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Carbon payment strategies in coffee agroforests shape climate and biodiversity outcomes

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Emily Pappo [1,2], Susan Cook-Patton [3], Damien Beillouin [4,5], Rémi Cardinael [6,7,8], Fernando Cesario[3], Katherine Culbertson[9], Vivian Griffey [10], Jeff Hall [2], Starry Sprenkle Hyppolite [10], Alison Lovdal[3], Cyril Melikov[11], Todd Rosenstock [12], Peter Steward[12], Drew Terasaki Hart[3,13] & Ruth Bennett [1]

Agricultural supply chains increasingly mitigate climate change and biodiversity loss through initiatives that either plant trees or protect threatened carbon stocks on farmlands. 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. For aboveground carbon, we estimated coffee farms currently hold 481.59 TgC globally and could sequester an additional 81.53-86.50 TgC under different agroforestry adoption scenarios. However, more than twice as much aboveground carbon could be lost under intensification scenarios (174.23-221.45 TgC). While tree diversity supports overall biodiversity in agroforestry, we found it does not independently increase carbon, indicating carbon and biodiversity outcomes may be decoupled. Ultimately, tree planting programs in coffee can sequester meaningful carbon volumes but may fail to achieve global carbon and biodiversity goals if they do not also protect existing agroforestry and diversify planting efforts.

As global ecosystems face the complex threat of anthropogenic climate change, initiatives have expanded to mitigate climate change through natural climate solutions that protect, manage, or restore lands[1–4]. Among these solutions, adoption and management of agroforestry, defined as farming systems that combine trees with crops or livestock[5], has emerged as a valuable approach for climate change mitigation and adaptation[6].

Despite ecological and climate adaptation benefits of agroforestry systems[7–9], farmers often face economic pressures to remove trees to increase yields or reduce labor costs[10–12]. Although economic pressures are not the only barrier to agroforestry maintenance or adoption[13] and there are livelihood benefits associated with agroforestry including food, fuel, fodder, and income that can improve household resilience[14], financial incentives are often necessary to sustain or expand agroforestry. Increasingly, farmers are compensated through carbon payment programs for the climate services their agroforests provide. Typically, programs provide direct payments or access to materials and trainings to incentivize either carbon stock creation (hereafter, creation) or carbon stock protection (hereafter, protection). Creation initiatives incentivize planting new trees into or near farmland, while protection initiatives incentivize conservation of threatened agroforests and forests to avoid carbon emissions caused by tree removal (Fig. 1)[15,16]. Both strategies must meet the criterion of carbon additionality, defined as demonstrating more carbon is sequestered post-intervention compared to a relevant baseline[17], a requirement that ensures carbon credits reflect measurable and verifiable climate benefits beyond what would have occurred without the intervention. Despite progress of global protection initiatives that incentivize the avoidance of deforestation, such as REDD + [18], creation is often prioritized in agricultural supply chains due to its potential for

[1]Migratory Bird Center, Smithsonian National Zoological Park and Conservation Biology Institute, Washington, DC, USA. [2]Smithsonian Tropical Research Institute, Panama City, Panama. [3]The Nature Conservancy, 22203 Arlington, VA, USA. [4]CIRAD, UPR HortSys, F-34398 Montpellier, France. [5]HortSys, Univ Montpellier, CIRAD, Montpellier, France. [6]CIRAD, UPR AIDA, Harare, Zimbabwe. [7]IDA, CIRAD, Université Montpellier, Montpellier, France. [8]Department of Plant Production Sciences and Technologies, University of Zimbabwe, Harare, Zimbabwe. [9]Department of Environmental Science, Policy, and Management, University of California, Berkeley, 94710 Berkeley, CA, USA. [10]Conservation International, 22202 Arlington, VA, USA. [11]Ecological Carbon Offset Partners LLC, dba EP Carbon, Minneapolis, MN, USA. [12]Climate Action, Alliance of Biodiversity International and CIAT, Nairobi, Kenya. [13]CSIRO Environment, Brisbane, QLD, Australia.
e-mail: pappoEE@si.edu

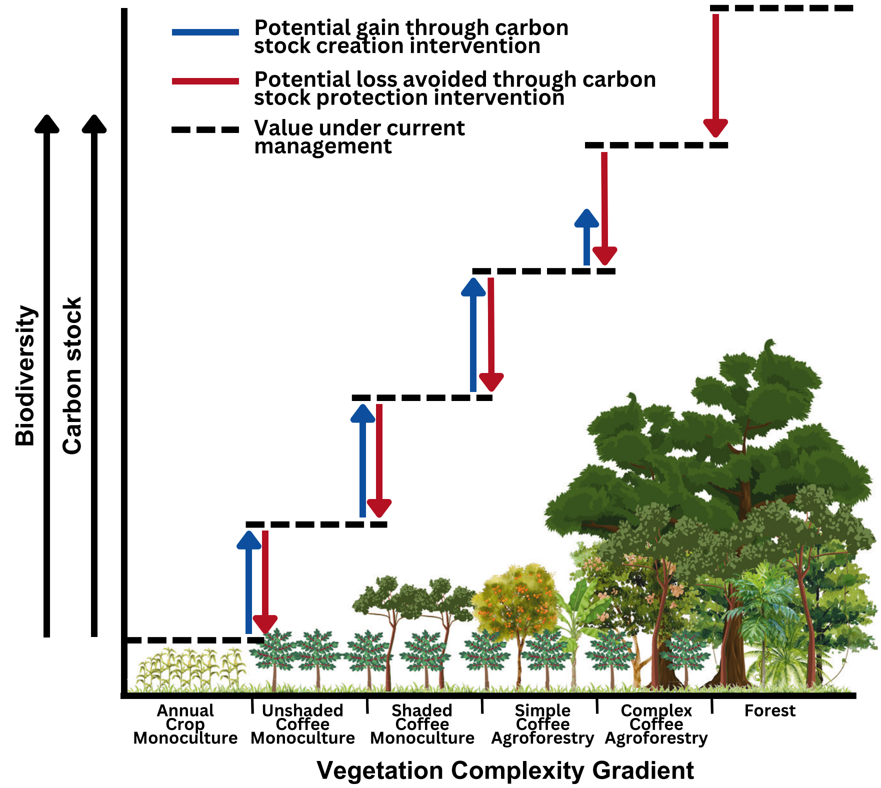

Fig. 1 | Conceptual representation of carbon stock and biodiversity value across a gradient of coffee agroforestry complexity. Conceptual representation of potential changes in carbon stock and biodiversity value (*y*-axis) of carbon stock creation and carbon stock protection interventions across six land management systems spanning a vegetation complexity gradient common in coffee farming landscapes. Dotted black lines illustrate baseline values under current management. Solid arrows show the theoretical gain (blue arrow) through carbon stock creation interventions that facilitate transition of a system to a greater level of complexity or the theoretical loss (red arrow) avoided through carbon stock protection interventions that prohibit transition to a lower level of complexity. Potential gains from carbon stock creation interventions do not reach the maximum value of carbon and biodiversity because tree planting is unlikely to reach the carbon and biodiversity value of land uses with mature native trees (i.e., complex coffee agroforestry and forest) within management-relevant time scales. The depicted scale of carbon and biodiversity changes are illustrative, not hypothetical or data-driven.

rapid, measurable carbon sequestration[16]. This preference may reflect a common, albeit erroneous, assumption that adding trees is more likely to demonstrate carbon additionality than protecting existing trees[2].

Maintaining existing agroforests at high risk of intensification (i.e., removal of existing vegetation) may prevent the release of substantial carbon stocks[19,20] and preserve the structural complexity that better supports high levels of biodiversity[9,21–24]. These protection strategies may provide greater climate and biodiversity benefits than creation strategies that plant trees into monocultures, as complex agroforestry systems often retain mature native trees that take decades or centuries to regrow[25]. Ultimately, prioritizing creation strategies, especially for climate mitigation, in agricultural landscapes risks favoring young, fast-growing trees over biodiversity-rich, mature agroforests.

To evaluate the potential impact of creation and protection strategies on carbon and biodiversity, we use coffee (*Coffea arabica, C. canephora*) as a global case study. Coffee is a major commodity grown on 10.2 million hectares in the tropics and subtropics[9], contributing an estimated $200 billion USD to the global economy[26]. Until the 1970s, most coffee was produced in agroforestry systems, but pressure to increase production drove widespread loss of tree cover and associated biodiversity[24,27]. By 2010, only 24% of coffee was managed in agroforests under a diverse shade canopy (>40% cover and >10 shade tree species), while 35% and 41% were managed under scant or no shade, respectively[9]. While diverse coffee agroforests provide a critical suite of ecosystem services[28] including climate adaptation services like temperature regulation and soil moisture maintenance[8], they can face production challenges leading to low yields[29,30], and there is evidence from coffee systems in Central America that carbon-positive farms tend to have lower net income[31]. These challenges make the maintenance of agroforestry systems frequently reliant on economic incentives. Coffee agroforestry simplification also persists alongside coffee-driven deforestation[12], which is forecasted to further encroach on high elevation forests as climate change shifts production upslope[32,33]. Carbon payment programs in coffee therefore present opportunities both to sequester carbon through rebuilding agroforestry systems (creation) and to protect existing carbon by maintaining complex agroforests and adjacent forests at risk of intensification (protection).

Given the need to simultaneously address ongoing climate change and biodiversity loss, it is critical to evaluate whether agroforestry programs can be better designed to support both outcomes. Here, we examined the potential impact of carbon stock creation and carbon stock protection strategies through a meta-analysis of carbon in global coffee farming systems (Fig. 2). We evaluated the potential impact of creation and protection strategies on carbon stocks in coffee systems, assessed the relationship between carbon sequestration and biodiversity conservation potential, and calculated global estimates of carbon stocks in coffee systems under scenarios of agroforestry adoption and intensification. Our goal is to inform the design of improved carbon payment programs that can simultaneously mitigate climate change, support biodiversity, and improve rural livelihoods.

Results

Literature review

We quantified mean estimates of carbon stocks across a vegetation complexity gradient common in coffee-growing landscapes (Fig. 1) to evaluate the carbon impact of interventions that increase or maintain farm system complexity. We classified coffee farming systems in order of increasing complexity[24], which tends to correspond with an increase in associated biodiversity[21,22,24] (Supplementary Table 1): 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.

The most commonly reported carbon stock was soil organic carbon ($n = 287$ observations), followed by aboveground carbon ($n = 242$) and litter

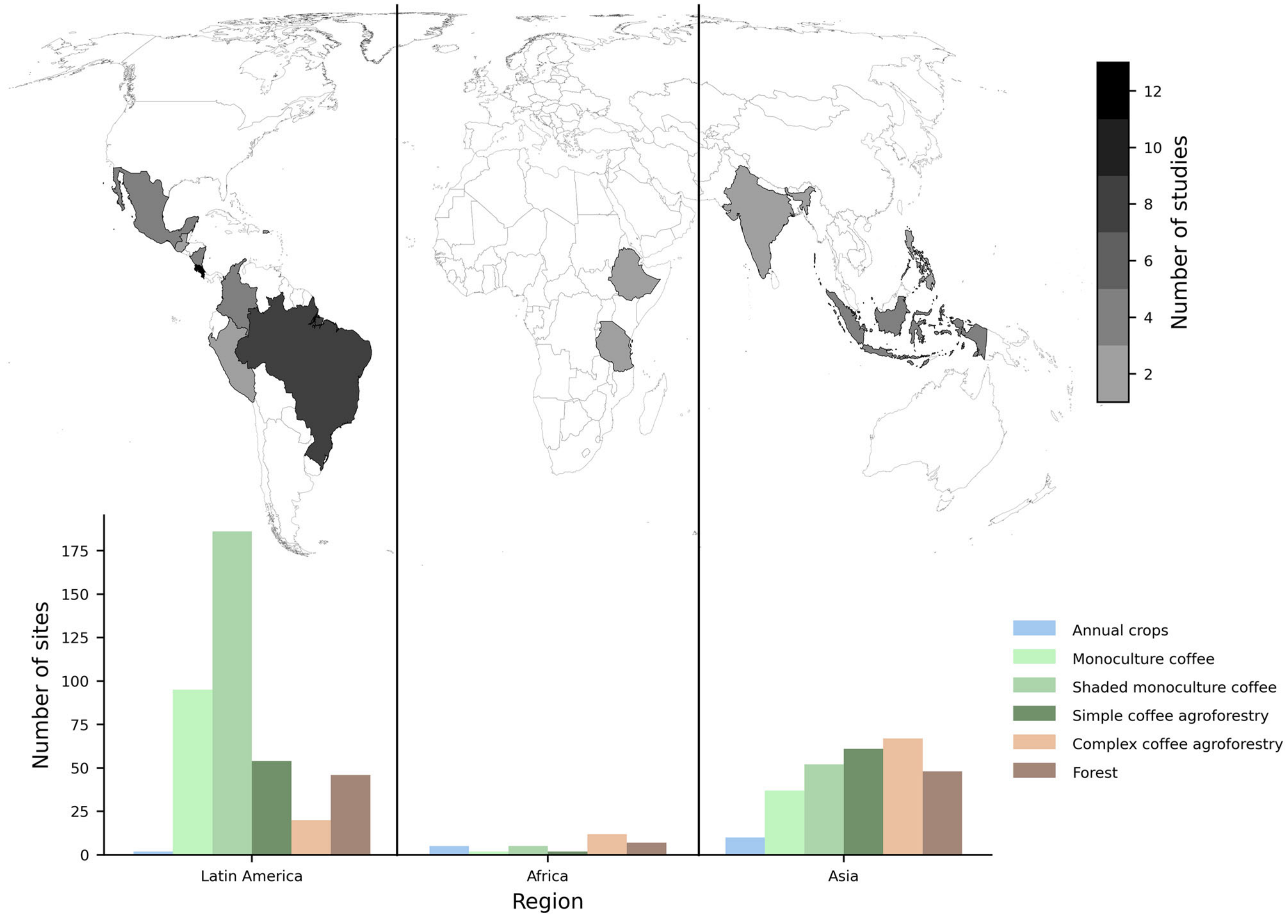

Fig. 2 | Top: Global distribution of studies included in this meta-analysis. Bottom: Count of measurement sites representing each of six land management systems spanning the vegetation complexity gradient of coffee farming landscapes, organized into three broad geographic regions.

carbon ($n = 133$). Data for coarse woody debris carbon ($n = 24$) and field-derived belowground carbon ($n = 7$) were limited. In addition, there were $n = 138$ observations of soil percent carbon. Here we focused on aboveground and soil carbon stocks, given the limited contribution to system carbon (litter) or low sample sizes of other pools, but complete summary statistics are available in Supplementary Table 2. Ultimately, average carbon stocks tended to increase with system complexity, though trends varied across pools (Supplementary Fig. 1).

The carbon stock creation approach: quantifying carbon addition across a management gradient

The carbon stock creation approach adds carbon to a farm system through the addition of new trees. This addition typically transitions a farm along a gradient of complexity (e.g., from unshaded monoculture to shaded monoculture and from shaded monoculture to simple agroforestry). Therefore, to assess potential for creation initiatives to sequester new carbon in coffee farms, we conducted a meta-analysis using Hedges' g[34,35] as the measure of effect size, evaluating paired comparisons of carbon between each system and the next most structurally complex system in the gradient (Fig. 3). Transition from simpler systems, such as annual crops or monocultures, to complex agroforestry systems characterized by mature forest trees[24] would likely require long establishment times, so we only evaluated comparisons between systems differing by one level of complexity. For reference, Hedges' g statistics for all comparisons can be found in Supplementary Table 3.

For aboveground carbon, significant positive effects occurred in the simplest system comparisons: annual crops to unshaded monoculture and unshaded monoculture to shaded monoculture (Fig. 3). This suggests that introducing trees into monocultures offers the greatest opportunity to increase aboveground carbon in coffee, and that establishment of a new coffee plantation on existing cropland is carbon-positive. Complex coffee agroforestry also had significantly greater aboveground carbon than simple coffee agroforestry, though 95% confidence intervals (CIs) for comparisons of shaded monoculture to simple agroforestry and complex agroforestry to forest overlapped zero.

To assess soil carbon, we grouped the paired comparisons of soil organic carbon and soil percent carbon, which is permissible as our analysis compares effect sizes (via Hedges' g) and not raw values. For this soil carbon metric, effects were smaller than for aboveground carbon, and no significant Hedges g' values were observed (Fig. 3). Comparisons of shaded monoculture to simple agroforestry exhibited the highest mean Hedges' g, though CIs were large and overlapped zero. Hedges' g values approached zero for comparisons among more structurally complex systems.

The carbon stock protection approach: quantifying the loss of carbon from intensification of complex agroforestry and forest

The carbon stock protection approach aims to conserve existing stocks in high-complexity systems at risk of simplification and deforestation. To understand the scale of potential carbon loss that protection initiatives could mitigate, we conducted a meta-analysis of effect sizes (Hedges' g) for paired comparisons between intact forests or complex coffee agroforests and simpler farming systems (Fig. 4). For comparisons with forests, unshaded monoculture coffee had significantly lower Hedges' g values for aboveground carbon and both unshaded and shaded monoculture coffee had significantly lower Hedges' g values for soil carbon metrics (Fig. 3) Although fewer studies reported paired comparisons with complex agroforestry, we found significantly lower aboveground carbon in all simpler systems except

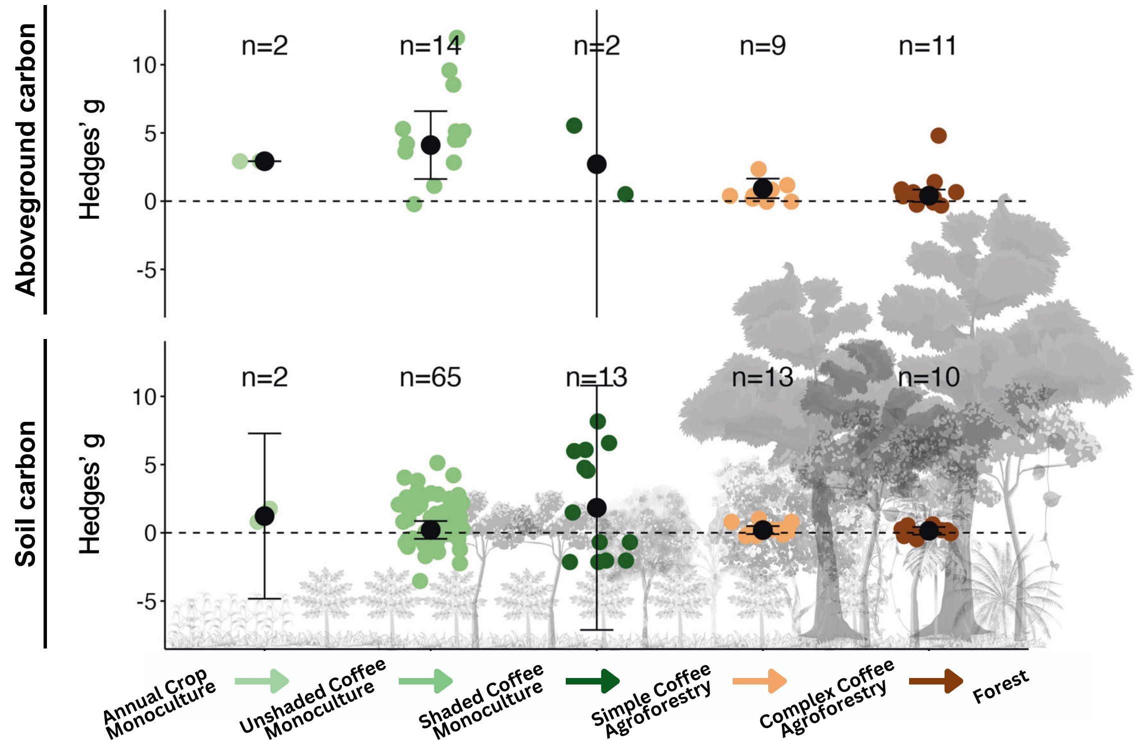

Fig. 3 | Model-derived mean Hedges' *g* values with 95% confidence intervals (CIs) for sequential comparisons of aboveground carbon (top panel) and soil carbon metrics (bottom panel) across a management gradient common in coffee-farming landscapes. Positive values indicate that the more complex system has greater carbon than the less complex system, with statistical significance inferred when 95% CIs do not overlap zero. For comparison of shaded coffee monoculture to simple coffee agroforestry, aboveground carbon CIs extend beyond y-axis limits (−29.0 to 34.4). Hedges g' values for individual sets of paired comparisons (n = number of paired comparisons) are displayed as colored points.

shaded monoculture when compared to complex agroforestry. For soil carbon metrics, we observed significant negative Hedges' g values only in comparisons of annual crops and unshaded monoculture to complex agroforestry (Fig. 4).

Carbon and biodiversity in coffee systems: aligning multiple objectives

To better understand the relationship between carbon stocks and biodiversity conservation potential in coffee systems, we conducted meta-regression models for individual and aggregated carbon metrics, with the Hedges' g values of paired comparisons of coffee monocultures (unshaded or shaded) to coffee agroforests (simple or complex) as dependent variables. Monocultures and agroforestry systems were clustered to ensure sufficient sample sizes. 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[16,21,22,36,37] and these metrics were the most consistently reported indicators of biodiversity across studies (Supplementary Tables 4-5).

Model results indicated a limited relationship between agroforestry structure and carbon stock. Tree density (estimate: 0.0018; $p = 0.018$) but not tree diversity (estimate: 0.0421; $p = 0.317$) explained carbon differences in the full model that included comparisons across aboveground and soil stocks (Fig. 5). Tree density (estimate: 0.002; $p = 0.010$) also explained carbon differences in the model of soil carbon metrics alone, while neither tree density nor diversity were significant predictors ($p > 0.05$) of aboveground carbon (Supplementary Tables 4-5).

Carbon consequences of coffee landscape conversion

Finally, we estimated global carbon held in coffee systems and the potential carbon impact of carbon stock creation and protection interventions. We ran linear mixed-effects models for each stock, including study as a random effect and region, system type, and bioclimatic variables as fixed effects (Supplementary Tables 6–7). Here we analyze and present only aboveground carbon because it varied significantly among farm systems and is often prioritized by carbon payment programs in agriculture[16]. Model results (marginal R^2: 0.471; conditional R^2: 0.620) indicate significantly higher aboveground carbon stocks for all coffee systems except unshaded monoculture in comparison to the baseline of annual crops ($p < 0.05$). The other regional and bioclimatic fixed effects were not significant ($p > 0.05$).

We used our model to predict aboveground carbon stocks for each system type and region (Latin America, Africa, Asia) and then calculated a global average aboveground carbon (MgC ha^{-1}) for each system, weighted by regional contribution to global coffee production. We applied the predicted aboveground carbon values for complex agroforestry, shaded monoculture, and unshaded monoculture to the only known global assessment of coffee farm system area[9], which estimated 24%, 35%, and 41% of coffee land area in systems with >10 shade tree species, <10 shade tree species, and no shade trees, respectively. Keeping estimates of total coffee land use across the tropics and subtropics constant at 10.2 million ha[9], we estimated the current global aboveground carbon stock of coffee to be 481.59 (SE: 123.11) teragrams carbon (TgC).

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. Notably, the amount of carbon gained under all agroforestry adoption scenarios was lower than the amount of carbon that would be lost under all intensification scenarios. These results highlight the potential ineffectiveness of creation

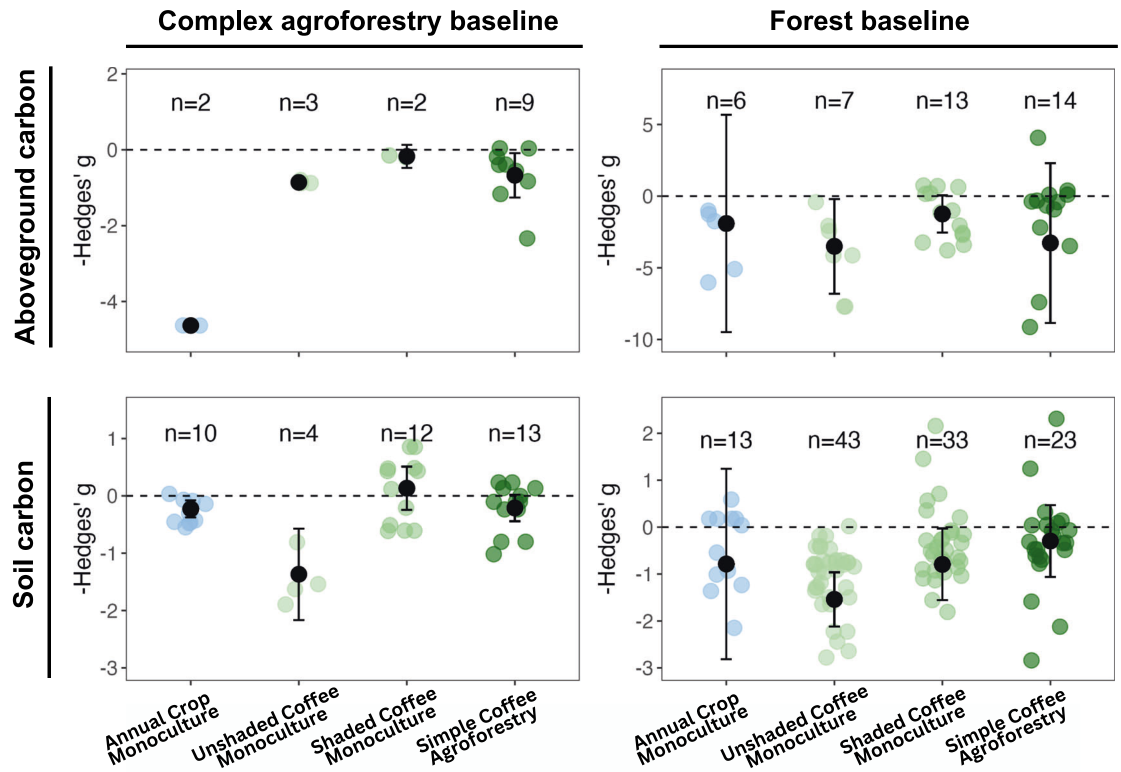

Fig. 4 | Model-derived mean Hedges' *g* values with 95% confidence intervals (CIs) for aboveground carbon (top row) and soil carbon metrics (bottom row) for comparisons of complex coffee agroforestry (left panel) or forest (right panel) with less complex farming systems. Negative values indicate less carbon in the lower complexity farming system than in complex agroforestry or forest, and statistical significance is inferred when CIs do not overlap zero. Hedges g' values for individual sets of paired comparisons (*n* = number of paired comparisons) are displayed as colored points. For paired comparisons of complex coffee agroforestry to forest, see Fig. 3.

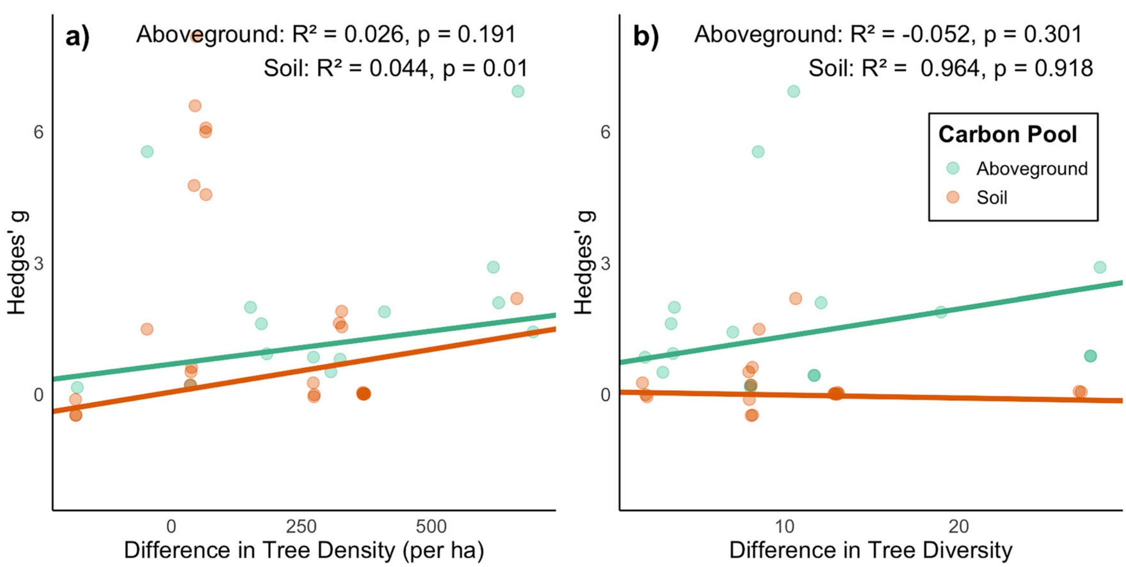

Fig. 5 | Relationships between tree density, tree diversity, and carbon stock in coffee farming systems. Effect size differences in stored carbon (Hedges' g) for comparisons of coffee monoculture (unshaded and shaded) to coffee agroforest (simple and complex) plotted against the difference in (**a**) tree density and (**b**) tree diversity between systems.

mechanisms implemented without concurrent protection initiatives to prevent carbon emissions from tree removal what farms intensify. A mixed scenario, where all monocultures and complex agroforestry converted to simple agroforestry through tree planting and large tree removal resulted in a mean loss of ~5% of the current global aboveground carbon stock in coffee systems (Table 1).

Discussion

This meta-analysis examined the potential impact of carbon stock creation and carbon stock protection strategies on carbon in coffee farming systems, explored the relationship between carbon and biodiversity, and provided, to our knowledge, the first global estimates of carbon stored across coffee farming systems. We demonstrated that continued simplification of coffee

Table 1 | Estimated aboveground carbon stock of global coffee systems under scenarios of agroforestry adoption and intensification

Scenario	Aboveground Carbon (TgC)	SE (TgC)	Change from baseline (%)
Baseline: Current estimated global coffee aboveground carbon stock	481.59	123.11	0.00
Agroforestry adoption scenarios			
Scenario 1: All unshaded monoculture coffee becomes shaded monoculture coffee	568.09	159.37	+17.96
Scenario 2: All unshaded monoculture coffee becomes shaded monoculture coffee, and all shaded monoculture coffee becomes simple coffee agroforestry	563.12	123.32	+16.93
Intensification scenarios			
Scenario 3: All coffee becomes unshaded monoculture	260.14	206.19	−45.98
Scenario 4: All complex coffee agroforestry becomes simple coffee agroforestry, and all shaded monoculture coffee becomes unshaded monoculture coffee	307.36	164.69	−36.18
Mixed scenario			
Scenario 5: All coffee becomes simple agroforestry	456.90	211.06	−5.13

Estimated global aboveground carbon stock in coffee systems under scenarios of coffee agroforestry adoption and intensification. Baseline scenario is based on the estimation[9] of 10.2 million ha under global coffee production with 41% produced in unshaded monoculture, 35% in shaded monoculture, and 24% in complex agroforestry. Agroforestry adoption scenarios assume conversion of monocultures to simple agroforestry, as complex agroforestry is defined by the presence of remnant forest trees[24] (Supplementary Table 1). Scenarios hold total global coffee land use constant.

systems can drive steep carbon emissions, which tree planting programs may be unable to offset. Because tree diversity is an important driver of biodiversity in agroforestry[21], our finding that tree diversity did not independently improve carbon sequestration potential of interventions demonstrates the risk that biodiversity may not benefit from creation programs without explicit prioritization. Overall, these findings show that a preference for carbon stock creation in carbon payment programs in agriculture may miss larger opportunities to mitigate carbon and biodiversity losses from agricultural intensification and expansion.

This study highlights the importance of understanding existing land uses, management trends, and timescales when developing creation or protection incentive programs. Our finding that carbon addition potential declined once shade trees were integrated into monocultures suggests that creation interventions provide limited value for the 24−59% of global coffee farms that already use shade trees[9]. Moreover, the presence of remnant native forest trees in the definition of complex agroforestry[24] may preclude creation-incentivized transition from simpler systems to complex coffee agroforestry under most management-relevant timeframes, despite greater aboveground carbon in complex agroforestry than simple agroforestry. 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. Ultimately, while creation interventions provide value in specific scenarios, such as converting annual monocultures and unshaded coffee monocultures to shaded coffee, it is likely less effective for existing coffee agroforestry systems.

Carbon stock protection approaches offer an important pathway to maintain the substantial carbon stocks and biodiversity of coffee agroforestry systems. Given ongoing coffee intensification trends[12], this carbon should be considered potentially at risk, necessitating strong protection mechanisms to mitigate its loss. In Latin America, for example, the area of coffee grown under diverse shade declined steeply between 1996 and 2012 in El Salvador, Nicaragua, and Guatemala and nearly disappeared in Costa Rica[12]. Though the scope of evidence required for a given agroforestry system to be considered at risk is currently debated, the rapidity at which coffee agroforests have intensified suggest that mechanisms to protect existing agroforests are urgently needed.

We demonstrated that aboveground carbon in complex agroforestry was significantly higher than most other coffee systems, due presumably to the persistence of remnant forest trees (Supplementary Table 1). However, removal of these trees impacts more than just carbon, as large, old trees play a range of important ecological roles within the farm and landscape[38,39]. Additionally, coffee-driven deforestation still continues in some regions as coffee moves into new growing areas[12], leading to carbon emissions, loss of forest-dependent biodiversity[22,23], and incursion of market risks under emerging regulations such as the European Union Deforestation Regulation (EUDR)[40], which will require systems of traceability and evidence of deforestation-free supply chains.

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 barriers to adoption and impact, including persistent challenges with monitoring, reporting, and verification (MRV), as well as governance and financing constraints[41]. 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. However, complementary frameworks have emerged that support or improve upon protection programs, including land use conversion risk forecasting[42] and the integration of land-sparing and land-sharing approaches within working landscapes[43]. Our results, coupled with the reality of carbon marketplaces, indicate an urgent need for innovation in the protection sector.

The biodiversity supported in coffee farms is known to increase with agroforestry complexity[21,27], 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[44] or sequester carbon at similar rates[45], and carbon accumulation in agroforests can be impacted by inter-specific interactions[46].

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[16,21,22,36,37]. 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[47]) 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. 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[48,49]. Tree species sequester carbon at different rates[45] and provide distinct ecosystem services[50], 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[22,23]. 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[8].

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.

By synthesizing all direct measurements of carbon in coffee systems through our comprehensive literature search, we provide novel estimates of carbon stocks across system types in global coffee agriculture. These estimates fill an important gap, as challenges associated with remote sensing of coffee systems have precluded robust global carbon estimates[51]. For perspective, the current aboveground carbon stock we estimate for coffee is roughly a third of the carbon stock of European temperate conifer forests (1.5 ± 0.5 PgC)[52], underscoring the degree to which coffee systems can contribute to global carbon management.

Our estimates suggest that creation initiatives, as illustrated by our scenarios of agroforestry adoption, offer meaningful potential for aboveground carbon sequestration. For example, the estimated carbon gain in the scenario where unshaded monocultures converted to shaded monocultures through planting trees in coffee monocultures was comparable to offsetting the annual emissions of 84 coal-fired plants[53]. However, these gains are limited compared to the severe carbon losses we see under intensification scenarios, which could be avoided through protection initiatives. Our scenarios reveal that transitioning shaded coffee systems to unshaded coffee systems results in carbon losses that could far exceed the potential gains from tree-planting initiatives. Therefore, prioritizing carbon stock protection alongside targeted tree planting efforts is essential to achieve meaningful climate mitigation outcomes in coffee systems.

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[24] and quantitatively[54]. 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.

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.

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. 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.

Conclusions

With this global meta-analysis, we showed that carbon stock creation and carbon stock protection are complementary approaches to offset carbon emissions and protect biodiversity within global coffee systems. Together, these mechanisms can protect the substantial carbon stocks that are at risk of loss through intensification while also increasing carbon stored in coffee monocultures by converting them to agroforestry through tree planting initiatives. 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, particularly as the presence of remnant native forest trees in complex agroforestry may limit its expansion from simpler systems within typical management timeframes. 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. 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.

Methods

Full agroforestry literature synthesis: data preparation and cleaning

The papers included in this study were subset from a larger, and on-going, literature synthesis that aims to characterize variation in carbon stocks across global agroforestry systems[55]. The larger dataset involved two Web of Science searches conducted on 19 April 2017 and then repeated on 6 May 2021 using the search term "(biomass OR carbon OR agb OR recover* OR accumulat*) AND (forest) AND (restorat* OR reforest* OR afforest* OR plantation* OR agroforest* OR secondary*)". We also identified additional papers that were cited within publications from the original searches, which was especially useful for identifying additional papers written in a language other than English (e.g., papers written in Spanish tended to cite other relevant papers also written in Spanish). We noticed that many of these papers cited within other papers (but missed via the original Web of Science searches) were published within the journal *Agroforestry Systems*. We thus searched specifically within that journal on 24 Sept 2021 using the search term "carbon AND (sequestration OR biomass)". We identified an additional 110 relevant papers through our peer networks. We conducted a final Web of Science search on 27 July 2022 using the terms most commonly occurring within the keywords of papers previously identified as relevant: "agroforestry AND (carbon sequestration OR biomass OR soil organic carbon OR carbon stock* OR soil carbon OR carbon OR aboveground biomass OR climate change mitigation)". We included papers published through 2021 (Fig. 6).

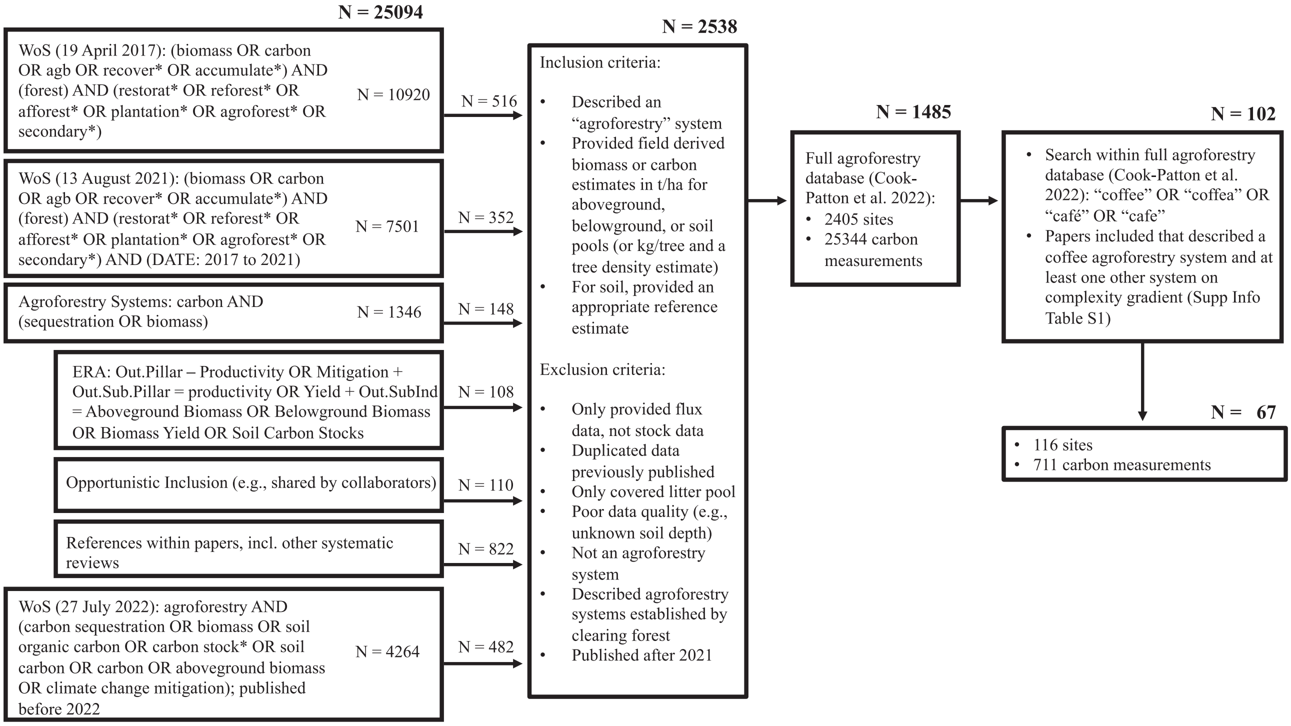

Fig. 6 | PRISMA flow diagram[66] of the identification and screening of published data for this meta-analysis. This diagram shows the screening process for inclusion in the agroforestry database that was leveraged to identify studies[55] as well as the subsequent screening of relevant papers for inclusion in this meta-analysis.

Finally, we incorporated data directly from a prior evidence synthesis, the Evidence for Resilient Agriculture (ERA) platform (https://era.ccafs.cgiar.org/), which synthesizes literature quantifying the outcomes of shifting from one agricultural system to another ($N = 108$ papers). Because ERA is focused on multiple outcomes, not just carbon, we pulled a subset of the data (ERA: Out.Pillar = Productivity OR Mitigation + Out.Sub.Pillar = Productivity OR Yield + Out.SubInd = Aboveground Biomass OR Belowground Biomass OR Biomass Yield OR Soil Carbon Stocks). In sum, we searched through 25094 papers, of which 2538 appeared relevant based on abstract review and 1485 ultimately contained carbon data. The majority of this review was done manually, though we used abstrackr[56] for the final Web of Science search to identify relevant papers based on the words within the abstracts.

For a paper to be fully included in the database, it had to describe an agroforestry or other managed tree system and provide a field-derived estimate of carbon stocks or fluxes that could be converted into an MgC ha^{-1} or MgC ha^{-1} yr^{-1}. For example, we would include a paper that provided MgC $tree^{-1}$ only if it also provided an estimate of trees per hectare. For papers that quantified soil organic carbon, a non-agroforestry reference point had to be provided so that we could calculate how agroforestry adoption changed soil carbon stocks. This reference could be an adjacent agricultural system without trees or a measurement of how soil carbon changes through time (e.g., a chronosequence or measurements from before and after implementation). We did not include papers where the only reference point for soil was an intact ecosystem, since our focus is on establishing agroforestry on open agricultural lands rather than by thinning forests. In general, we focused on papers that describe a transition from an open system (crop, pasture, degraded lands) to a more tree covered system, since thinning of forest to establish agroforestry can lead to greater emissions, as well as negative biodiversity impacts[57]. However, prior land use was reported infrequently.

The most common reason for exclusion at the full-paper review stage was that the paper did not provide field-derived estimates of carbon stocks or time-averaged fluxes ($N = 310$ papers). The next most common reason was that a paper was not the primary source ($N = 197$ papers) or we could not access the primary source ($N = 153$ papers that we could not access and $N = 22$ papers that we could not translate). Because we were interested in evaluating which factors influence the climate mitigation potential of agroforestry systems, we needed the primary papers to extract fully the contextual details (e.g., geolocation, species choice, management regimes, see details below). These contextual details were usually lost as data were synthesized and reused. Moreover, in some cases, our search for the primary source would lead to papers that were not appropriate (e.g., the primary paper would describe carbon stocks in natural desert ecosystems in the North American Sonoran Desert but would have been used to characterize agroforestry in sub-Saharan Africa). Thus, we only extracted data from primary sources in languages that we were able to translate (English, Portuguese, Spanish, and French).

We also focused on the largest carbon stocks within agroforestry systems (above and belowground biomass, soil organic carbon). We excluded papers that only included information on other pools, such as only litter, fine roots, or non-woody crops ($N = 159$). Other reasons for exclusion were that the systems were not agroforestry or managed tree systems ($N = 130$), the study did not provide an appropriate control for soil ($N = 128$), the carbon data could not be converted to MgC ha^{-1} or MgC ha^{-1} yr^{-1} ($N = 60$ due to the units provided and $N = 38$ due to data quality), and/or that it was a small scale (e.g., greenhouse) experiment rather than a field trial ($N = 10$).

As this analysis focused on carbon in coffee systems only (*Coffea arabica* and/or *Coffea canephora*), we identified and screened $N = 102$ papers from the above described database[55] that contained data on carbon in coffee systems and retained $N = 67$ papers that contained comparisons of field derived carbon between at least two coffee system types (unshaded coffee monoculture, shaded coffee monoculture, simple coffee agroforestry, complex coffee agroforestry; classification criteria described in detail in Supplementary Table 1) or between a coffee system and annual crop monoculture (e.g., maize, wheat, sorghum, etc.) or nearby forest (Table 2).

Coffee-specific agroforestry literature synthesis: data preparation and cleaning

From the studies that met our inclusion criteria ($n = 67$), we extracted all records of directly measured aboveground carbon, belowground

Table 2 | Summary of the studies included in this meta-analysis

First author	Year	Country	Systems	Stocks	Included in effect size analysis	Coffee species
Andrade	2014	Colombia	Shaded Coffee Monoculture; Unshaded Coffee Monoculture	Aboveground Carbon	Yes	Coffea arabica
Hergoualc'h	2012	Costa Rica	Shaded Coffee Monoculture; Unshaded Coffee Monoculture	Litter Carbon; Soil Organic Carbon	Yes	Coffea arabica
Lapeyre	2004	Peru	Forest; Annual Crop Monoculture; Shaded Coffee Monoculture	Aboveground Carbon	No	Coffea arabica
Alvarado	2012	Colombia	Unshaded Coffee Monoculture; Shaded Coffee Monoculture	Soil Percent Carbon	Yes	Coffea arabica
Brakas	2011	Philippines	Complex Coffee Agroforestry; Simple Coffee Agroforestry; Unshaded Coffee Monoculture; Forest; Annual Crop Monoculture	Aboveground Carbon	Yes	Unspecified
Dechert	2004	Indonesia	Annual Crop Monoculture	Litter Carbon; Soil Organic Carbon	No	Unspecified
Mganga	2014	Tanzania	Forest; Simple Coffee Agroforestry; Unshaded Coffee Monoculture; Annual Crop Monoculture	Soil Percent Carbon	Yes	Unspecified
Tumwebaze	2016	Uganda	Simple Coffee Agroforestry; Unshaded Coffee Monoculture	Soil Organic Carbon	No	Coffea arabica; Coffea canephora
Verchot	2006	Indonesia	Forest; Unshaded Coffee Monoculture; Simple Coffee Agroforestry	Soil Percent Carbon	No	Unspecified
Siles	2010	Costa Rica	Shaded Coffee Monoculture; Unshaded Coffee Monoculture	Aboveground Carbon; Soil Percent Carbon	Yes	Coffea arabica
Badari	2020	Brazil	Complex Coffee Agroforestry; Forest	Aboveground Carbon	Yes	Unspecified
Betemariyam	2020	Ethiopia	Simple Coffee Agroforestry; Complex Coffee Agroforestry	Aboveground Carbon; Litter Carbon; Soil Organic Carbon	Yes	Coffea arabica
Ortiz-Ceballos	2020	Mexico	Simple Coffee Agroforestry; Complex Coffee Agroforestry	Aboveground Carbon	Yes	Coffea arabica
Espinoza-Dominguez	2012	Mexico	Forest; Shaded Coffee Monoculture	Aboveground Carbon; Soil Organic Carbon; Litter Carbon	No	Coffea arabica
Goncalves	2021	Brazil	Simple Coffee Agroforestry	Aboveground Carbon	No	Unspecified
Hernandez Nunez	2021	Colombia	Simple Coffee Agroforestry; Forest	Aboveground Carbon; Litter Carbon; Soil Organic Carbon	Yes	Coffea arabica
Karthika	2021	India	Forest; Complex Coffee Agroforestry	Soil Organic Carbon	No	Unspecified
Matos	2020	Brazil	Simple Coffee Agroforestry; Forest	Soil Percent Carbon	Yes	Coffea arabica
Guillemot	2018	India	Forest; Complex Coffee Agroforestry	Aboveground Carbon; Litter Carbon; Soil Organic Carbon;	Yes	Coffea arabica; Coffea canephora
Coltri	2015	Brazil	Unshaded Coffee Monoculture; Shaded Coffee Monoculture	Aboveground Carbon;	Yes	Coffea arabica
Zaro	2020	Brazil	Shaded Coffee Monoculture; Unshaded Coffee Monoculture	Soil Organic Carbon; Aboveground Carbon; Litter Carbon	Yes	Coffea arabica
Haggar	2011	Costa Rica	Shaded Coffee Monoculture; Unshaded Coffee Monoculture	Soil Percent Carbon	Yes	Coffea arabica
Moraga	2011	Nicaragua	Unshaded Coffee Monoculture; Shaded Coffee Monoculture	Aboveground Carbon	Yes	Coffea arabica
Hairiah	2002	Indonesia	Simple Coffee Agroforestry; Shaded Coffee Monoculture; Unshaded Coffee Monoculture; Forest	Aboveground Carbon	Yes	Unspecified
van Noordwijk	2002	Indonesia	Simple Coffee Agroforestry; Unshaded Coffee Monoculture; Forest	Aboveground Carbon	No	Unspecified
Soto-Pinto	2015	Mexico	Shaded Coffee Monoculture; Complex Coffee Agroforestry	Soil Organic Carbon; Litter Carbon; Aboveground Carbon; Coarse Woody Debris Carbon;	Yes	Coffea arabica
Avila Vargas	2000	Costa Rica	Shaded Coffee Monoculture; Unshaded Coffee Monoculture	Aboveground Carbon; Soil Organic Carbon	No	Coffea arabica
De Miguel Magana	2004	Costa Rica	Unshaded Coffee Monoculture; Shaded Coffee Monoculture	Litter Carbon; Aboveground Carbon;	No	Coffea arabica
Denu	2016	Ethiopia	Complex Coffee Agroforestry; Forest	Aboveground Carbon	Yes	Coffea arabica
Guimaraes	2014	Brazil	Forest; Unshaded Coffee Monoculture; Shaded Coffee Monoculture	Soil Organic Carbon	Yes	Coffea arabica
Harmand	2007	Costa Rica	Shaded Coffee Monoculture; Unshaded Coffee Monoculture	Aboveground Carbon; Litter Carbon	No	Coffea arabica
Peeters	2003	Mexico	Complex Coffee Agroforestry; Simple Coffee Agroforestry	Aboveground Carbon	Yes	Unspecified
Powell	1998	Guatemala	Shaded Coffee Monoculture; Annual Crop Monoculture; Forest	Aboveground Carbon; Litter Carbon; Soil Organic Carbon	Yes	Coffea arabica
Saurez	2002	Nicaragua	Simple Coffee Agroforestry; Shaded Coffee Monoculture; Complex Coffee Agroforestry	Litter Carbon; Aboveground Carbon; Soil Organic Carbon;	No	Coffea arabica
de Souza	2012	Brazil	Forest; Simple Coffee Agroforestry; Unshaded Coffee Monoculture	Soil Percent Carbon	Yes	Coffea arabica
Toru	2019	Ethiopia	Forest; Shaded Coffee Monoculture; Annual Crop Monoculture	Aboveground Carbon; Litter Carbon; Soil Organic Carbon	Yes	Coffea arabica

Table 2 (continued) | Summary of the studies included in this meta-analysis

First author	Year	Country	Systems	Stocks	Included in effect size analysis	Coffee species
Aviles-Vazquez	2009	United States	Unshaded Coffee Monoculture; Shaded Coffee Monoculture; Forest	Aboveground Carbon; Soil Organic Carbon	No	Coffea arabica
De Beenhouwer	2016	Ethiopia	Complex Coffee Agroforestry	Aboveground Carbon; Soil Organic Carbon; Litter Carbon	No	Coffea arabica
Meylan	2017	Costa Rica	Unshaded Coffee Monoculture; Shaded Coffee Monoculture	Soil Percent Carbon	No	Coffea arabica
Nesper	2019	India	Complex Coffee Agroforestry	Soil Percent Carbon	No	Coffea canephora
Pinoargote	2017	Nicaragua	Unshaded Coffee Monoculture; Simple Coffee Agroforestry	Aboveground Carbon	Yes	Coffea arabica
Cannavo	2011	Costa Rica	Shaded Coffee Monoculture; Unshaded Coffee Monoculture	Soil Percent Carbon	No	Coffea arabica
Cardoso	2003	Brazil	Simple Coffee Agroforestry; Unshaded Coffee Monoculture	Soil Percent Carbon	Yes	Coffea arabica
Lopez-Rodriguez	2015	United States	Unshaded Coffee Monoculture; Shaded Coffee Monoculture; Forest	Soil Percent Carbon	Yes	Coffea arabica
Ayala-Montejo	2022	Mexico	Shaded Coffee Monoculture; Simple Coffee Agroforestry	Soil Organic Carbon; Litter Carbon	Yes	Unspecified
Mena-Mosquera	2008	Costa Rica	Forest; Shaded Coffee Monoculture	Aboveground Carbon; Litter Carbon; Soil Organic Carbon	Yes	Coffea arabica
Cogo	2012	Brazil	Unshaded Coffee Monoculture; Complex Coffee Agroforestry; Forest	Soil Organic Carbon	Yes	Coffea arabica
Noponen	2013	Costa Rica	Shaded Coffee Monoculture; Unshaded Coffee Monoculture	Aboveground Carbon; Litter Carbon; Coarse Woody Debris Carbon;	No	Coffea arabica
Markum	2013	Indonesia	Forest; Simple Coffee Agroforestry	Aboveground Carbon; Litter Carbon; Coarse Woody Debris Carbon; Soil Organic Carbon	Yes	Coffea canephora
Cerda	2016	Costa Rica	Unshaded Coffee Monoculture; Shaded Coffee Monoculture; Simple Coffee Agroforestry	; Aboveground Carbon;	Yes	Coffea arabica
Cristobal-Acevedo	2019	Mexico	Forest; Complex Coffee Agroforestry; Simple Coffee Agroforestry; Unshaded Coffee Monoculture	Aboveground Carbon; Soil Organic Carbon	Yes	Coffea arabica
Solis	2020	Peru	Simple Coffee Agroforestry; Shaded Coffee Monoculture; Unshaded Coffee Monoculture	Aboveground Carbon; Litter Carbon; Soil Organic Carbon	Yes	Coffea arabica
Sahoo	2021	India	Simple Coffee Agroforestry; Forest; Annual Crop Monoculture	Aboveground Carbon; Soil Organic Carbon	Yes	Unspecified
De Leijster	2021	Colombia	Unshaded Coffee Monoculture; Simple Coffee Agroforestry	Aboveground Carbon	Yes	Coffea arabica
Vanderhaegen	2015	Ethiopia	Annual Crop Monoculture; Simple Coffee Agroforestry; Complex Coffee Agroforestry	Soil Organic Carbon; Litter Carbon; Coarse Woody Debris Carbon	Yes	Coffea arabica
Marinho	2014	Brazil	Unshaded Coffee Monoculture; Shaded Coffee Monoculture	Soil Percent Carbon	Yes	Coffea arabica
Notaro	2014	Brazil	Simple Coffee Agroforestry; Forest; Unshaded Coffee Monoculture	Soil Percent Carbon; Litter Carbon	Yes	Coffea arabica
Haggar	2013	Guatemala	Unshaded Coffee Monoculture; Shaded Coffee Monoculture; Complex Coffee Agroforestry; Forest	Aboveground Carbon;	Yes	Unspecified
Schmitt-Harsh	2012	Guatemala	Simple Coffee Agroforestry; Forest	Aboveground Carbon; Soil Organic Carbon	Yes	Coffea arabica
Hager	2012	Costa Rica	Simple Coffee Agroforestry; Complex Coffee Agroforestry	Aboveground Carbon; Litter Carbon; Soil Organic Carbon	Yes	Coffea arabica
Soto-Pinto	2010	Mexico	Shaded Coffee Monoculture; Simple Coffee Agroforestry; Complex Coffee Agroforestry	Soil Organic Carbon	Yes	Coffea arabica
Hergoualc'h	2008	Costa Rica	Shaded Coffee Monoculture; Unshaded Coffee Monoculture	Soil Percent Carbon	Yes	Coffea arabica
Dossa	2008	Togo	Shaded Coffee Monoculture; Unshaded Coffee Monoculture	Aboveground Carbon; Belowground Carbon; Litter Carbon;	Yes	Coffea canephora
Ehrenbergerova	2016	Peru	Shaded Coffee Monoculture; Unshaded Coffee Monoculture	Aboveground Carbon; Soil Organic Carbon; Litter Carbon;	Yes	Coffea arabica
Hairiah	2006	Indonesia	Simple Coffee Agroforestry; Shaded Coffee Monoculture; Unshaded Coffee Monoculture; Forest	Soil Percent Carbon	Yes	Unspecified
Pinard	2014	Rwanda	Unshaded Coffee Monoculture; Shaded Coffee Monoculture	Soil Percent Carbon	Yes	Coffea arabica
Polzot	2004	Costa Rica	Shaded Coffee Monoculture; Simple Coffee Agroforestry; Forest	Aboveground Carbon	No	Unspecified

Summary of the $N = 67$ studies included in this meta-analysis. The column "Included in effect size analysis" indicate the $N = 48$ studies for which we could calculate Hedges' g from paired comparisons.

Table 3 | Summary of observations for each carbon measurement and system type

System Type	Observations (N)					
	Aboveground Carbon	Litter Carbon	Soil Organic Carbon	Soil Percent Carbon	Below-ground Carbon	Coarse Woody Debris Carbon
Annual Crops	4	2	9	2	0	0
Unshaded Monoculture Coffee	27	11	41	43	1	2
Shaded Monoculture Coffee	55	34	68	56	1	6
Simple Coffee Agroforestry	37	13	35	19	0	2
Complex Coffee Agroforestry	21	17	39	3	0	4
Forest	27	12	41	15	0	2

Summary of the number of individual observations (N) for each carbon measurement and system type across the $N = 67$ studies included in our dataset.

carbon, coarse woody debris carbon, litter carbon, soil organic carbon, and soil percent carbon (Table 3). 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. Data for shade tree and coffee aboveground carbon were extracted separately, if reported separately in the original manuscript, and aggregated into a single aboveground carbon metric by summing the means and combining variance by taking the square root of the sum of each squared SD. Due to unacceptably high levels of uncertainty[58], we did not include published observations of belowground carbon when it was derived from aboveground biomass, opting to include only direct measurements of belowground carbon ($n = 2$ observations).

Synthesizing carbon by system and carbon stock

To assess the variation in carbon stocks across systems, we first calculated mean, median, standard deviation (SD), range, and n for each carbon stock and system type (Supplementary Table 2). Aboveground carbon data collection methodology varied by the minimum diameter at breast height (DBH) of trees that were counted, but ANOVA of mean carbon between different DBH categories (with an interaction term that included land use) showed no significant differences ($p > 0.05$), so we kept all aboveground carbon observations for the full analysis. For soil organic carbon, ANOVA showed that observations varied by soil depth ($p < 0.05$). Therefore, we subset the data by depth and included only SOC measurements for the 0−30 cm soil depth profile, which maximized the sample size across all systems. This category included observations originally reported at 0−30 cm depth and also combined measurements when a study reported multiple measurements for a land use that could be combined to 0-30 cm (i.e. 0−10, 10−20, and 20−30 cm).

Assessing impact of vegetation management on carbon stocks

We ran linear mixed effect models to explore the impact of system type on carbon using the package lme4[59] in RStudio (R version 4.3.3). We ran four models, one for the full dataset, including the three largest carbon stock datasets together (aboveground carbon, soil organic carbon [0−30 cm], litter carbon), and one for each stock individually. For all models we included study region (Africa, Asia, Latin America) and the first three principal components derived from bioclimatic variables as fixed effects. Bioclimatic variables – minimum temperature (°C), maximum temperature (°C), average temperature (°C), precipitation (mm), and elevation – were extracted from WorldClim[60] using coordinates extracted from each study, when available. For studies that provided a range of latitude/longitude coordinates, we selected a midpoint using Google Earth (version 10.59.0.2) ensuring that the midpoint reflected the land use and approximate elevation reported in the study ($N = 7$ sites). We excluded sites from the principal components analysis (PCA) if coordinates reported in a range were separated by >40 km ($N = 30$ sites excluded), or if coordinates were not reported and could not be determined ($N = 5$ sites excluded). Due to high correlations among all bioclimatic variables, we conducted a PCA on the variables using built-in function prcomp() in RStudio (R version 4.3.3) and used the first three principal components that accounted for 98.6% of the variation (PC1: 76.2%, PC2: 19.3%, PC3: 3.1%) as fixed effects in the models. Additionally, a study identifier was included as a random effect to account for variability between studies. Linear mixed-effect model results are reported in Supplementary Tables 6–7, and we used $p < 0.05$ as the threshold for significance.

Global estimation of aboveground carbon stock in coffee systems

To calculate global estimates of aboveground carbon stored in coffee systems under current and postulated scenarios of coffee system conversion, we used the predict() function in RStudio (R version 4.3.3) to predict aboveground carbon values for each region using the linear mixed effects model described above, employing mean PCA values and removing random effect of study. Standard error (SE) was calculated for the predicted values using the Delta method which uses the variance-covariance matrix of the fixed effects to estimate variance and SE[61]. Then, we summarized six marketing years of country-level coffee production data from 2019/2020 to 2024/2025[62] to estimate the approximate percentage of global coffee grown in the Americas (58.6%), Africa (11.3%), and Asia (30.1%) and used those values to weight the predictions of aboveground carbon per hectare for each coffee system type, producing weighted predicted values (MgC ha^{-1} ± SE) of 25.5 ± 20.2 for unshaded monoculture, 46.2 ± 19.2 for shaded monoculture, 44.8 ± 20.7 for simple agroforestry, and 85.8 ± 23.6 for complex agroforestry.

We then leveraged the estimates of global coffee land use under different types of shade cover[9] to create a baseline estimate of global aboveground carbon stock in global coffee systems. These land use estimates are based on data from 2010 from 19 countries across Latin America, Africa, and Asia showing that coffee land area covered an ~10.2 million ha globally with 41% grown as "sun coffee", 35% grown with "scant shade", defined as 1-40% shade cover with <10 (though typically 1 or 2) species of shade tree, and 24% with traditional "diverse shade", defined as >40% shade cover with >10 shade tree species present[9]. Although the relative proportions and total area of coffee farmed in different systems may have shifted since 2010, we know of no other global estimate calculated more recently that would improve our inference.

To apply these land use estimates to our dataset, we aligned our land management categories via reported shade tree species diversity, with unshaded monoculture considered "sun coffee", shaded monoculture considered "scant shade", and complex agroforestry considered "dense shade"[9]. To estimate current global aboveground carbon stock of coffee, we multiplied the weighted predictions of aboveground carbon stock for each land management category by the corresponding percent of the global land area of coffee (10.2 million hectares) covered by that land use (sun coffee, scant shade, or diverse shade). 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[16]: (1) all unshaded monoculture coffee becomes shaded monoculture coffee, (2) all unshaded monoculture coffee becomes shaded monoculture coffee, and all shaded monoculture coffee becomes simple coffee agroforestry. We also included scenarios where land management intensifies, representing scenarios that could be prevented with carbon stock protection initiatives: (3) all coffee becomes unshaded monoculture, (4) all complex coffee agroforestry becomes simple coffee agroforestry, and all shaded monoculture coffee becomes unshaded monoculture coffee. De-intensification scenarios assume conversion of monocultures to simple agroforestry, as our complex agroforestry category requires the presence of remnant forest trees as shade[24] (Supplementary Table 1). Finally, we included a mixed scenario where a subset of the land area intensifies and a subset de-intensifies: (5) All coffee becomes simple agroforestry (Table 1).

Assessing potential impact of carbon stock creation and carbon stock protection approaches

To assess how stored carbon would change under carbon stock creation and carbon stock protection approaches, we calculated Hedges' g[34] as a metric of effect size for within-study paired comparisons of carbon between system types. The calculation requires mean, standard deviation (SD) and sample size (n) to be reported for each observation in a paired comparison, thus we discarded any observations that did not report data that could be transformed into these variables. For observations that did not contain measures of statistical dispersion but did contain information on sample size (n), we imputed standard deviations (SD) via previously reported protocols[63]. Specifically, we assessed SD distribution for those reported in the full dataset; as the distribution was skewed, we calculated the median SD for each category of carbon pool and land use and used those imputed SDs when an SD was not originally reported. Of the 601 total observations, 208 had SD values that could be used for imputation. Not all categories had SDs that could be used for imputation; belowground and coarse woody debris carbon had very few observations with SDs for all systems, and litter carbon lacked SD values for annual crop systems. For other categories, the number of SDs used for imputation ranged from 2−24 values. After imputation and filtering of rows with neither imputed nor original SD values and those that compare only understory or overstory carbon (as opposed to combined aboveground carbon), our final dataset for analyses of effect size contained 48 studies with 422 paired comparisons (Table 2).

We used a manually defined function in RStudio to calculate Hedges' g and associated variance[34] using the following equation:

$$g = \frac{\bar{X}_1 - \bar{X}_2}{pooled\ SD}$$

$$pooled\ SD = \sqrt{\frac{(n_1 - 1) \cdot SD_1^2 + (n_2 - 1) \cdot SD_2^2}{n_1 + n_2 - 2}}$$

$$variance = \frac{n_1 + n_2}{n_1 \cdot n_2} + \frac{g^2}{2 \cdot (n_1 + n_2)}$$

$\bar{X}_1$ and $\bar{X}_2$: sample means
SD_1 and SD_2: sample standard deviations
n_1 and n_2: sample sizes

All comparisons were made with the less complex system as group 1 and the more complex system as group 2, so a positive Hedges' g value indicates that the more complex system has more carbon than the less complex system, and a negative Hedges' g value indicates that the more complex system has less carbon than the less complex system. However, for the visualization in Fig. 5 which assesses effect size relative to the more complex systems with native shade tree cover (i.e., forest, complex coffee agroforestry), the more complex system is displayed as the reference system. Therefore, for Fig. 4 only we multiplied the Hedges' g values by −1 for a more intuitive interpretation. We also combined comparisons for soil organic carbon stock and soil percent carbon into a single category named "soil carbon metrics" to increase sample size and streamline analyses. Although soil percent carbon is a measure of the percentage of carbon in a soil sample and not a measure of carbon stock, because we compare effect sizes (Hedges' g) and not raw values these measures can be effectively grouped.

We used Hedges' g values as the measure of effect size to estimate the relative effectiveness of carbon stock creation and carbon stock protection approaches in global coffee systems. For the carbon stock creation analysis, we conducted a meta-analysis using the rma.mv function in the metafor package[64] in RStudio (R version 4.3.3). We used a random-effects model, specifying a random effect of study ID to address non-independence of effect sizes derived from the same study. The meta-analytic models were fit using restricted maximum likelihood (REML) estimation to derive pooled estimates of Hedges' g, and the Knapp-Hartung adjustment[65] was applied to account for small-sample bias in confidence interval estimation. Paired comparisons were evaluated for systems differing by one level of complexity (e.g., annual crops to unshaded coffee monoculture, unshaded coffee monoculture to shaded coffee monoculture, etc.), approximating the potential change in carbon storage as systems advance across the complexity gradient (Fig. 3). For the carbon stock protection analysis, we applied the same random-effects meta-analytic approach to evaluate paired comparisons of carbon stocks between (1) intact forests and simpler systems and (2) complex coffee agroforestry systems and simpler systems, aiming to understand the potential for carbon loss as complex systems simplify (Fig. 4). For both carbon stock creation and protection figures, we report mean and 95% confidence interval and interpret a significant result as one where the 95% confidence interval does not overlap zero. All model-derived Hedges' g means and confidence intervals are reported in Supplementary Table 3.

Assessing effect of agroforest composition on carbon stocks

To better understand the potential tradeoffs between biodiversity and carbon in coffee systems, we assessed the availability of habitat metrics across the studies in our dataset. Most habitat metrics known to predict wild biodiversity in coffee systems (e.g., percent canopy coverage, canopy height)[37], were not sufficiently reported to support inclusion in our analysis. Instead, we included metrics of tree density, which is known to correlate with diversity of some (though not all) taxonomic groups and tree diversity, which is known to predict biodiversity of multiple taxa in coffee agroforests, as these were most widely reported habitat metrics[22,36,37].

Tree density was included if it was reported as the number of individual trees per hectare (trees/ha) or could be converted to trees/ha. Tree diversity was typically reported as the number of woody species (including coffee species) per plot, but the plot sizes were variable, ranging from 0.02 ha to >1 ha. In some instances, diversity was stated at the system level without any description of methodology. To account for this variability, we calculated Δdensity and Δdiversity (i.e., the absolute change in the metrics between the sites being compared) for use in our analyses.

To understand the effect of habitat metrics (i.e., tree density and diversity) on carbon sequestration potential, we ran mixed-effects meta-regression models using the rma.mv function in the metafor package[64] in RStudio (R version 4.3.3) and specifying a random effect of study ID. The models were fit using restricted maximum likelihood (REML) estimation to derive pooled estimates of Hedges' g, and the Knapp-Hartung adjustment[65] was applied to account for small-sample bias in confidence interval estimation. We ran four model sets with Hedges' g as the dependent variable and Δdensity and Δdiversity as moderators. The model sets included individual models for each of the two most reported carbon stocks (aboveground carbon and soil carbon metrics) and one model on the full dataset including both carbon stocks. We were specifically interested in the differences in potential for carbon sequestration between monocultures and agroforestry systems, so we included Hedges' g values from all paired comparisons of coffee monocultures (unshaded and shaded) to coffee agroforestry systems (simple and complex) for studies with available data on tree system composition ($n = 34$ comparisons). The model results are reported in Fig. 5 and Supplementary Tables 4-5 and we interpret $p < 0.05$ as a threshold for significance.

Ethics & Inclusion statement

Roles and responsibilities of collaborators and co-authors were clearly designated in advance of this research. This meta-analysis synthesized global carbon data and therefore did not involve risk to health, safety, or security for researchers or participants.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Our coffee agroforestry carbon dataset is available at: https://doi.org/10.6084/m9.figshare.28477115.v1

Code availability

The custom code used for our meta-analyses is available upon request from the corresponding author, EP.

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Author contributions

E.P. and R.B. conceived the study. E.P. conducted the analyses and led the writing of the manuscript. S.C.P. led the development of the global agroforestry carbon database used to identify studies for this meta-analysis and wrote the section of the manuscript detailing database development. E.P., S.C.P., D.B., R.C., F.C., K.C., V.G., S.S.H., A.L., C.M., T.R., P.S., and D.T.H. all contributed to identification and data extraction of the papers included in this meta-analysis. E.P., S.C.P., D.B., R.C., F.C., K.C., V.G., J.H., S.S.H., A.L., C.M., T.R., P.S., D.T.H., and R.B. provided conceptual guidance and editing.

Competing interests

The authors declare no competing interests.

Additional information

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Correspondence and requests for materials should be addressed to Emily Pappo.

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