may affect both ecological goals and agricultural goals positively and/or negatively, and by providing clear examples of ways to balance both goals.

Overall Impression: This review is highly needed. It is a crucial addition to the discussion of how ecological restoration applies to lands with multiple uses and/or that are recognized as areas where “pristine” conditions or maximum ecological functioning may not return, and how on these lands we can (and should) still support the maximum ecological functioning possible. I commend the authors for the work they have done so far towards refining this manuscript’s analysis and readability. I renew my suggestion that a good goal of the current paper could be outlining the tools available to make these decisions so practitioners have a toolbelt of tools (SER principles for restoration to non-pristine conditions, literature reviews of the impacts of heavy machinery with effect sizes and habitats considered; etc.), and then walking hypothetical practitioners with specific scenarios through using those tools to develop strategies most appropriate for their situation, rather than trying to provide a view of all the possible actions and outcomes. It is a challenging task indeed, to try to outline all potential actions and goals irrespective of specific location, situation, etc. And perhaps more useful to outline context, logic, and pillars / frameworks that can be called-on and improved-upon for agricultural scenarios.

*Authors’ response:*

*We thank the reviewer for the overall positive evaluation and constructive comments. We have taken all of them into consideration and incorporated them as much as possible into the revised version of the manuscript. In our detailed response below we either copy and/or refer the edits in the text by giving line number in the Track-Change version of our manuscript.*

Recommendations:

- Figure 1 contains an enormous amount of useful information. However, the figure remains busy enough that I suggest it will be challenging for folks to use. Suggest breaking it up into a couple figures. The paths of arrows are challenging to follow, for example. Additionally, the “negative” color is difficult to separate visually from the “both” color for arrows. Additionally, since it would be hard to include an exhaustive list, how do we know whether the most important factors in each category are included under each heading? How were those included under each heading determined (interviews with practitioners / farmers’ systematic review of literature?)?

*Authors’ response:*

*We changed the colour of the “both” category to a lighter pink for easing differentiation. We agree that the purple colour chosen before corresponded well with being a mix of positive (blue) and negative (red) but was not easily distinguishable. Further we considered splitting up the figure into different parts as suggested, but finally would prefer to keep the figure as one piece. The figure is indeed dense in information, but our main goal was to show the main trends rather than details i.e. most restoration activities supporting ecosystem attributes and finally ecosystem supporting services while having negative or mixed effects on provisioning services (yield).*

- Figure 2 and its associated supplemental information would benefit from similar attention. For example, how were the items listed in each category determined and how was it determined that those were the most impactful or important ones to list (interviews with practitioners? Systematic review of the literature?)? What criteria were used to determine “weak” or “strong” relationships? What is a relationship is indirect but strong? How is that conveyed / considered? What relationships were left out of this consideration and why?

*Authors’ response:*

*We added information in the Figure captions of Fig 1 and Fig 2 (and the respective Supplementary Tables) explaining the criteria of choice for the selected restoration activities etc. We also changed the labelling of the arrow types to “direct” and “indirect”, which we indeed rather had in mind than “strong” and “weak”. We, too, explained these meanings in the figure caption. The information on activity selection now reads as follows:*

The selection of listed restoration actions are those suggested by the group of authors (stemming from different disciplines of soil and restoration ecology) and recent publications of the topic to improve the most pressing soil threats suggested by the FAO (OECD FAO 2022) and reach the restoration goals suggested by this review. The list of restoration actions albeit not exhaustive should reflect the most straight forward and most applied soil restoration actions.

*Direct and indirect arrows are explained like this:*

Impact strength of sustainable agriculture on soil threats and restoration actions is differentiated as main impacts i.e. those directly addressed by sustainable agricultural strategies, and side impacts i.e. those not directly prioritized by the agricultural strategy and/or occurring indirectly alongside the intended agricultural measures. Intended, direct measures are expected to have generally stronger impact than indirect side impacts.

- Generally throughout, the manuscript could still benefit greatly from a review of the English terms being used, and simplification of the language.

*Authors’ response:*

*We revised the English to improve clarity of the text.*

- Generally, reader understanding, and application of the material would benefit from developing more detailed scenarios and helping a hypothetical farmer work through their particular scenario to make a specific choice.

*Authors’ response:*

*We thank the reviewer for the suggestion and now extended the implication section by introducing two applied restoration examples in a box item (Box 1). Corresponding to the reviewer’s general comments on better integrating the logic of choosing one restoration activity over another and making use of the existing SER material (e.g. see new Table 1), we also introduced the SER framework for measuring restoration success on production sites together with the examples (II426-459) and at relevant places within the restoration section (II485-489, 550-552, 555-560).*

*Introduction to the examples and SER framework at the beginning of the implication section (II 426-459):*

To illustrate the possible implementation and prioritization of restoration goals for agricultural soils, we present the most common restoration activities and apply them to two examples – cases of typical degradation of agricultural soils (Box 1). Decision on specific restoration activities depends not only on the type and severity of soil degradation (Fig 2), and the desired restoration goal (Fig. 1), but also on the level of ambition. The Society of Ecological Restoration (SER) suggests in their international standards of ecological restoration a useful framework guiding the decision making around the implementation of restoration activities (Gann et al. 2019). The cornerstones of this framework are a set of measurable ecosystem attributes and a 5-star system of levels of restoration ambition to define the restoration goal as a baseline to measure restoration success. This framework has the advantage to allow for measuring restoration success also in cases where defining a pristine reference ecosystem as restoration goal is not feasible, like anthropogenic ecosystems such as agricultural land. Although without a reference system predefining the restoration goals, they should be selected in correspondence to the environmental conditions (e.g. increasing organic matter content in arid regions should match in quantity and quality those of the surrounding ecosystems). The restoration goals developed in this review specify the general ecosystem attributes for soil restoration (Fig. 1) that can be diversified into different levels of ambition from restoration solely basic soil functioning to the full restoration the entire soil ecosystem with its native communities and biotic interactions (Table 1). In agriculture systems, on-site restoration within the site under agricultural use, has typically lower levels of restoration ambition, such as maintaining or increasing sustainable functioning of soils (i.e. soils supporting services, Fig 1, SER suggestion 1 in Table 1, Box 1 non ambitious restoration vision). However, agricultural sites and other ecosystems in the surrounding landscape may have higher levels of ambition, such as restoration of native (soil) communities and species interactions (SER's suggestion 2-4 in Table 1, Box 1 ambitious restoration vision).

Below we describe a broad collection of the most common restoration activities for on-site and landscape-scale soil restoration as an inspiration how soil restoration in agriculture could be applied. As ecosystems vary in environmental conditions, and restoration goals, (levels of ambition) depend on individual farm management, this compilation of activities is not exhaustive but is a starting point to define actions adapted to the environmental context, economic feasibility and ambition of soil restoration (as illustrated in Box 1).

*Example for textual adjustment within the implication section (ll 485-489):*

The level of ambition for on-site soil restoration is commonly limited to the recovery of ecosystem service provisioning and the stability of this capacity (Fig. 1), which implies a focus on the recovery of on-site ecosystems functions and the minimizing of negative impacts such as nutrient leaching to adjacent ecosystems (Gann et al. 2019, Table 1).

- Generally, throughout the manuscript, recommendations made in the manuscript would benefit by viewing them through a lense of quantity and quality. It seems that in many areas “more” may be conflated with “better”, or that the language used could lead readers to believe that is the case. For example, are more crops always better? Or might there be gains in the quality of the crop that could be equally important, such as the nutritive value of the crop (especially since climate change is expected to reduce the nutritional value of crops) and/or the increased value of the crop at market that stems from its organic, sustainable nature or improvements in taste? Similarly, is more biodiversity always better? Or might it sometimes be less desirable than biodiversity appropriate to the ecosystem / site? For example, lush locations in the US may have more biodiversity, but my goal as a farmer in the

arid southwestern US wouldn't be to replicate that biodiversity. Similarly, more organic matter might be better sometimes. But in arid regions of the southwestern US, the contents and appropriateness of that organic matter might matter more than simply "more". Although I understand the desire to develop indicators and attempt to make them feasible and useful, the current discussion, in my humble opinion, needs more development around these kinds of issues in order to avoid replicating some of the past oversimplifications that it is trying to improve upon, like just using vegetation as an indicator rather than key ecosystem structures and functions. I suggest that this is a rather important point that needs more refinement within the current framework prior to publishing.

*Authors' response:*

*We now put more emphasis on this aspect of context dependency in selecting/defining restoration goals in the implication section (II453-459). We still think that the restoration goals highlight general biological processes, e.g. higher organic matter has certain effects on soil moisture, and thus need no specification to environmental conditions. At the stage of definition the restoration goals, however, this aspect becomes relevant (aiming for higher organic matter content as typical/feasible at a site is not sustainable). We understand that different challenges and traditions in agricultural practices exist in different parts of the world and there is no 'one solution'. Hence, we suggest multiple options and highlight some examples in the new Box 1.*

- The Introduction seems to need clarification around the fact that updated SER goals include those for places that are not intended to be returned to pristine, and contains a framework for this. International Standards for the Practice of Ecological Restoration - Society for Ecological Restoration (ser.org) (previously referenced per their suggestion as Gann et al. 2019, but the full document is available at the link). I am not sure why this is not described, since it fits well with the authors' tasks and could shed some light on the "more" vs. "better" questions, etc. as well. It seems like a crucial piece of information and source of discussion that should not be left out of this consideration. Focus on this from the beginning of the Introduction could also help make the Introduction more concise (I got lost in the extended discussion at the start of traditional ecosystem restoration and the problems with not having good data on pristine systems. I am not sure that is necessary, since the paper is not discussing restoration to pristine systems, and I found it confusing since the paper is about agricultural lands. At the same time, this space could be used to discuss restoration goals for areas that are not intended to be restored to pristine conditions, and explain what the goals for that are, based on SER / UN goals and principles.)

*Authors' response:*

*We agree with the reviewer. The introduction now stronger focusses on the restoration of sites, where application of a pristine reference system as restoration goals is not feasible, referencing the SER standards (II45-71).*

*The paragraph reads now like this (text in yellow is new):*

Traditionally, ecosystem restoration has targeted re-establishment of a 'pristine' reference ecosystem (e.g., Török et al. 2021, definition of ecosystem restoration by the Society for Ecological Restoration). This reference is, often only defined by basic abiotic properties and a few key community indices such as plant species composition. Scientists, stakeholders, and politicians, however, agree that we need broader restoration goals if we are to properly measure restoration success (e.g., Osborne et al. 2021; United Nations 2022 Global Land Outlook, 2<sup>nd</sup> edition). This is especially the case for restoration guidelines for ecosystems such as agricultural soils where severe former or continued disturbance disables returning the location to a pristine reference ecosystem (Gann et al. 2019). Therefore, recent

restoration guidelines have incorporated wider ecological theory and have begun to integrate other ecosystem properties as targets, including trophic interactions, ecosystem functioning and ecosystem service provisioning (Wainwright et al. 2018). Such aspects are increasingly recognized as relevant indicators of ecosystem condition (*'ecosystem health'*), among scientists, stakeholders, and politicians (Comin et al. 2018, Aronson et al. 2020, Bardgett et al. 2021, Bullock et al. 2022, Sustainable Development Goals). However, application of these broader or extended goals is still nascent.

- Line 12, I would not blame just agriculture solely.

*Authors' response:*

*We added now economy as additional force focussing on food production and not sustainability (ll12-13):*

Although focus on effective and profitable food production has led to severely degraded soils, the tools and standards for restoration strategies in agricultural soils are still largely under-developed.

- Line 23 & 53, I would suggest not using “holistic” which has hippie-ish connotations sometimes. I would suggest using a more scientific English word that conveys the intended meaning, such as “comprehensive” or “integrative”, etc.

*Authors' response:*

*Changed accordingly to comprehensive throughout the text (e.g. l504).*

- There seem to be some benefits / costs that are particularly crucial that are left out of figures / tables / textual discussion in some places: For example, introducing native inoculum is said to contain a risk / cost of introducing a pathogen. “Usage or enhancement of native, diverse soil inoculums (i.e., from native soils) can reduce the risk of losing soil diversity and production stability, but also comes with the risks of co-inoculation with pathogenic soil organisms in the original soil, which if also co-enhanced would likely reduce crop plant yield (Wubs et al. 2016).” However, one has to weigh every choice against the opportunity cost, and using non-native inoculums include a high risk / cost of introducing non-native pests, pathogens, invasive species of microbiota that are not yet known or there, and precluding the establishment of the native biodiversity. The analysis could benefit from a discussion of what it means to spread risk (Schindler et al. 2015), and consider the opportunity cost of each action. If the goal is to provide a decision framework for folks, these and what SER has to say about restoration to non-pristine land conditions seem like crucial pillars needed. Along these lines, it seems like the goal of the current paper could be outlining the tools available to make these decisions so practitioners have a toolbelt of tools, and then walking hypothetical practitioners with specific scenarios through using those tools to develop strategies most appropriate for their situation, rather than trying to provide a view of all the possible actions and outcomes?

Schindler DE, Armstrong JB, Reed TE (2015) The portfolio concept in ecology and evolution. *Frontiers in Ecology and the Environment* 13:257–263. <https://doi.org/10.1890/140275>

*Authors' response:*

*We agree that this is an important point and strengthened it in the respective section about inoculum risks (ll 353-360). Nevertheless, we did not make the topic of risk assessment a separate new section, as we feel this would go beyond the scope of this review. Our textual extension reads as follows:*



To choose the most feasible way to restore a particular soil, risk analysis is recommendable weighing the costs and benefits of each action (Schindler et al. 2015). For example, in the case of microbial inoculants, the costs of potentially introducing native pathogens with native inoculum might yet still be lower in terms of yield reduction than those of introducing non-native pests, pathogens, and invasive microbial species, for which tools to control them are still unknown and that can preclude the establishment of the native biodiversity. Farmers' precaution with pest control, however, might limit the acceptance of applying any measures that come with any risk of pest introduction.

- Similarly, I would suggest that if the article is to delve into discussions of ecosystem services, some references for and discussion of what constitutes an ecosystem service and how they are divided up would be needed (it is a bit odd to talk about "provisioning services" for example, without a discussion of what that is, and "supporting" and "regulating". I understand because of the work I've done, but many potential readers might not be familiar with all of the ecosystem service -specific vocabulary.

*Authors' response:*

*Ecosystem services were indeed poorly introduced in the previous version of the manuscript, and we now extended this introduction as suggested (ll 119-134):*

Ecosystem services are defined as the benefits people obtain from ecosystems and are commonly divided into four groups (Millennium Ecosystem Assessment 2005). Ecosystem services are often linked via shared underlying drivers (e.g., Bianco et al. 2023) and these links should be acknowledged in ecosystem restoration. The first group are (i) supporting services such as soil formation, photosynthesis and nutrient cycling that can be understood as ecosystems' basal capacity to function. Supporting ecosystem services such as nutrient cycling or soil formation reinforce many other ecosystem services (Millennium Ecosystem Assessment 2005, Bianco et al. 2023). Thus, ecological restoration of agricultural soils should prioritize these supporting services due to its strong links to other services. The three other groups of services, reinforced by supporting services are (ii) regulating services such as climate, water, pest regulation, that can be understood as capacity of an ecosystem to regulate ecosystem processes and to buffer against environmental changes; (iii) provisioning services such as food, fibre, timber and water that can be understood as ecosystems' capacity to provide people with resources; and (iv) cultural services such as flower diversity, landscape structural diversity that can be understood as ecosystems' capacity to provide recreational, aesthetic and spiritual benefits.

- This manuscript is striving to cover a huge amount of territory and is improving. I suggest it still needs more refinement prior to publishing, and I commend the authors for the work they have done so far towards that end. I renew my suggestion that a good goal of the current paper could be outlining the tools available to make these decisions, so practitioners have a toolbelt of tools, and then walking hypothetical practitioners with specific scenarios through using those tools to develop strategies most appropriate for their situation, rather than trying to provide a view of all the possible actions and outcomes.

*Authors' response:*

*We thank the reviewer for acknowledging the task of bringing all information on soil restoration and agriculture together and helping with this through his/her constructive comments. Hopefully, the way we included the suggestions, has sufficiently improved the manuscript and it's utility for farmers.*



## **Reviewed: Neuenkamp et al., Ecological restoration of soils to foster sustainable use and resilience of agricultural land**

### **Summary:**

This study adds to crucial scientific knowledge about agro ecology regarding the need for considering soil communities. This review is unique in providing clear outlines of how different actions may affect both ecological goals and agricultural goals positively and/or negatively, and by providing clear examples of ways to balance both goals.

### **Overall Impression:**

This review is highly needed. It is a crucial addition to the discussion of how ecological restoration applies to lands with multiple uses and/or that are recognized as areas where “pristine” conditions or maximum ecological functioning may not return, and how on these lands we can (and should) still support the maximum ecological functioning possible.

I commend the authors for the work they have done so far towards refining this manuscript’s analysis and readability. I renew my suggestion that a good goal of the current paper could be outlining the tools available to make these decisions so practitioners have a toolbelt of tools (SER principles for restoration to non-pristine conditions, literature reviews of the impacts of heavy machinery with effect sizes and habitats considered; etc.), and then walking hypothetical practitioners with specific scenarios through using those tools to develop strategies most appropriate for their situation, rather than trying to provide a view of all the possible actions and outcomes. It is a challenging task indeed, to try to outline all potential actions and goals irrespective of specific location, situation, etc. And perhaps more useful to outline context, logic, and pillars / frameworks that can be called-on, and improved-upon for agricultural scenarios.

### **Recommendations:**

- Figure 1 contains an enormous amount of useful information. However, the figure remains busy enough that I suggest it will be challenging for folks to use. Suggest breaking it up into a couple figures. The paths of arrows are challenging to follow, for example. Additionally, the “negative” color is difficult to separate visually from the “both” color for arrows. Additionally, since it would be hard to include an exhaustive list, how do we know whether the most important factors in each category are included under each heading? How were those included under each heading determined (interviews with practitioners / farmers’ systematic review of literature?)?
- Figure 2 and its associated supplemental information would benefit from similar attention. For example, how were the items listed in each category determined and how was it determined that those were the most impactful or important ones to list (interviews with practitioners? Systematic review of the literature?)? What criteria were used to determine “weak” or “strong” relationships? What is a relationship is indirect but strong? How is that conveyed / considered? What relationships were left out of this consideration and why?

- Generally throughout, the manuscript could still benefit greatly from a review of the English terms being used, and simplification of the language.
- Generally, reader understanding and application of the material would benefit from developing more detailed scenarios and helping a hypothetical farmer work through their particular scenario to make a specific choice.
- Generally, throughout the manuscript, recommendations made in the manuscript would benefit by viewing them through a lense of quantity and quality. It seems that in many areas “more” may be conflated with “better”, or that the language used could lead readers to believe that is the case. For example, are more crops always better? Or might there be gains in the quality of the crop that could be equally important, such as the nutritive value of the crop (especially since climate change is expected to reduce the nutritional value of crops) and/or the increased value of the crop at market that stems from its organic, sustainable nature or improvements in taste? Similarly, is more biodiversity always better? Or might it sometimes be less desirable than biodiversity appropriate to the ecosystem / site? For example, lush locations in the US may have more biodiversity, but my goal as a farmer in the arid southwestern US wouldn’t be to replicate that biodiversity. Similarly, more organic matter might be better sometimes. But in arid regions of the southwestern US, the contents and appropriateness of that organic matter might matter more than simply “more”. Although I understand the desire to develop indicators and attempt to make them feasible and useful, the current discussion, in my humble opinion, needs more development around these kinds of issues in order to avoid replicating some of the past over-simplifications that it is trying to improve upon, like just using vegetation as an indicator rather than key ecosystem structures and functions. I suggest that this is a rather important point that needs more refinement within the current framework prior to publishing.
- The Introduction seems to need clarification around the fact that updated SER goals include those for places that are not intended to be returned to pristine, and contains a framework for this. [International Standards for the Practice of Ecological Restoration - Society for Ecological Restoration \(ser.org\)](https://ser.org/) (previously referenced per their suggestion as Gann et al. 2019, but the full document is available at the link). I am not sure why this is not described, since it fits well with the authors’ tasks and could shed some light on the “more” vs. “better” questions, etc. as well. It seems like a crucial piece of information and source of discussion that should not be left out of this consideration. Focus on this from the beginning of the Introduction could also help make the Introduction more concise (I got lost in the extended discussion at the start of traditional ecosystem restoration and the problems with not having good data on pristine systems. I am not sure that is necessary, since the paper is not discussing restoration to pristine systems, and I found it confusing since the paper is about agricultural lands. At the same time, this space could be used to discuss restoration goals for areas that are not intended to be restored to pristine conditions, and explain what the goals for that are, based on SER / UN goals and principles.)
- Line 12, I would not blame just agriculture solely.

- Line 23 & 53, I would suggest not using “holistic” which has hippie-ish connotations sometimes. I would suggest using a more scientific English word that conveys the intended meaning, such as “comprehensive” or “integrative”, etc.
- There seem to be some benefits / costs that are particularly crucial that are left out of figures / tables / textual discussion in some places: For example, introducing native inoculum is said to contain a risk / cost of introducing a pathogen. “Usage or enhancement of native, diverse soil inoculums (i.e., from native soils) can reduce the risk of losing soil diversity and production stability, but also comes with the risks of co-inoculation with pathogenic soil organisms in the original soil, which if also co-enhanced would likely reduce crop plant yield (Wubs et al. 2016).” However, one has to weigh every choice against the opportunity cost, and using non-native inoculums include a high risk / cost of introducing non-native pests, pathogens, invasive species of microbiota that are not yet known or there, and precluding the establishment of the native biodiversity. The analysis could benefit from a discussion of what it means to spread risk (Schindler et al. 2015), and consider the opportunity cost of each action. If the goal is to provide a decision framework for folks, these and what SER has to say about restoration to non-pristine land conditions seem like crucial pillars needed. Along these lines, it seems like the goal of the current paper could be outlining the tools available to make these decisions so practitioners have a toolbelt of tools, and then walking hypothetical practitioners with specific scenarios through using those tools to develop strategies most appropriate for their situation, rather than trying to provide a view of all the possible actions and outcomes?
  - Schindler DE, Armstrong JB, Reed TE (2015) The portfolio concept in ecology and evolution. *Frontiers in Ecology and the Environment* 13:257–263.  
<https://doi.org/10.1890/140275>
- Similarly, I would suggest that if the article is to delve into discussions of ecosystem services, some references for and discussion of what constitutes an ecosystem service and how they are divided up would be needed (it is a bit odd to talk about “provisioning services” for example, without a discussion of what that is, and “supporting” and “regulating”. I understand because of the work I’ve done, but many potential readers might not be familiar with all of the ecosystem service -specific vocabulary.
- This manuscript is striving to cover a huge amount of territory, and is improving. I suggest it still needs more refinement prior to publishing, and I commend the authors for the work they have done so far towards that end. I renew my suggestion that a good goal of the current paper could be outlining the tools available to make these decisions so practitioners have a toolbelt of tools, and then walking hypothetical practitioners with specific scenarios through using those tools to develop strategies most appropriate for their situation, rather than trying to provide a view of all the possible actions and outcomes.