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Peer Review File

Carbon payment strategies in coffee agroforests shape climate and biodiversity outcomes

Corresponding Author: Dr Emily Pappo

This file contains all editorial decision letters 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:

Decision Letter:

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Dear Dr Pappo,

Your manuscript titled "Carbon payment strategies in coffee agroforests shape climate and biodiversity outcomes" has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication. In summary, we ask you to include:

* Provide a compelling analysis of impact of creation and protection strategies in coffee systems on carbon stocks and biodiversity, including full explanations of the study novelty in the context of previous research and specific recommendations for policymakers and practitioners, relevant to concerns raised by reviewers #1 and #2
* Make clear descriptions and justifications for the metrics used for the biodiversity evaluation.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

We are committed to providing a fair and constructive peer-review process. Please don't hesitate to contact us if you wish to discuss the revision in more detail.

Please use the following link to submit your revised manuscript, point-by-point response to the referees' comments (which should be in a separate document to any cover letter), a tracked-changes version of the manuscript (as a PDF file) and the completed checklist:
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We hope to receive your revised paper within six weeks; please let us know if you aren't able to submit it within this time so that we can discuss how best to proceed. If we don't hear from you, and the revision process takes significantly longer, we may close your file. In this event, we will still be happy to reconsider your paper at a later date, as long as nothing similar has been accepted for publication at Communications Earth & Environment or published elsewhere in the meantime.

Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Paula Ribeiro Prist, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0003-2809-0434

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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

I have reviewed the paper titled "Carbon payment strategies in coffee agroforests shape climate and biodiversity outcomes." The topic is of interest to the readers, especially given the increasing role of agroforestry in climate change mitigation and biodiversity conservation. However, while the study is valuable, some issues need to be addressed to strengthen the paper. Below are my comments and suggestions.

A. General Comments
The paper presents an interesting discussion on carbon payment strategies in agroforestry systems, particularly coffee production, but it does not clearly differentiate its novelty from existing literature. The study should better articulate how its findings contribute beyond previous studies on agroforestry and carbon sequestration. The scenarios of agroforestry adoption and intensification should be more clearly defined, with a stronger justification for the assumptions underlying these models. Some important recent studies on agroforestry and carbon sequestration are missing. The authors should incorporate recent references to strengthen the literature review. The conclusions should provide clearer recommendations for policymakers and practitioners regarding the balance between carbon sequestration and biodiversity conservation.

B. Specific Comments
1. Clarity and Novelty of Agroforestry Practices
1.1 The paper describes agroforestry as a "promising" approach, yet agroforestry has long been established as a climate mitigation and adaptation strategy. The authors should clarify whether their innovation lies in policy mechanisms, financial incentives, or carbon payment structures.
1.2 The discussion should acknowledge existing agroforestry frameworks and explicitly state how this study advances knowledge beyond prior work.

2. Review of Agroforestry Scenarios and Methodology
2.1 The agroforestry adoption scenarios are not well justified. How were these scenarios constructed, and how do they align with real-world conditions in major coffee-growing regions?
2.2 The classification of "simple agroforestry" versus "complex agroforestry" should be better defined in terms of biodiversity and carbon storage.
2.3 Provide clearer details on the criteria used to assess different land management types.

3. Strengthening the Literature Review
3.1 The paper relies heavily on older references (e.g., Jha et al., 2014). The authors should integrate more recent studies, such as:
• Muthuri, C. W., Kuyah, S., Njenga, M., Kuria, A., Öborn, I., & van Noordwijk, M. (2023). Agroforestry's contribution to livelihoods and carbon sequestration in East Africa: A systematic review. Trends in Food Processing, 100432. (doi).
• Walsh, C., Haggar, J., Cerretelli, S., Van Oijen, M., & Cerda, R. H. (2025). Comparing carbon agronomic footprint and sequestration in Central American coffee agroforestry systems and assessing trade-offs with economic returns. Science of The Total Environment, 961, 178360. (doi)
• Dossa et al. (2022) - Meta-analysis of carbon sequestration potential in coffee agroforestry across different regions.
3.2 Updating the literature review would provide a stronger foundation for the study's arguments. This is a good paper for the authors to read: Mendham et al., 2022, as it provides relevant insights into carbon sequestration and agroforestry systems.

4. Carbon and Biodiversity Tradeoffs
4.1 The study finds that tree density affects carbon sequestration but tree diversity does not. This is a critical finding but is not fully explored in the discussion.
4.2 The paper should explain why tree diversity does not enhance carbon sequestration—potential reasons could be species-specific growth rates or ecological interactions.
4.3 The tradeoffs between carbon-first approaches (favoring high-density fast-growing species) versus biodiversity-first approaches (favoring diverse native species) should be explicitly addressed.

5. Carbon Payment Mechanisms and Market Alignment
5.1 The discussion of carbon payment programs should include an evaluation of how well existing mechanisms align with the study's findings.
5.2 The authors should reference and critically analyze:
• Verra's Verified Carbon Standard (VCS) and Climate, Community & Biodiversity Standards (CCB).
• Gold Standard methodologies for agroforestry projects.
• The impact of the European Union Deforestation Regulation (EUDR) on carbon crediting in coffee agroforestry.

6. Policy and Implementation Implications
6.1 The study should discuss the practical challenges of implementing carbon stock protection programs, especially given the economic incentives for intensification.
6.2 What role do governments, supply chain actors, and certification bodies play in promoting agroforestry protection?
6.3 What are the biggest barriers to ensuring that carbon payment programs protect existing agroforests rather than just incentivizing new tree planting?

7. Writing and Language Suggestions
7.1 Some sections use passive voice excessively. Shifting to active voice would improve clarity.
7.2 Technical terms such as "carbon additionality" and "intensification gradient" should be explained in layman's terms where possible.

8. Conclusion and Future Directions
8.1 The conclusion should provide stronger, actionable recommendations on how policymakers and businesses can design more effective carbon payment mechanisms.
8.2 The authors should suggest future research directions, particularly regarding long-term carbon sequestration trends in coffee agroforestry.

Final Recommendation:
The study addresses an important topic, but it requires clarifications on novelty, methodological justification, integration of recent literature, and a stronger discussion on carbon-biodiversity tradeoffs. With these revisions, the paper will be significantly strengthened.

Reviewer #2 (Remarks to the Author):

Reviewer Report:
The overall manuscript is well written and justified providing important clarity towards the effects of coffee agroforestry strategies on biodiversity and C stocks. While I do think the analysis was robust, I might suggest the authors add some additional clarity in the results on how carbon stocks and biodiversity might vary across ecological regions for example, Latin American, South America, Africa, and Asia, etc as I suspect there could be important and meaningful insights provided knowing how baseline metrics of baseline biodiversity might vary. Further, I suggest the authors provide the following:

- Improved metrics for how biodiversity was estimated or better justification for assumptions towards the how the complexity of vegetation gradients and tree density relates to quantifiable metrics of biodiversity. Overall, it's not clear to me how tree density being used as a proxy for diversity is a sound assumption as the authors do not provide even qualitative metrics of diversity across the study regions such as known species the might commonly coexist by region.
- Perhaps it is not possible due to the sample size, but geographic variation in C stocks could also help provide some added clarity, ie., are all coffee agroforests within this typology created equal, or is there variation in C stocks and complexity across regions even if they aren't significant which on it's own could be informative.
- The discussion should include a more nuanced perspective of protection to inform how that could cause leakage or a shift in emissions elsewhere.
- Furthermore, additional thoughts on how incentives might vary globally and its relationship to C stock protection or creation could be a salient point to inform policy and planning
- Limitations should similarly include something on how changes in incentives and priorities can lead to unintended consequences for the shifting of emissions

L87-88: While I think this is true, providing a citation here would be good

L338-340: I'm not sure proforestation is being used in the proper context as I see that relating to timber production more so than other non-timber forest products. Additionally, I think other complementary frameworks could include something like intensification or increased regeneration/resilience of working lands to reduce pressures for forest-use elsewhere (ie., freeing up areas for conservation) and/or more comprehensive land-use policies as there is evidence that conserving certain areas leads to either leaked emissions elsewhere and leap frogging of deforestation for human developments.

L520: Include assumptions for how biomass estimates were converted to carbon

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Version 1:

Decision Letter:

** Please ensure you delete the link to your author home page in this e-mail if you wish to forward it to your coauthors **

Dear Dr Pappo,

Your manuscript titled "Carbon payment strategies in coffee agroforests shape climate and biodiversity outcomes" has now been seen by our reviewers, whose comments appear below. In light of their advice we are delighted to say that we are happy, in principle, to publish a suitably revised version in Communications Earth & Environment.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Please review our specific editorial comments and requests regarding your manuscript in the attached "Editorial Requests Table".

*****Please take care to match our formatting and policy requirements. We will check revised manuscript and return manuscripts that do not comply. Such requests will lead to delays. *****

Please outline your response to each request in the right hand column. Please upload the completed table with your manuscript files as a Related Manuscript file.

If you have any questions or concerns about any of our requests, please do not hesitate to contact me.

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We hope to hear from you within two weeks; please let us know if you need more time.

Best regards,

Mengjie Wang
Associate Editor, Communications Earth & Environment
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Consulting Editor, Communications Sustainability
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Paula Ribeiro Prist, PhD
Editorial Board Member

Communications Earth & Environment
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REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

I have reviewed the revised manuscript “Carbon payment strategies in coffee agroforests shape climate and biodiversity outcomes” and the accompanying rebuttal letter. I am satisfied that the authors have thoroughly addressed all of my previous concerns.
The manuscript now presents a clear, well-justified analysis of how different agroforestry strategies and carbon payment mechanisms influence both carbon sequestration and biodiversity in coffee systems. The authors successfully distinguish the novelty of their work through their use of global meta-analysis and scenario modeling. The findings offer actionable insights for policymakers, certification bodies, and carbon market stakeholders.
The statistical analyses appear appropriate and transparent, and the study design is reproducible based on the level of methodological detail provided. The integration of updated literature and nuanced discussion on carbon–biodiversity tradeoffs further strengthens the contribution.
I believe this paper will be of broad interest to the agroforestry, climate policy, and biodiversity conservation communities, and that it has the potential to influence both academic and applied discourse on climate-smart land use.

Reviewer #2 (Remarks to the Author):

The manuscript is much improved and I'm happy to recommend for publication. The strengthening of both the motivations/importance and discussion have provided additional clarity. Although, I do have a few minor suggestions to improve the manuscript further.

Comments:
L64: measurable "and verifiable" climate benefits

Results:
- It isn't readily apparent how the hedge's g value for each type of agroforest effects the scale of change for AGB carbon and soil C. Suggestions for each creation and protection approach below:

The carbon stock creation approach: quantifying carbon addition across a management gradient:
- If possible, adding percentages or scale of change across the complexity gradient would provide even further salience in L178-180 & L189-192. Do to the data transformation it isn't apparent the scale of increases in ABG carbon and soil C. For example, does shifting from unshaded crop monoculture to simple coffee agroforestry double the AGB or is it more modest??

The carbon stock protection approach: quantifying the loss of carbon from intensification of complex agroforestry and forest:
- Same as above for L212-214 & L217-219 for both AGB and Soil C differences

L315-317: this should be highlighted stronger in the conclusion as it seems to be quite an important implication

Meeting the dual objectives of carbon sequestration and biodiversity conservation:
- Potentially something to highlight here to strengthen the discussion are the temporal trade-offs between protection and creation. The authors rightfully highlight that creation of C stocks is dependent on complex forest dynamics like growth rates and species competitions. However, a point to strengthen a key takeaway (protection provides co-benefits) is that near-term forest protection could potentially provide greater mitigation benefits in the short term whereas C creation can potentially provide mitigation benefits over a longer timeframe. This could highlight tradeoffs discussed in Table 1 providing additional clarity by digging further into the temporal nature of different natural climate solutions which seems to be oftentimes overlooked. Highlighting near-term approaches could strength this.

Reviewer #3 (Remarks to the Author):

I’ve previously reviewed this manuscript and I only have a few comments.

In general, apart from protect and restore agroforest, management can also contribute to increase carbon sequestration and conserve biodiversity. Management trends is mostly considered in terms of structural complexity, but I wonder if within an agroforestry type there is a range of management options that could affect the delivery of ecosystem services. This could be added in the discussion.

When calculating the current aboveground carbon stock, a note of caution should be included. For instance, I guess that there should be large differences in plantation density within each type which could lead to large errors in the estimation of the stock.

Regarding the decoupled trend in carbon and biodiversity, an additional explanation could be that it is limited knowledge on the structure of this agroforest, which can have large effects on biodiversity. For example, given a similar tree density, having various vegetation lager can be more beneficial.

Reviewer Report:

The overall manuscript is well written and justified providing important clarity towards the effects of coffee agroforestry strategies on biodiversity and C stocks. While I do think the analysis was robust, I might suggest the authors add some additional clarity in the results on how carbon stocks and biodiversity might vary across ecological regions for example, Latin American, South America, Africa, and Asia, etc as I suspect there could be important and meaningful insights provided knowing how baseline metrics of baseline biodiversity might vary. Further, I suggest the authors provide the following:

- Improved metrics for how biodiversity was estimated or better justification for assumptions towards the how the complexity of vegetation gradients and tree density relates to quantifiable metrics of biodiversity. Overall, it's not clear to me how tree density being used as a proxy for diversity is a sound assumption as the authors do not provide even qualitative metrics of diversity across the study regions such as known species the might commonly coexist by region.
- Perhaps it is not possible due to the sample size, but geographic variation in C stocks could also help provide some added clarity, ie., are all coffee agroforests within this typology created equal, or is there variation in C stocks and complexity across regions even if they aren't significant which on it's own could be informative.
- The discussion should include a more nuanced perspective of protection to inform how that could cause leakage or a shift in emissions elsewhere.
- Furthermore, additional thoughts on how incentives might vary globally and its relationship to C stock protection or creation could be a salient point to inform policy and planning
- Limitations should similarly include something on how changes in incentives and priorities can lead to unintended consequences for the shifting of emissions

L87-88: While I think this is true, providing a citation here would be good

L338-340: I'm not sure proforestation is being used in the proper context as I see that relating to timber production more so than other non-timber forest products. Additionally, I think other complementary frameworks could include something like intensification or increased regeneration/resilience of working lands to reduce pressures for forest-use elsewhere (ie., freeing up areas for conservation) and/or more comprehensive land-use policies as there is evidence that conserving certain areas leads to either leaked emissions elsewhere and leap frogging of deforestation for human developments.

L520: Include assumptions for how biomass estimates were converted to carbon

May 2, 2025

Rebuttal Letter: “Carbon payment strategies in coffee agroforests shape climate and biodiversity outcomes” (Manuscript ID: COMMSENV-25-0547-T)

Reviewer #1 (R1)

R1: I have reviewed the paper titled "Carbon payment strategies in coffee agroforests shape climate and biodiversity outcomes." The topic is of interest to the readers, especially given the increasing role of agroforestry in climate change mitigation and biodiversity conservation. However, while the study is valuable, some issues need to be addressed to strengthen the paper. Below are my comments and suggestions.

Authors: Thank you for your positive assessment of our paper’s value. We hope that we sufficiently address the issues you identify in this revision in our responses below.

A. General Comments

R1: The paper presents an interesting discussion on carbon payment strategies in agroforestry systems, particularly coffee production, but it does not clearly differentiate its novelty from existing literature. The study should better articulate how its findings contribute beyond previous studies on agroforestry and carbon sequestration. The scenarios of agroforestry adoption and intensification should be more clearly defined, with a stronger justification for the assumptions underlying these models. Some important recent studies on agroforestry and carbon sequestration are missing. The authors should incorporate recent references to strengthen the literature review. The conclusions should provide clearer recommendations for policymakers and practitioners regarding the balance between carbon sequestration and biodiversity conservation.

Authors: We thank the authors for these insightful comments and suggestions. We address each specific comment in detail below and throughout the manuscript text.

B. Specific Comments

R1: 1. Clarity and Novelty of Agroforestry Practices
1.1 The paper describes agroforestry as a "promising" approach, yet agroforestry has long been established as a climate mitigation and adaptation strategy. The authors should clarify whether their innovation lies in policy mechanisms, financial incentives, or carbon payment structures.

Authors: We agree that the term “promising” may not be the best descriptor here for agroforestry as a climate mitigation and adaptation strategy. It may be interpreted as suggesting that agroforestry has not yet been implemented successfully, which is clearly not accurate. To address this issue, we edited this sentence to communicate the ongoing value of agroforestry more clearly as a climate mitigation and adaptation solution:

> **Lines 44-46:** “Among these solutions, adoption and management of agroforestry, defined as farming systems that combine trees with crops or livestock (Nair et al. 2021), has emerged as a valuable approach for climate change mitigation and adaptation (Terasaki Hart et al. 2023).”

R1: 1.2 The discussion should acknowledge existing agroforestry frameworks and explicitly state how this study advances knowledge beyond prior work.

Authors: Thank you for this suggestion. We certainly do not mean to present our framework for understanding and classifying coffee agroforest typologies without context. While other methods of defining coffee agroforestry systems exist have been proposed and utilized, we selected a modified version of the typology outlined by Moguel & Toledo (1999) because it has been used as a classification system in the literature across multiple coffee-growing regions and has clear delineation criteria that could be applied to the limited information often provided by the papers included in this meta-analysis.

Of course, agroforestry system types are much more complicated than any one framework can capture. However, meta-analyses must synthesize broad categories for comparison, necessitating a reliance on a selected framework. To address these comments, we added context to the discussion of study limitations in the manuscript text:

> **Lines 432-439:** “Inference limitations exist for this study due to the types of data commonly reported or excluded from published literature that met our inclusion criteria. For example, data availability informed our classification of agroforest typologies. Agroforestry typology frameworks are complicated and the permeable borders between categories have been defined both qualitatively (e.g., Moguel & Toledo 1999) and quantitatively (e.g., Somarriba et al. 2024). However, despite this complexity, meta-analyses must synthesize broad categories for comparison, necessitating a reliance on a single accepted framework which can be applied across various studies and systems.”

R1: 2. Review of Agroforestry Scenarios and Methodology
2.1 The agroforestry adoption scenarios are not well justified. How were these scenarios constructed, and how do they align with real-world conditions in major coffee-growing regions?

Authors: In constructing our scenarios of agroforestry adoption and intensification (Table 1), our aim was to understand the range of potential for aboveground carbon sequestration in global coffee systems. Therefore, we opted to look at two extreme scenarios, one in which tree planting initiatives were implemented across all unshaded monocultures (Scenario 1) and one where tree planting initiatives were implemented across all unshaded and shaded monocultures (Scenario 2). Realistically, of course, it is unlikely that there would be 100% adoption of shade trees across all coffee monocultures in practice. However, the aim here was to understand the scale of potential impact that is possible under agroforestry adoption in relation to the scale of potential impact under intensification. To better clarify this justification and contextualize the scenarios in relation to real-world conditions in major coffee growing regions, we modified the following text in our Results, Discussion, and Methods sections:

> **Lines 280-286:** “Finally, we leveraged our global aboveground carbon stock estimates to evaluate the carbon outcomes of coffee agroforestry adoption scenarios that could be achieved through creation initiatives and of intensification scenarios that could be avoided through protection initiatives (Table 1). The aim of comparing these scenarios was to evaluate the relative scale of potential carbon impacts under agroforestry adoption and intensification, so we designed scenarios of change that reflected the high-end of potential vegetation management changes in global coffee systems.”
>
> **Lines 455-459:** “Finally, while the agroforestry adoption and intensification scenarios we present are reflective of realistic vegetation management transitions, they are necessarily illustrative, as accurately determining specific areas where trees could be added without negatively impacting yield or where existing trees in agroforests are genuinely threatened would require further spatial and ecological analysis.”
>
> **Lines 654-658:** “Subsequently, we assessed multiple extreme scenarios to estimate the range of potential change in aboveground carbon. We included agroforestry adoption scenarios where land management de-intensifies, as these represent scenarios that could be achieved through carbon stock creation initiatives, like tree-planting programs, which are currently common in coffee and other agricultural supply chains (Atangana et al. 2014)”

R1: 2.2 The classification of "simple agroforestry" versus "complex agroforestry" should be better defined in terms of biodiversity and carbon storage.

Authors: We based our classification criteria on the framework proposed by Moguel and Toledo (1999), which is common for coffee agroforestry system classifications, with modifications to allow us to apply the framework to papers in our dataset. As noted in **Supplementary Information Table S1** (first referenced in the manuscript text on **Line 144**), simple agroforestry corresponds with the Moguel and Toledo (1999) category of Commercial Polyculture, characterized by a complete removal of the native forest canopy and integration of other cash crops and shade trees alongside coffee trees. Complex agroforestry, on the other hand, corresponds to the Moguel and Toledo (1999) categories of Traditional Polyculture and Rustic. Traditional Polyculture and Rustic systems differ from each other in their use of introduced species and agrochemicals, but they are both characterized by their maintenance of remnant forest trees in the shade canopy. The level of detail provided in the papers we analyzed didn’t allow for accurate differentiation between Traditional Polyculture and Rustic systems, so we opted to group these systems into one category, identified by their native remnant forest tree canopy. The following modifications were made to the text and the caption of Supp. Info. Table S1 to clarify this distinction:

> **Lines 139-152:** "We quantified mean estimates of carbon stocks across a vegetation complexity gradient common in coffee-growing landscapes (Figure 1) to evaluate the carbon impact of interventions that increase or maintain farm system complexity. We classified coffee farming systems following Moguel and Toledo (1999) in order of increasing complexity, which tends to correspond with an increase in associated biodiversity (Moguel and Toledo 1999, Bennett et al. 2022, Manson et al. 2024; Supp. Info. Table S1): unshaded monoculture (no shade trees), shaded monoculture (coffee grown under 1-2 specialized shade tree species), simple agroforestry (i.e., commercial polycultures with complete removal of native forest canopy and integration of other cash crops and shade trees), and complex agroforestry (i.e., traditional polycultures and rustic systems with remnant native forest trees). Traditional polyculture and rustic systems were grouped into one category (complex agroforestry) due to limited management description beyond indications that remnant native forest trees were maintained within the shade canopy, which distinguishes them from simple agroforestry systems. We also include non-coffee systems that represent minimal (annual crops) and maximal (forest) levels of vegetation structural complexity."

> **Lines 1-7 (Supplementary Information):** Supp. Info. Table S1 – Protocols for categories of coffee vegetation management, adapted from Moguel and Toledo (1999). Rustic and Traditional Polyculture/Coffee Garden systems were grouped into one category (Complex Coffee Agroforestry) for the purposes of our analyses due to limited details about shade tree species and agrochemical usage provided by the included manuscripts. Therefore, references to remnant forest trees maintained within the shade canopy allowed us to categorize the system as Complex Agroforestry, whereas Simple Agroforestry systems did not indicate that remnant forest trees were present."

Additionally, while the estimated carbon storage within each of these categories is addressed in detail within our results **(Figure 3, Figure 4, Supp. Info Table S2, Figure S1)**, to address your suggestion regarding the biodiversity value of simple vs. complex agroforestry, we also added language to provide further context:

> **Lines 141-144:** "We classified coffee farming systems following Moguel and Toledo (1999) in order of increasing complexity, which tends to correspond with an increase in associated biodiversity (Moguel and Toledo 1999, Bennett et al. 2022, Manson et al. 2024; Supp. Info. Table S1)"

R1: 2.3 Provide clearer details on the criteria used to assess different land management types.

Authors: While our original approach was to provide detailed criteria for land management classification within **Supplementary Information Table S1**, it appears that there is not sufficient detail within the main text to facilitate a clear understanding of our methods. We appreciate that insight. Here, we also amend the following text to add more context to the system classifications the first time they are introduced:

> **Lines 141-151:** "We classified coffee farming systems following Moguel and Toledo (1999) in order of increasing complexity, which tends to correspond with an increase in associated biodiversity (Moguel and Toledo 1999, Bennett et al. 2022, Manson et al. 2024; Supp. Info. Table S1): unshaded monoculture (no shade trees), shaded monoculture (coffee grown under 1-2 specialized shade tree species), simple agroforestry (i.e., commercial polycultures with complete removal of native forest canopy and integration of other cash crops and shade trees), and complex agroforestry (i.e., traditional polycultures and rustic systems with remnant native forest trees). Traditional polyculture and rustic systems were grouped into one category (complex agroforestry) due to limited management description beyond indications that remnant native forest trees were maintained within the shade canopy, which distinguishes them from simple agroforestry systems."

R1: 3. Strengthening the Literature Review
3.1 The paper relies heavily on older references (e.g., Jha et al., 2014). The authors should integrate more recent studies, such as:
• Muthuri, C. W., Kuyah, S., Njenga, M., Kuria, A., Öborn, I., & van Noordwijk, M. (2023). Agroforestry's contribution to livelihoods and carbon sequestration in East Africa: A systematic review. Trends in Food Processing, 100432. (doi).
• Walsh, C., Haggar, J., Cerretelli, S., Van Oijen, M., & Cerda, R. H. (2025). Comparing carbon agronomic footprint and sequestration in Central American coffee agroforestry systems and assessing trade-offs with economic returns. Science of The Total Environment, 961, 178360. (doi)
• Dossa et al. (2022) - Meta-analysis of carbon sequestration potential in coffee agroforestry across different regions.

Authors: Thank you for this suggestion! We appreciate the additional references. While we do reference Jha et al. 2014 throughout the text, this is because their estimates of global coffee land use across different vegetation categories are the most comprehensive for the purposes of our analyses, and we therefore used their data in our methods. However, we do truly appreciate the insights from the Muthuri et al (2023) and Walsh et al. (2025) papers and believe that their findings help us to contextualize the advances we make in this manuscript. Unfortunately, we were unable to locate the Dossa et al (2022) paper. We adjusted text within the introduction and discussion sections to include these references:

> **Lines 51-54: "**Although economic pressures are not the only barrier to agroforestry maintenance or adoption (Bogado et al. 2024) and there are livelihood benefits associated with agroforestry including food, fuel, fodder, and

income that can improve household resilience (Muthuri et al. 2023), financial incentives are often necessary to sustain or expand agroforestry.”

Lines 104-110: “While diverse coffee agroforests provide ecosystem services (Mokondoko et al. 2022) including climate adaptation services like temperature regulation and soil moisture maintenance (Verburg et al. 2019), they can face production challenges leading to low yields (Haggar et al. 2017; Schnabel et al. 2018), and there is evidence from coffee systems in Central America that carbon-positive farms tend to have lower net income (Walsh et al. 2025). These challenges make the maintenance of agroforestry systems frequently reliant on economic incentives.”

R1: 3.2 Updating the literature review would provide a stronger foundation for the study’s arguments. This is a good paper for the authors to read: Mendham et al., 2022, as it provides relevant insights into carbon sequestration and agroforestry systems.

Authors: Thank you very much for this reference, and for the suggestion. We’re not sure which paper is being referred to here but appreciate the insight that our literature review would benefit from being updated. In addition to the incorporation of the recent studies noted in the above comment - Muthuri et al (2023) and Walsh et al. (2025) – we also integrated other more recently published works (i.e., Mokondoko et al. 2022) to provide an updated context for the advancement of our argument.

Lines 51-54: “Although economic pressures are not the only barrier to agroforestry maintenance or adoption (Bogado et al. 2024) and there are livelihood benefits associated with agroforestry including food, fuel, fodder, and income that can improve household resilience (Muthuri et al. 2023), financial incentives are often necessary to sustain or expand agroforestry.”

Lines 104-110: “While diverse coffee agroforests provide ecosystem services (Mokondoko et al. 2022) including climate adaptation services like temperature regulation and soil moisture maintenance (Verburg et al. 2019), they can face production challenges leading to low yields (Haggar et al. 2017; Schnabel et al. 2018), and there is evidence from coffee systems in Central America that carbon-positive farms tend to have lower net income (Walsh et al. 2025). These challenges make the maintenance of agroforestry systems frequently reliant on economic incentives.”

R1: 4. Carbon and Biodiversity Tradeoffs
4.1 The study finds that tree density affects carbon sequestration but tree diversity does not. This is a critical finding but is not fully explored in the discussion.

Authors: We appreciate the suggestion that further attention be paid to the finding that tree density, but not diversity, impacts carbon outcomes. In the discussion sub-section titled “Meeting the dual objectives of carbon sequestration and biodiversity conservation”, our aim is to provide some context, possible explanations, and explanation of the impact of this result. To deepen this discussion, we made several changes to improve the clarity of the sub-section's text, which I include in full here:

> **Lines 369-407:** "The biodiversity supported in coffee farms is known to increase with agroforestry complexity (Perfecto et al. 2005, Manson et al. 2024), which should indicate a correlation between carbon stocks and biodiversity. However, we found that shade tree density, but not shade tree diversity, predicted carbon aggregation in comparisons of coffee monocultures and agroforestry systems. Several explanations may underlie this divergence in carbon and biodiversity outcomes. For example, not all tree species contribute equally to carbon sequestration (Lugo-Pérez et al. 2023) or sequester carbon at similar rates (Kaul et al. 2010), and carbon accumulation in agroforests can be impacted by inter-specific interactions (Carvalho et al. 2023).
>
> Although both tree density and tree diversity can predict associated biodiversity, tree diversity is a stronger and more consistent predictor for multiple taxa in tropical agroforests (Van Bael et al. 2007, Philpott et al. 2008, Atangana et al. 2014, Bennett et al. 2022, Manson et al. 2024). Therefore, a carbon-first approach to tree-planting initiatives, prioritizing high-density, fast-growing species, may miss an opportunity to maximize biodiversity co-benefits, unless shade tree diversity is explicitly prioritized. While some coffee sustainability programs provide market support for shade tree diversity (e.g. the Smithsonian Bird Friendly® certification program, Wright et al. 2024), the design of biodiversity-first approaches that prioritize diverse native species must be carefully considered to ensure positive farm outcomes. Therefore, the need and opportunity to integrate carbon and biodiversity objectives remains.
>
> A more robust understanding of not only *how many* but also *which* tree species are most valuable for both carbon and biodiversity in specific regions and contexts is crucial (Narango et al. 2019, Schroth 1995). Tree species sequester carbon at different rates (Kaul et al. 2010) and provide distinct ecosystem services (German et al. 2006), and, while sample size and available data limited our ability to test broader biodiversity metrics in this study, it is also likely that biodiversity of other taxa supported by agroforests may vary across regions and contexts (Bennett et al. 2022, De Beenhouwer et al. 2013). Moreover, agroforestry systems can help coffee production adapt to climate change, as shade trees provide temperature regulation and soil moisture conservation that protects coffee plants from the effects of extreme and variable weather (Verburg et al. 2019).
>
> Various carbon project frameworks have successfully pursued holistic or integrative goals, including Verra's Verified Carbon Standard (VCS), Climate, Community, and Biodiversity Standards (CCB), and Gold Standard for the Global Goals methodologies. These frameworks all promote multiple benefits beyond carbon alone, indicating that these integrative approaches are actionable in the market. As future carbon payment programs expand, our findings suggest that

> they can increase impact by designing and promoting agroforestry systems that simultaneously sequester carbon, protect productivity, and provide high quality habitat resources for biodiversity."

R1: 4.2 The paper should explain why tree diversity does not enhance carbon sequestration—potential reasons could be species-specific growth rates or ecological interactions.

Authors: While we want to be cautious about speculating on causality, we agree that the lack of correlation between tree diversity and carbon sequestration in our results merits some additional details. Please see the following addition to the text:

> **Lines 373-376:** "Several explanations may underlie this divergence in carbon and biodiversity outcomes. For example, not all tree species contribute equally to carbon sequestration (Lugo-Pérez et al. 2023) or sequester carbon at similar rates (Kaul et al. 2010), and carbon accumulation in agroforests can be impacted by inter-specific interactions (Carvalho et al. 2023)."

R1: 4.3 The tradeoffs between carbon-first approaches (favoring high-density fast-growing species) versus biodiversity-first approaches (favoring diverse native species) should be explicitly addressed.

Authors: Thank you for this insight. We added text to the discussion section to clarify the trade-offs between these approaches:

> **Lines 378-387:** "Although both tree density and tree diversity can predict associated biodiversity, tree diversity is a stronger and more consistent predictor for multiple taxa in tropical agroforests (Van Bael et al. 2007, Philpott et al. 2008, Atangana et al. 2014, Bennett et al. 2022, Manson et al. 2024). Therefore, a carbon-first approach to tree-planting initiatives, prioritizing high-density, fast-growing species, may miss an opportunity to maximize biodiversity co-benefits, unless shade tree diversity is explicitly prioritized. While some coffee sustainability programs provide market support for shade tree diversity (e.g. the Smithsonian Bird Friendly® certification program, Wright et al. 2024), the design of biodiversity-first approaches that prioritize diverse native species must be carefully considered to ensure positive farm outcomes. Therefore, the need and opportunity to integrate carbon and biodiversity objectives remains."

R1: 5. Carbon Payment Mechanisms and Market Alignment
5.1 The discussion of carbon payment programs should include an evaluation of how well existing mechanisms align with the study's findings.

Authors: Excellent point. We edited the relevant section in the discussion to respond to this suggestion and integrate references to relevant carbon programs that pursue multi-benefit objectives alongside carbon credits.

Lines 400-407: “Various carbon project frameworks have successfully pursued holistic or integrative goals, including Verra’s Verified Carbon Standard (VCS), Climate, Community, and Biodiversity Standards (CCB), and Gold Standard for the Global Goals methodologies. These frameworks all promote multiple benefits beyond carbon alone, indicating that these integrative approaches are actionable in the market. As future carbon payment programs expand, our findings suggest that they can increase impact by designing and promoting agroforestry systems that simultaneously sequester carbon, protect productivity, and provide high quality habitat resources for biodiversity.”

R1: 5.2 The authors should reference and critically analyze:
• Verra’s Verified Carbon Standard (VCS) and Climate, Community & Biodiversity Standards (CCB).
• Gold Standard methodologies for agroforestry projects.
• The impact of the European Union Deforestation Regulation (EUDR) on carbon crediting in coffee agroforestry.

Authors: As noted in the previous comment, we added references to these programs on lines 396-407. We appreciate the suggestion, as it provides context for how our findings can inform practice in the market. Additionally, we added supplemental information onto our original (and brief) mention of the EUDR to contextualize the potential impact of the regulation on carbon credit programs in coffee agroforests.

Lines 400-407: “Various carbon project frameworks have successfully pursued holistic or integrative goals, including Verra’s Verified Carbon Standard (VCS), Climate, Community, and Biodiversity Standards (CCB), and Gold Standard for the Global Goals methodologies. These frameworks all promote multiple benefits beyond carbon alone, indicating that these integrative approaches are actionable in the market. As future carbon payment programs expand, our findings suggest that they can increase impact by designing and promoting agroforestry systems that simultaneously sequester carbon, protect productivity, and provide high quality habitat resources for biodiversity.”

Lines 346-351: “Additionally, coffee-driven deforestation still continues in some regions as coffee moves into new growing areas (Harvey et al. 2021), leading to carbon emissions, loss of forest-dependent biodiversity (e.g., Bennett et al. 2022, De Beenhouwer et al. 2013), and incursion of market risks under emerging regulations such as the European Union Deforestation Regulation (EUDR; Council of the European Union 2023), which will require systems of traceability and evidence of deforestation-free supply chains.”

R1: 6. Policy and Implementation Implications
6.1 The study should discuss the practical challenges of implementing carbon stock protection programs, especially given the economic incentives for intensification.

Authors: Thank you for the suggestion. We have added additional details to our discussion of the challenges experienced during implementation of REDD+ initiatives, which provides an example of a well-known protection strategy and the barriers it has faced to successful implementation.

> **Lines 353-359:** "While protection mechanisms can theoretically prevent carbon losses from existing agroforestry systems that are at risk of removal, ensuring that carbon payment programs effectively protect existing agroforests remains challenging due to difficulties in demonstrating additionality, limited financial incentives, and complex land tenure. For example, existing forest carbon offset programs such as REDD+ have faced significant barriers to adoption and impact, including persistent challenges with monitoring, reporting, and verification (MRV), as well as governance and financing constraints (West et al. 2023)."

R1: 6.2 What role do governments, supply chain actors, and certification bodies play in promoting agroforestry protection?

Authors: That is an important question, as each of these stakeholders play a critical, yet distinct, role in the design of effective strategies for agroforestry protection. Clarifying the role of these different stakeholders is helpful in our call to action at the conclusion of our paper. Here we add brief descriptions of the role of each stakeholder identified:

> **Lines 474-478:** "Collaborative research across sectors, paired with coordinated support from governments through policy, supply chain actors through sourcing commitments, and certification bodies through improved standards, is urgently needed to ensure that future incentive schemes mitigate unintended biodiversity losses, sequester carbon, and sustain economic returns."

R1: 6.3 What are the biggest barriers to ensuring that carbon payment programs protect existing agroforests rather than just incentivizing new tree planting?

Authors: This question highlights a key tension in current carbon payment program design. One of the biggest barriers is the challenge of proving additionality (i.e., demonstrating that carbon would have been lost without the intervention) in protection efforts. This is often substantially more difficult than demonstrating gains from new tree planting. Moreover, limited existing financial incentives for agroforest protection and complex land tenure arrangements can make it harder to implement and verify protection initiatives. We have revised the discussion text to briefly highlight these barriers in the context of existing forest carbon offset programs such as REDD+.

> **Lines 353-359:** "While protection mechanisms can theoretically prevent carbon losses from existing agroforestry systems that are at risk of removal, ensuring that carbon payment programs effectively protect existing agroforests remains challenging due to difficulties in demonstrating additionality, limited financial

> incentives, and complex land tenure. For example, existing forest carbon offset programs such as REDD+ have faced significant barriers to adoption and impact, including persistent challenges with monitoring, reporting, and verification (MRV), as well as governance and financing constraints (West et al. 2023)."

R1: 7. Writing and Language Suggestions
7.1 Some sections use passive voice excessively. Shifting to active voice would improve clarity.

Authors: Thank you for pointing this out. We made multiple changes throughout the text to shift to active voice whenever possible.

R1: 7.2 Technical terms such as "carbon additionality" and "intensification gradient" should be explained in layman's terms where possible.

Authors: You are correct. Here is the definition/explanation provided in the text at the first mention of the term "additionality":

> **Lines 61-64:** "Both strategies must meet the criterion of carbon additionality, defined as demonstrating more carbon is sequestered post-intervention compared to a relevant baseline (Michaelowa et al 2019), a requirement that ensures carbon credits reflect measurable climate benefits beyond what would have occurred without the intervention."

Regarding the term "intensification gradient", that is not a commonly employed term here. We did, however, use it in the abstract, and I see how that might have been confusing in the context of the paper, since we employed the term "vegetation complexity gradient" instead to better reflect the relevant differences between the systems. We adjusted the verbiage in the abstract:

> **Lines 24-27:** "We conducted a global meta-analysis to evaluate how these programs may impact carbon and biodiversity outcomes across coffee agriculture, which spans a vegetation complexity gradient from monoculture to biodiverse agroforestry."

We also describe our meaning for the term "vegetation complexity gradient" at length in our description of how we classified system types during our literature review process. Here is that updated description:

> **Lines 139-152:** "We quantified mean estimates of carbon stocks across a vegetation complexity gradient common in coffee-growing landscapes (Figure 1) to evaluate the carbon impact of interventions that increase or maintain farm system complexity. We classified coffee farming systems following Moguel and Toledo (1999) in order of increasing complexity, which tends to correspond with an increase in associated biodiversity (Moguel and Toledo 1999, Bennett et al. 2022, Manson et al. 2024; Supp. Info. Table S1): unshaded monoculture (no

> shade trees), shaded monoculture (coffee grown under 1-2 specialized shade tree species), simple agroforestry (i.e., commercial polycultures with complete removal of native forest canopy and integration of other cash crops and shade trees), and complex agroforestry (i.e., traditional polycultures and rustic systems with remnant native forest trees). Traditional polyculture and rustic systems were grouped into one category (complex agroforestry) due to limited management description beyond indications that remnant native forest trees were maintained within the shade canopy, which distinguishes them from simple agroforestry systems. We also include non-coffee systems that represent minimal (annual crops) and maximal (forest) levels of vegetation structural complexity."

R1: 8. Conclusion and Future Directions
8.1 The conclusion should provide stronger, actionable recommendations on how policymakers and businesses can design more effective carbon payment mechanisms.

Authors: Thank you for this valuable suggestion, which improves the impact of our manuscript. We have revised the conclusion to include more specific and actionable recommendations, including calls for prioritization of protection-based incentives, land tenure processes, and improved monitoring. We also call for businesses to incorporate standards and long-term commitments that support both carbon and biodiversity outcomes. Here is our adjusted text:

> **Lines 467-478:** "To achieve these outcomes, corporate climate action planning must incentivize both the creation of new carbon stocks and the protection of existing carbon stocks, which will require innovation and investment, especially for carbon stock protection initiatives. These efforts must occur alongside improvements in monitoring frameworks, land tenure security, and long-term sourcing commitments and must consider global variability in appropriate and accessible incentive mechanisms. However, a carbon-first approach risks failing to achieve biodiversity co-benefits unless shade tree diversity and mature tree protection are prioritized. Collaborative research across sectors, paired with coordinated support from governments through policy, supply chain actors through sourcing commitments, and certification bodies through improved standards, is urgently needed to ensure that future incentive schemes mitigate unintended biodiversity losses, sequester carbon, and sustain economic returns."

R1: 8.2 The authors should suggest future research directions, particularly regarding long-term carbon sequestration trends in coffee agroforestry.

Authors: We added to our conclusion a brief but specific call for future research on long-term carbon sequestration trends in coffee agroforestry systems to improve understanding of carbon permanence and inform baseline setting in incentive programs. Thanks for that suggestion.

> **Lines 478-481:** "Additionally, longitudinal studies tracking carbon sequestration in coffee systems over time are needed to better inform program baselines.

> Achieving these goals would allow tropical agroforestry systems to lead agricultural sectors in biodiversity conservation and climate mitigation."

R1: Final Recommendation:
The study addresses an important topic, but it requires clarifications on novelty, methodological justification, integration of recent literature, and a stronger discussion on carbon-biodiversity tradeoffs. With these revisions, the paper will be significantly strengthened.

Authors: Thank you so much for your comprehensive edits and suggestions. We believe that your commentary on our literature review, methods, and discussion vastly improve the quality and potential impact of our manuscript. We are grateful for your time and attention.

Reviewer #2 (R2)

R2: Reviewer Report:
The overall manuscript is well written and justified providing important clarity towards the effects of coffee agroforestry strategies on biodiversity and C stocks. While I do think the analysis was robust, I might suggest the authors add some additional clarity in the results on how carbon stocks and biodiversity might vary across ecological regions for example, Latin American, South America, Africa, and Asia, etc as I suspect there could be important and meaningful insights provided knowing how baseline metrics of baseline biodiversity might vary.

Authors: Thank you very much for your positive comments and your constructive suggestions for improvement of our manuscript.

We certainly agree that geographic variation in carbon and biodiversity is an important piece of context. For carbon, we included study region (Latin America, Asia, Africa) in the linear mixed effect models that we used to assess the impact of system type on carbon stocks but did not find any significant effects (complete model results are shared in **Supplementary Information Tables S6-S7**). In the interest of brevity in the results section, we had originally simply noted that other fixed effects were non-significant. To make it clearer that we are reporting on the outcome of region on carbon in the model, we added the following clarification:

> **Lines 266-267:** "The other regional and bioclimatic fixed effects were not significant ($p > 0.05$)."

Regarding the geographic variation in biodiversity, we recognize that the relationship between region and biodiversity is often variable (e.g., Bennett et al. 2022, De

Beenhouwer et al. 2013). This is an element that we had not previously addressed explicitly, and we appreciate the suggestion. To address this comment, and provide more context around the impact that geographic variation in system characteristics may have on biodiversity, we added the following text to the discussion:

> **Lines 389-395:** "A more robust understanding of not only *how many* but also *which* tree species are most valuable for both carbon and biodiversity in specific regions and contexts is crucial (Narango et al. 2019, Schroth 1995). Tree species sequester carbon at different rates (Kaul et al. 2010) and provide distinct ecosystem services (German et al. 2006), and, while sample size and available data limited our ability to test broader biodiversity metrics in this study, it is also likely that biodiversity of other taxa supported by agroforests may vary across regions and contexts (Bennett et al. 2022, De Beenhouwer et al. 2013)."

R2: Further, I suggest the authors provide the following:

Improved metrics for how biodiversity was estimated or better justification for assumptions towards the how the complexity of vegetation gradients and tree density relates to quantifiable metrics of biodiversity. Overall, it's not clear to me how tree density being used as a proxy for diversity is a sound assumption as the authors do not provide even qualitative metrics of diversity across the study regions such as known species the might commonly coexist by region.

Authors: Thank you for identifying the need for clarification here. We sought, within the papers included in this meta-analysis, a broad suite of agroforestry habitat metrics that are known to correlate with biodiversity in coffee agroforestry systems (e.g., percent shade cover, basal area, tree height, tree diversity, tree density, etc.). However, the only metrics that were available across a large enough sample of papers were tree diversity and tree density. We acknowledge that including other metrics would have added strength and nuance in the text while reporting results and we are explicit in the methods about the correlation of tree density and tree diversity with biodiversity of other taxa (**lines 740-747**), providing more detailed reference to the existing evidence in the literature (Van Bael et al. 2007, Philpott et al. 2008, Atanga et al. 2014, Bennett et al. 2022).

We can see now that we were not sufficiently explicit within the main body of the text about the strength of the existing evidence connecting both tree density and tree diversity to biodiversity in agroforests. This is critical to interpreting the results of our study, and we are grateful that our attention was called to the oversight. Therefore, we added details and justification in multiple places throughout the text to better support our assumptions for the reader:

> **Lines 236-242:** "We included study ID as a random effect and used differences in tree density and tree diversity between monoculture and agroforestry systems as fixed effects, as tree density and tree diversity are both recognized as drivers of biodiversity in coffee agroforests (Van Bael et al. 2007, Philpott et al. 2008,

> Atanga et al. 2014, Bennett et al. 2022, Manson et al. 2024) and these metrics were the most consistently reported indicators of biodiversity across studies (Supp. Info. Tables S4-S5)."
>
> **Lines 444-450**: "Relevant habitat variables for biodiversity beyond tree density and diversity (e.g. tree size, understory vegetation diversity) were also inconsistently reported across studies and the precision of tree diversity data varied substantially by tree inclusion criteria, sampled plot size, and methodological rigor. Availability of a more robust suite of biodiversity metrics would have strengthened our results, and the inconsistency of metrics within studies used to inform critical land use decisions highlights an urgent need for consensus-building and collaboration."

R2: Perhaps it is not possible due to the sample size, but geographic variation in C stocks could also help provide some added clarity, ie., are all coffee agroforests within this typology created equal, or is there variation in C stocks and complexity across regions even if they aren't significant which on it's own could be informative.

Authors: Geographic variability among C stocks was not significant in our models, which we report in the text (**Lines 266-267**) and in **Supplementary Information Tables S6-S7**. It is possible that this result was influenced by sample size, as you mention. Additionally, we do see differences in the relative frequency of different agroforest typologies across the regions – these are reported via the bar graphs in **Figure 2.** To provide some additional context for why we may not have seen variation among region for carbon stocks, we added the following text:

> **Lines 452-455:** "Moreover, our model results did not pick up on significant variation in carbon stocks between geographic regions. This may be related to issues of sample size, and further assessment of how region and bioclimate influences carbon stocks within agroforestry typologies would be informative."

R2: The discussion should include a more nuanced perspective of protection to inform how that could cause leakage or a shift in emissions elsewhere.

Authors: Thank you for this suggestion. While this is perhaps not exactly the same challenge in agroforestry protection initiatives as it may be in forest protection initiatives (i.e., maintaining shade in agroforests does not remove that agroforest from use in the same way that avoided deforestation removes that forest from 'use', which may lead to deforestation elsewhere), it is still a concept worth calling attention to in the discussion. To address this point, we added the following text to contextualize the potential unintended consequences of protection approaches:

> **Lines 353-361:** "While protection mechanisms can theoretically prevent carbon losses from existing agroforestry systems that are at risk of removal, ensuring that carbon payment programs effectively protect existing agroforests remains challenging due to difficulties in demonstrating additionality, limited financial

> incentives, and complex land tenure. For example, existing forest carbon offset programs such as REDD+ have faced significant barriers to adoption and impact, including persistent challenges with monitoring, reporting, and verification (MRV), as well as governance and financing constraints (West et al. 2023). Moreover, caution must be taken to ensure that the maintenance of agroforestry systems in protection initiatives does not lead to an emissions shift through further conversion of forest to agriculture."

R2: Furthermore, additional thoughts on how incentives might vary globally and its relationship to C stock protection or creation could be a salient point to inform policy and planning

Authors: Thank you for this suggestion. We modified our conclusion section to include reference to this consideration within the design of effective creation and protection mechanisms:

> **Lines 467-473:** "To achieve these outcomes, corporate climate action planning must incentivize both the creation of new carbon stocks and the protection of existing carbon stocks, which will require innovation and investment, especially for carbon stock protection initiatives. These efforts must occur alongside improvements in monitoring frameworks, land tenure security, and long-term sourcing commitments and must consider global variability in appropriate and accessible incentive mechanisms."

R2: Limitations should similarly include something on how changes in incentives and priorities can lead to unintended consequences for the shifting of emissions

Authors: Thank you for this comment. We agree that it is important to note that changing incentives may lead to unintended consequences for shifting emissions. While our limitations section is focused on methodological limitations, we incorporated this critical point earlier in our discussion:

> **Lines 359-361:** "Moreover, caution must be taken to ensure that the maintenance of agroforestry systems in protection initiatives does not lead to an emissions shift through further conversion of forest to agriculture."

R2: L87-88: While I think this is true, providing a citation here would be good

Authors: Of course. We added a citation to the following statement.

> **Lines 90-92:** "…as complex agroforestry systems often retain mature native trees that take decades or centuries to regrow (Valencia et al. 2016)."

R2: L338-340: I'm not sure proforestation is being used in the proper context as I see that relating to timber production more so than other non-timber forest products. Additionally, I think other complementary frameworks could include something like intensification or increased regeneration/resilience of working lands to reduce pressures for forest-use elsewhere (ie., freeing up areas for conservation) and/or more comprehensive land-use policies as there is evidence that conserving certain areas leads to either leaked emissions elsewhere and leap frogging of deforestation for human developments.

Authors: Thank you for this insight. We removed the reference to proforestation to avoid confusion and replaced it with a more contextually appropriate complementary frameworks to this area of the discussion:

> **Lines 361-364:** "However, complementary frameworks have emerged that support or improve upon protection programs, including land use conversion risk forecasting (Olimb and Lendrum 2021) and the integration of land-sparing and land-sharing approaches within working landscapes (Valente et al. 2022)."

R2: L520: Include assumptions for how biomass estimates were converted to carbon

Authors: Thank you for calling attention to this oversight! Where biomass was reported we used a carbon factor of 0.5. We added this to the methods:

> **Lines 572-574:** "Aboveground carbon is defined as standing carbon from the biomass of shade trees and coffee plants aboveground. In studies that reported biomass only, we employed a carbon factor of 0.5 to convert biomass to carbon."

June 23, 2025

Second Rebuttal Letter: “Carbon payment strategies in coffee agroforests shape climate and biodiversity outcomes” (Manuscript ID: COMMSENV-25-0547-T)

Reviewer #1 (R1)

R1: I have reviewed the revised manuscript “Carbon payment strategies in coffee agroforests shape climate and biodiversity outcomes” and the accompanying rebuttal letter. I am satisfied that the authors have thoroughly addressed all of my previous concerns.
The manuscript now presents a clear, well-justified analysis of how different agroforestry strategies and carbon payment mechanisms influence both carbon sequestration and biodiversity in coffee systems. The authors successfully distinguish the novelty of their work through their use of global meta-analysis and scenario modeling. The findings offer actionable insights for policymakers, certification bodies, and carbon market stakeholders.
The statistical analyses appear appropriate and transparent, and the study design is reproducible based on the level of methodological detail provided. The integration of updated literature and nuanced discussion on carbon–biodiversity tradeoffs further strengthens the contribution.
I believe this paper will be of broad interest to the agroforestry, climate policy, and biodiversity conservation communities, and that it has the potential to influence both academic and applied discourse on climate-smart land use.

Authors: Thank you very much for your positive assessment of our paper’s value. We certainly hope that with its publication we will be able to inform academic and applied discourse. We appreciate your time and consideration.

Reviewer #2 (R2)

R2: The manuscript is much improved and I'm happy to recommend for publication. The strengthening of both the motivations/importance and discussion have provided additional clarity. Although, I do have a few minor suggestions to improve the manuscript further.

Authors: Thank you so much for your recommendation. We appreciate your time and effort in helping us improve the manuscript for publication.

Comments:

R2: L64: measurable "and verifiable" climate benefits

Authors: Great addition. This line has been edited to read:

> **Lines 62-64: "**Both strategies must meet the criterion of carbon additionality, defined as demonstrating more carbon is sequestered post-intervention compared to a relevant baseline (Michaelowa et al 2019), a requirement that ensures carbon credits reflect measurable and verifiable climate benefits beyond what would have occurred without the intervention."

R2: Results:
- It isn't readily apparent how the hedge's g value for each type of agroforest effects the scale of change for AGB carbon and soil C. Suggestions for each creation and protection approach below:

The carbon stock creation approach: quantifying carbon addition across a management gradient:
- If possible, adding percentages or scale of change across the complexity gradient would provide even further salience in L178-180 & L189-192. Do to the data transformation it isn't apparent the scale of increases in ABG carbon and soil C. For example, does shifting from unshaded crop monoculture to simple coffee agroforestry double the AGB or is it more modest??

The carbon stock protection approach: quantifying the loss of carbon from intensification of complex agroforestry and forest:
- Same as above for L212-214 & L217-219 for both AGB and Soil C differences

Authors: Thank you for this insightful comment. We agree that understanding the scale of carbon change across the gradient is critical for interpreting its ecological significance. To enable comparisons across studies that use differing units and methods, we chose Hedges' g as a standardized measure of effect size to capture how much more (or less) carbon one farm system has relative to another, expressed in units of its variability, mitigating the need for direct percentage or raw quantity comparisons across these diverse studies. This approach allows us to reliably compare the strength of carbon differences across the gradient, regardless of variation in sample sizes or other variables between studies, and provides a robust, comparable measure of change across both aboveground and soil carbon metrics.

However, we certainly agree that it is important to assess the scale of raw carbon values across system types. Therefore, we also provide raw carbon values in the Supplementary Information, in Supplementary Table 2 and Supplementary Figure 1, to help visualize and conceptualize the scale of increase across the complexity gradient.

R2: L315-317: this should be highlighted stronger in the conclusion as it seems to be quite an important implication

Authors: Thank you for identifying this salient point. We have added some text to the conclusion to further highlight this point:

> **Lines 458-461:** "However, a carbon-first approach risks failing to achieve biodiversity co-benefits unless shade tree diversity and mature tree protection are prioritized, particularly as the presence of remnant native forest trees in complex agroforestry may limit its expansion from simpler systems within typical management timeframes."

R2: Meeting the dual objectives of carbon sequestration and biodiversity conservation:
- Potentially something to highlight here to strengthen the discussion are the temporal trade-offs between protection and creation. The authors rightfully highlight that creation of C stocks is dependent on complex forest dynamics like growth rates and species competitions. However, a point to strengthen a key takeaway (protection provides co-benefits) is that near-term forest protection could potentially provide greater mitigation benefits in the short term whereas C creation can potentially provide mitigation benefits over a longer timeframe. This could highlight tradeoffs discussed in Table 1 providing additional clarity by digging further into the temporal nature of different natural climate solutions which seems to be oftentimes overlooked. Highlighting near-term approaches could strength this.

Authors: We certainly agree that highlighting the temporal dimension of protection versus creation strengthens the discussion. To ensure that this point is made effectively, we added the following text to underscore that protection provides more immediate climate benefits, while creation operates on longer timescales:

> **Lines 318-321:** "Tree establishment times must therefore be included in assessments of potential creation interventions, which also highlights an important temporal consideration wherein protection of existing agroforests may deliver more immediate climate benefits, while creation interventions may realize their full potential over longer timescales."

Reviewer #3 (R3)

R3: I've previously reviewed this manuscript and I only have a few comments.

In general, apart from protect and restore agroforest, management can also contribute to increase carbon sequestration and conserve biodiversity. Management trends is mostly considered in terms of structural complexity, but I wonder if within an agroforestry type there is a range of management options that could affect the delivery of ecosystem services. This could be added in the discussion.

Authors: Thank you for pointing out this omission. There are certainly a suite of management actions in coffee farming systems, beyond tree planting alone, which can encourage biodiversity. Here we add text to the discussion to ensure this point is made:

> **Lines 375-397:** "While some coffee sustainability programs provide market support for shade tree diversity (e.g. the Smithsonian Bird Friendly® certification program, Wright et al. 2024), the design of biodiversity-first approaches that prioritize diverse native species and other management actions that support biodiversity must be carefully considered to ensure positive farm outcomes."

R3: When calculating the current aboveground carbon stock, a note of caution should be included. For instance, I guess that there should be large differences in plantation density within each type which could lead to large errors in the estimation of the stock.

Authors: We acknowledge that within each system type, differences in planting density could contribute to variability in carbon estimates. Thank you for making that point. To maintain a robust global sample, we included studies regardless of density data availability, as restricting the dataset only to those with reported planting densities would have reduced sample sizes to an unworkable degree. However, we certainly agree that planting density is an important variable and we examined its role in other analyses (e.g., **Figure 5, Supplementary Tables 4-5**), where its contribution to explaining carbon stock variability can be evaluated.

R3: Regarding the decoupled trend in carbon and biodiversity, an additional explanation could be that it is limited knowledge on the structure of this agroforest, which can have large effects on biodiversity. For example, given a similar tree density, having various vegetation lager can be more beneficial.

Authors: Absolutely. We ran into a barrier of data availability on habitat structure with the studies included in this meta-analysis. While we hoped to be able to examine a more robust suite of indicators of biodiversity, tree diversity and density were the only variables that were consistently available. Here we describe this inference limitation and point to the critical need for consistent reporting of relevant habitat metrics in future studies:

> **Line 430-439:** "We also found that longitudinal studies on carbon sequestration in coffee systems were rare, thus we compared estimates from paired systems at a single point in time, rather than assessing carbon accumulation as systems mature or diversify. Future research tracking carbon sequestration over time will be essential for enhancing carbon forecasting. Relevant habitat variables for biodiversity beyond tree density and diversity (e.g. tree size, understory vegetation diversity) were also inconsistently reported across studies and the precision of tree diversity data varied substantially by tree inclusion criteria,

sampled plot size, and methodological rigor. Availability of a more robust suite of biodiversity metrics would have strengthened our results, and the inconsistency of metrics within studies used to inform critical land use decisions highlights an urgent need for consensus-building and collaboration.”