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Carbon footprints and CO_2 removal in primary production of coffee: a meta-analytical review

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Abstract

Producing countries and value-chain participants are seeking to minimize the effect of coffee production on global warming. In support of this goal, we present a global review of carbon footprints and atmospheric-CO_2 removal rates in primary production of coffee, based on 21 studies of carbon footprint and 16 with data on CO_2 removal rate. We aimed to characterize typical values, identify determinants, compare arabica and robusta coffee, compare cropping systems, and suggest ways of reducing footprints and increasing CO_2 removal rates. The median ± interquartile range of carbon footprints of coffee production were 2954 ± 3636 CO_2e ha^{-1} year^{-1} (area carbon footprint, ACF) and 2.18 ± 2.04 CO_2e kg^{-1} green beans (product carbon footprint, PCF). Manufacture and application of fertilizers, particularly nitrogenous fertilizers, were almost always the main emissions sources (65%–100% of the total). ACF was significantly higher in arabica than robusta, while ACFs of agroforestry and organic systems were <50% of those of unshaded and non-organic systems; these differences were also significant. PCF of organic production was significantly lower than that of non-organic production, but marginally so; no other significant differences in PCF were found. The median CO_2 removal rate of unshaded production was 6990 ± 3405 kg CO_2 ha^{-1} year^{-1}. For agroforestry production the median was much higher ($17\,676 \pm 3971$ kg CO_2 ha^{-1} year^{-1}). Removal rates of organic and non-organic production did not differ significantly. We present a generalized approach for reducing the overall global-warming effect of coffee production, consisting of 10 options for interventions within an overarching principle of zero deforestation. Wider use of agroforestry production and use of organic nitrogen sources are features of eight of the interventions. Implementation of the interventions will also require the building of enabling frameworks that allow farmers to meet climate-change mitigation goals without sacrificing productivity or profitability.

Key words: agroforestry, climate-change mitigation, *Coffea arabica*, *Coffea canephora*, greenhouse gas

1. Introduction

1.1. Background and justification

Agriculture, forestry, and other land-related activities accounted for ≈23% of human-caused greenhouse-gas emissions between 2007 and 2016 (Shukla et al. 2019). Consequently, the reduction of emissions from agriculture is an important component of efforts to slow global warming. In 2022, coffee was globally the fifth largest perennial crop in area (≈120 000 km^2) and the largest in seven of the 10 principal producing countries (FAOSTAT 2023). As such, greenhouse-gas emissions from coffee production are of concern both to producing countries, eight of which have prioritized mitigation actions in coffee in their nationally determined contributions under the Paris Accord (Climate Watch 2024), and to corporate and other actors in the coffee sector who wish to reduce their carbon footprints as part of corporate climate commitments (Global Coffee Platform 2023; Sustainable Coffee Challenge 2023).

In support of mitigation efforts, we reviewed published values of carbon footprint and atmospheric-CO_2 removal rate (CDR) in coffee.The carbon footprint and the CDR are, respectively, measures of the greenhouse-gas emissions produced and CO_2 removed by an activity (BSI 2008); that is, they relate respectively to global warming and its abatement. To our knowledge, this is the first such analysis to include data from the four continents where coffee is a major perennial crop. This information is valuable because both measures (emissions reductions and carbon removal) can inform strategies and actions to reduce the crop's contribution to global warming.

1.2. Carbon footprint and CO_2 removal rate

Researchers of climate-change mitigation in agricultural production have reported both the area carbon footprint (ACF) and the product carbon footprint (PCF). ACF is the mass of greenhouse-gas emissions in CO_2 equivalents (CO_2e) per unit area of cultivation, usually measured in kg CO_2e ha $^{-1}$ year^{-1}. PCF, sometimes termed "yield-scaled emissions", is the mass of greenhouse-gas emissions per unit mass of product, usually expressed as kg CO_2e kg^{-1} of product. To estimate carbon footprints, researchers use field observations and farmers' records of emissions-causing inputs (for example, fertilizer application rates), from which greenhouse-gas emissions are calculated using emissions factors from databases (for example, ecoinvent (2024)).

The CO_2 removal rate (mass of CO_2 ha^{-1} year^{-1}) is usually measured using equations that relate tree diameter to volume, assuming a biomass carbon content of around 50%. Carbon content is then converted to removed CO_2 by multiplying by the stoichiometric ratio of 3.66 (the quotient of molecular mass of CO_2 (44) and the atomic mass of C (12)). The CDR is of particular interest here because agroforestry practices, in which the crop is grown in the shade of other trees, are employed in around half of coffee plantations worldwide (Somarriba and López-Sampson 2018). Because shade trees also remove atmospheric CO_2, average removal rates in coffee agroforestry systems are therefore potentially higher than those of crops grown exclusively in unshaded conditions.

1.3. Approach, scope, and aims

In our analysis we identified the typical ranges of carbon footprint and CDR rate in coffee production, using meta-analysis. We included both principal commercial species: arabica (*Coffea arabica* L.) and robusta (*Coffee canephora* Pierre ex A. Froehner), which account for 60% and 40% of world production, respectively (Bozzola et al. 2021). We focus on primary production—that is, the agricultural phase from planting to harvesting, excluding prior land-use change. In our Section 6, we draw on our results to outline a systematic approach to climate-change mitigation in coffee production, considering both carbon footprint and carbon sequestration from CO_2 removal. Our overall aim is to provide evidence-based guidance for agencies and individuals engaged in supporting farmers in making transitions towards more climate-friendly production.

2. Meta-analysis procedure

2.1. Carbon footprint

2.1.1. Literature search

We searched titles, abstracts, and keywords on the Scopus bibliographic database (search expression: ["carbon footprint" OR "C footprint" OR "life cycle analysis" OR "life cycle assessment" OR "LCA" OR "huella de carbono" OR "empreinte carbone" OR "pegada de carbono" OR emission∗] AND [coffee OR café OR "Coffea arabica" OR "Coffea canephora"]). We screened titles to eliminate irrelevant articles and then excluded those without empirical estimates of the carbon footprint of primary coffee production.

2.1.2. Data extraction

We extracted estimates of the following continuous variables from each article: ACF (kg CO_2e ha^{-1} year^{-1}), PCF (kg CO_2e kg^{-1} green beans), yield (kg green beans ha^{-1} year^{-1}), and fertilizer-N application rates (kg N ha^{-1} year^{-1}). We used 1 kg of green beans as the common functional unit for PCF because green beans are the most traded form of the product (FAOSTAT 2023). Where authors used other functional units (fresh cherries, parchment coffee, ground coffee, or brewed coffee), we converted the values to the common unit (see results tables). Consistent with our system boundary (the agricultural phase from planting to harvesting, excluding prior land-use change), carbon footprints that included emission sources from processing or later value-chain stages were adjusted by subtracting the corresponding CO_2e emissions from the footprint estimate. Where authors did not provide fertilizer-N application rates, we calculated them from fertilizer application rates and formulas, if provided. If application rates of organic fertilizers were provided without specification of N content, we estimated N content based on information from the literature (see supplementary information Table S2).

Where possible, we also classified each estimate as deriving from agroforestry or unshaded production, and from either organic or non-organic production. We classified production as organic if no synthetic inputs were used, regardless of certification status.

Some studies included emissions due to land-use change. For clarity of analysis, we omitted these from our footprint calculations and present them separately in the results section.

2.1.3. Analysis

We constructed a summary dataset consisting of estimates of ACF, PCF, yield, and N-fertilizer application rate. The individual values in the summary dataset were either the means of the cases included in each study or, when cases within a study were from different countries, means by country-within-study.

We calculated the median, interquartile range (IQR), weighted grand mean, and weighted standard deviation of the summary dataset. The weighting factor, chosen to give higher weights to estimates with a broader sampling base, was the natural logarithm of $N + 1$, where N, which varied from 1 to 14 964, is the number of sites (usually farms) on which estimates were based. For completeness, we also calculated the simple arithmetic grand mean and SD.

To characterize the ranges of typical values of carbon footprint, we defined "typical" as encompassing observed case values from the first to the eighth decile. We used this range instead of the middle 80% (first to ninth decile) to avoid unrepresentative upper bounds generated by unusually large values (the distributions of carbon footprint tended to be right-skewed).

We made planned comparisons of ACF, PCF, yield, and fertilizer-N application rate of different production systems using the Wilcoxon rank-sum and signed-rank tests for unpaired and paired data, respectively (paired data were from cases within studies). We used non-parametric tests because of uncertainty about the population distributions. The signed-rank test on paired data has the advantage of greater comparability between the two samples, while the rank-sum test allows larger sample sizes, because studies without paired observations can be included.

To avoid lack of independence, we used one datum per study in the unpaired comparisons, except when cases within the same study were from different countries. We used the mean value of the duplicated state for studies with more than one estimate of relevance. For example, if two of three cases reported in the same study were organic, we used the mean of the two cases as the organic observation of the organic–nonorganic pair.

We expected fertilizer use to be lower in agroforestry production, principally because unshaded production requires higher fertilization rates. We also expected yields to be lower in both agroforestry and organic production than in conventional (sun production, non-organic) production. For these categories (agroforestry or unshaded, organic or non-organic), we therefore used one-tailed tests in the planned comparisons of fertilizer-N application (agroforestry–unshaded) and yield (both comparisons).

We used Microsoft Excel to calculate descriptive statistics, and R (R Core Team 2023) for statistical tests.

2.2. CO_2 removal rates

2.2.1. Literature search

For CDR rate, we used the search expression [“carbon stock∗” OR “carbon sequestration” OR “climate change mitigation” OR “carbon storage” OR “carbon flux” OR “carbon removal” OR “carbon dioxide removal” OR “CO_2 removal”] with the species term used for carbon footprint.

We screened titles to eliminate irrelevant publications and then excluded those that did not include empirical estimates of carbon sequestration in biomass. Because our specific interest was in removal rates rather than carbon stock, we also excluded articles that neither stated the removal rate nor provided a measurement age from which the rate could be calculated from carbon stock.

2.2.2. Data extraction

We collated or calculated from the selected articles estimates of above-ground CDR rate (divided into coffee plants, shade-trees, and other non-crop pools) and CDR in roots. If solely carbon values were given, we converted them to mass of CO_2 using the stoichiometric ratio (44/12). We did not calculate CDR in soil, because we lacked baseline estimates. This would have prevented us from distinguishing positive removal rates from negative removal rates (carbon loss), as found, for example, by Noponen et al. (2013).

A given rate of CO_2 removed from the atmosphere through biosequestration is not necessarily (or probably) equivalent to a negative CO_2e emission rate of the same mass. This is partly because the latter measures the global-warming effect over a specific time horizon (usually, 100 years) of a greenhouse-gas emission (relative, that is, to the same mass of CO_2). In addition, the neutralization potential (CFA and Quantis 2022) of a given mass of CO_2 removed—that is, the degree to which it corresponds to the same mass of CO_2e—depends also on its additionality, relative to a base scenario, and its reversibility (that is, whether and when the CO_2 removed will be released to the atmosphere). The source articles neither address the neutralization potential of removed CO_2 nor provide sufficient information for its estimation. For this reason, the CDR rates that we report below should not be interpreted as being equivalent to negative emissions. Rather, they express the potential for carbon neutralization, depending, in each case, on the degree of permanence, additionality, and nonreversibility (CFA and Quantis 2022).

2.2.3. Analysis

For CDR, we constructed separate datasets for unshaded production and agroforestry production. In doing so, we used mean values for studies that presented more than one agroforestry case (no study presented more than one unshaded case). To characterize ranges of typical values of CDR rate, we defined “typical” as encompassing observed case values from the first to the ninth decile—that is, the middle 80%.

We compared organic and non-organic production using the same approach as for the carbon footprint. Other planned comparisons could not be made because the number of data was insufficient.

3. Carbon footprint of primary production of coffee: findings

3.1. Source publications and representativeness

The search yielded 21 sources (16 on arabica and 5 on robusta), including two major grey literature reports made available to us (Agri-Logic 2020; Enveritas 2023). The sources are listed in Table S1, which comprises the summary dataset. The full data set and a list of papers excluded from consideration following the final screening are also included in the supplementary information (Tables S2 and S3, respectively).

Twelve of the source papers describe production in Latin America (including nine from Colombia or Costa Rica), eight describe production in Asia, and one describes production in Africa. All five robusta studies describe production in Southeast Asia. Agroforestry, unshaded, organic, and non-organic production are represented in the dataset. The 21 studies included 62 cases (Table S2).

The location of studies in the source papers is broadly representative of geographical patterns in coffee production: in 2022, the Americas were responsible for 56% of global coffee production (FAOSTAT 2023), while the region contributed 57% of the source papers.

Organic production was used in 10 of the 47 arabica cases in which we could assign a value to this variable. Globally, only about 7% of coffee plantations are certified organic (FiBL Survey 2023); this bias would likely remain even after

Table 1. Summary statistics for area carbon footprint (ACF), product carbon footprint (PCF), yield, and fertilizer-N application rates (FN), based on the summary dataset.

		Variable			
Species	Statistics	ACF (kg CO_2e ha^{-1} year^{-1}	PCF (kg CO_2e kg^{-1} green beans)	Yield (kg ha^{-1} year^{-1})	FN (kg ha^{-1} year^{-1})
Both	median ± IQR [a]	2954 ± 3616.5	2.18 ± 2.040	1182 ± 714.2	191 ± 121.1
	weighted mean ± SD	3515 ± 2151.1	2.61 ± 1.685	1720 ± 1051.6	300 ± 210.6
	mean ± SD	3479 ± 2199.7	2.70 ± 1.704	1480 ± 939.9	269 ± 201.5
Arabica	median ± IQR [a]	2943 ± 3495.5	2.72 ± 2.185	1106 ± 874	189 ± 94.5
	weighted mean ± SD	3832 ± 2146.7	3.23 ± 1.942	1198 ± 502.1	225 ± 71.9
	mean ± SD	3731 ± 2187.5	3.06 ± 1.763	1188 ± 452.2	226 ± 83.1
Robusta	median ± IQR [a]	3163 ± 3466	1.88 ± 1.235	2820 ± 2210	332 ± 388.8
	Weighted mean ± SD	3093 ± 2116.0	1.85 ± 0.819	2249 ± 1197.0	363 ± 268.1
	mean ± SD	2673 ± 2276.8	1.67 ± 1.057	2242 ± 1461.9	380 ± 391.0

[a] Interquartile range.

accounting for areas in transition to organic production or that are effectively organic but not certified. In robusta, only one of the 13 cases comprised organic production. This proportion is consistent with the overall prevalence of organic production in coffee; we do not know of any data that specifically quantify the proportion of organic production in robusta.

Twenty-one of the 29 arabica cases (73%) in which we could assign a value described agroforestry production; in robusta, the proportion was 46% (6 of 13 cases). Somarriba and López-Sampson (2018) estimated that 48% of coffee was grown under shade. However, they also reported great variation between countries, including low incidence of shade coffee in the two highest-producing countries (5% and 25% in Brazil and Vietnam, respectively) but high proportions of shade coffee in most Latin America countries.

3.2. Overall means and comparison with benchmark values

We present summary statistics in Table 1. We refer principally to the medians; because the estimates of carbon footprint were strongly right-skewed, the medians are more informative as measures of central tendency in the dataset than the means (Sokal and Rohlf 1995). The typical ranges of values of ACF and PCF, as defined in Section 2.1.3, were 1007–5602 CO_2e ha^{-1} year^{-1} and 0.78–4.48 kg CO_2e kg^{-1} green beans, respectively. In all but two cases, fertilizers, particularly nitrogen (N) fertilizers, were the main source of emissions (Table S2); where both production and application were accounted for, fertilizers accounted for a mean of 86% (range 66%–100%) of total emissions.

For benchmarking purposes, we have listed broadly representative carbon footprint values for 11 of the environmentally significant commodity crops described by Clay (2004) (supplementary information, Table S4). The median ACF and PCF of these crops were 3964 CO_2e ha^{-1} year^{-1} and 0.34 kg CO_2e kg^{-1} of product, respectively. The median ACF of coffee reported here (Table 1) is therefore of intermediate value compared to other crops. By contrast, the median product carbon footprint that we report is about eight times greater than the median value of the other crops listed in Table S4.

3.3. Characteristics of cases outside the range of typical values

Cases outside the typical ranges illustrate how atypical carbon footprints may occur. All of the cases with ACF < 1007 kg CO_2e ha^{-1} year^{-1} were organic or agroforestry, or both. A well-documented example is Noponen et al. (2012) (study 1; study and case numbers are included in tables S1 and S2). For example, case 1B4 (ACF = 580 kg CO_2e ha^{-1} year^{-1}) comprises organic agroforestry, in which no fossil fuels were used and in which emissions were derived almost entirely from coffee-pulp organic fertilizer (65%) and pruning residues (33%). There were no emissions from fertilizer manufacture, because no synthetic fertilizers were used.

In contrast, all cases with ACF higher than the upper limit of the typical range (ACF $>$ 5602 kg CO_2e ha^{-1} year^{-1}) were non-organic and either unshaded or shaded only by *Musa* spp. (except for cases 13.1–13.2, to which we could not assign a value to the shade-status variable). For example, case 12.1 (ACF = 6699 kg CO_2e ha^{-1} year^{-1}) (Acosta-Alba et al. 2020) comprised intensive coffee monoculture in Colombia (two harvests per year; coffee plants coppiced to stump every 6–7 years, applications of synthetic fertilizer adding 312.5 kg N ha^{-1} year^{-1}). Manufacture of fertilizer accounted for 63% of emissions from primary production in case 12.1, of which >80% was due to N, while emissions from fertilizer application accounted for 34% of total emissions.

Cases 1B4 and 12.1 illustrate how ACF tends to be high when applications of N fertilizer—the dominant source of emissions—are high, and vice versa. An initial linear regression of ACF on fertilizer-N application was not significant ($F_{\mathrm{df}=[1,8]} = 1.91$, $p = 0.20$). However, after omitting an outlying datum (study 19, in which fertilizer-N application rates were much higher than in other studies), the regression was highly significant ($F_{\mathrm{df}=[1,7]} = 14.25$, $p = 0.007$, $R^2 = 0.67$; supplementary information Fig. S1).

By contrast, the relationships of PCF with agricultural management practices were less clear. All except one of the PCF values <0.78 kg CO_2e kg^{-1} green beans (that is, less than the typical range) represent agroforestry or organic production, but not all of these had low fertilizer-N application rates. For example, in case 19.3 (Trinh et al. 2020) (unshaded organic robusta production in Vietnam), the PCF was 0.64 CO_2e kg^{-1} green beans, while the compost-N application rate was 165 kg N ha^{-1} year^{-1}. The PCF was low because of high yield (3000 kg green beans ha^{-1} year^{-1}). In the same way, PCF values >4.47 CO_2e kg^{-1} (greater than the typical range) were often associated with low yields rather than high emissions per ha. For example, all of the PCF values in the Kenyan smallholder systems described by Ortiz-Gonzalo et al. (2017) (study 6) were greater than the typical range, and the mean yield was the lowest in the summary data set. The ACF values, however, were within the typical range.

3.4. Comparisons of carbon footprints between coffee species and production systems

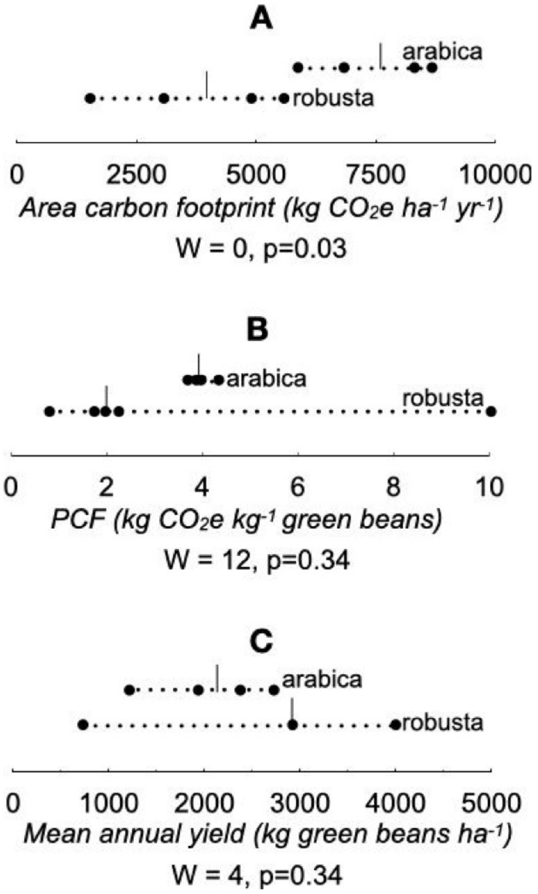
The median ACFs of arabica and robusta were similar to the overall median value (Table 1). The typical range in arabica was 1000–5858 kg CO_2e ha^{-1} year^{-1}, while in robusta it was 1319–3554 kg CO_2e ha^{-1} year^{-1}. The ACFs of the two species did not differ significantly (rank-sum test, $W = 49$, $p = 0.50$). However, when only unshaded production was considered, the ACF of arabica was significantly higher than that of robusta (Fig. 1A).

The median PCF and yield of arabica were respectively higher and lower than those of robusta (Table 1), but the differences were not significant either overall (respective rank-sum tests: $W = 28.5$, $p = 0.12$; $W = 16$, $p = 0.30$) or when only unshaded production was considered (Figs. 1B and 1C). In arabica, the typical range of PCF was 0.86–4.70 kg CO_2e kg^{-1} green beans. In robusta, the typical range was 0.68–2.62 kg CO_2e kg^{-1} green beans.

The median ACF of agroforestry production was less than half that of unshaded production (2301 and 6186 kg CO_2e ha^{-1} year^{-1}, respectively) (Fig. 2A); the difference was significant (Figs. 2A and 2B). Paired comparisons of yield and PCF between agroforestry and unshaded production did not show significant differences (yield: see Fig. 2C; PCF: six pairs, $V = 5$, $p = 0.31$, Fig. 2D (unpaired)). However, in the unpaired comparison of yields, for which more data points were available, the median for agroforestry production was 48% that of unshaded production; the difference was significant (Fig. 2E). Fertilizer-N application rate in unshaded production was significantly higher than in agroforestry production (Fig. 2F).

Eight of the 21 agroforestry cases were also organic, while none of the unshaded cases were. This suggests that the lower ACF and yield could have been caused by organic production rather than agroforestry as such. We therefore compared ACF and yield after excluding the organic cases. This did not change the results appreciably; the ACF of agroforestry production was still significantly lower than that of unshaded production (medians 2848 and 6230; rank sum test, $W = 14$, $p = 0.02$), and the PCF did not differ significantly ($W = 28$, $p = 0.21$). The median yields of non-organic agroforestry and non-organic unshaded production were 1380 and 2244 kg ha^{-1} year^{-1}, respectively, although the distributions did not differ significantly ($W = 17$, $p = 0.14$).

Fig. 1. Comparisons between unshaded arabica and unshaded robusta coffee: (A) area carbon footprint, (B) product carbon footprint (PCF), and (C) yield, with results of Wilcoxon rank-sum tests (test statistic, *W*, and probability, *p*). Solid circles indicate one or more case values or means, dotted lines span ranges of values. Vertical lines indicate medians.



The median area carbon footprint of organic production (1370 CO_2e ha^{-1} year^{-1}) was less than half that of non-organic production (3785 CO_2e ha^{-1} year^{-1}); the difference was significant (Figs. 3A and 3B). In the paired comparison, the PCF of non-organic production was higher than that of organic production in five of six cases; the difference was marginally significant ($p = 0.09$; Fig. 3C). Fertilizer-N application rates did not differ significantly between organic and non-organic production ($p = 0.54$; Fig. 3F).

In the paired comparison of organic versus non-organic production, yields did not differ significantly (four pairs, $V = 8$, $p = 0.375$), but with the unpaired dataset, which was larger, both the PCF and the yield of non-organic production were significantly higher (Figs. 3D and 3E). When we compared the PCF and yield of non-organic agroforestry and organic agroforestry—that is, excluding the unshaded and undefined cases—PCF did not differ significantly ($W = 39$,

Fig. 2. Comparisons between agroforestry and unshaded production of arabica and robusta coffee: (A, B) area carbon footprints, (C, E) yield, (D) product carbon footprint (PCF), and (F) fertilizer-N application rates, with results of Wilcoxon rank-sum (test statistic, *W*, and probability, *p*) and signed-rank tests (test statistic, *V*, and *p*). Solid circles indicate one or more case values or means. Horizontal dotted lines span ranges of values. Solid vertical lines (A, D–F) indicate medians. Angled dotted lines (B, C) link the paired observations used in the signed-rank tests.

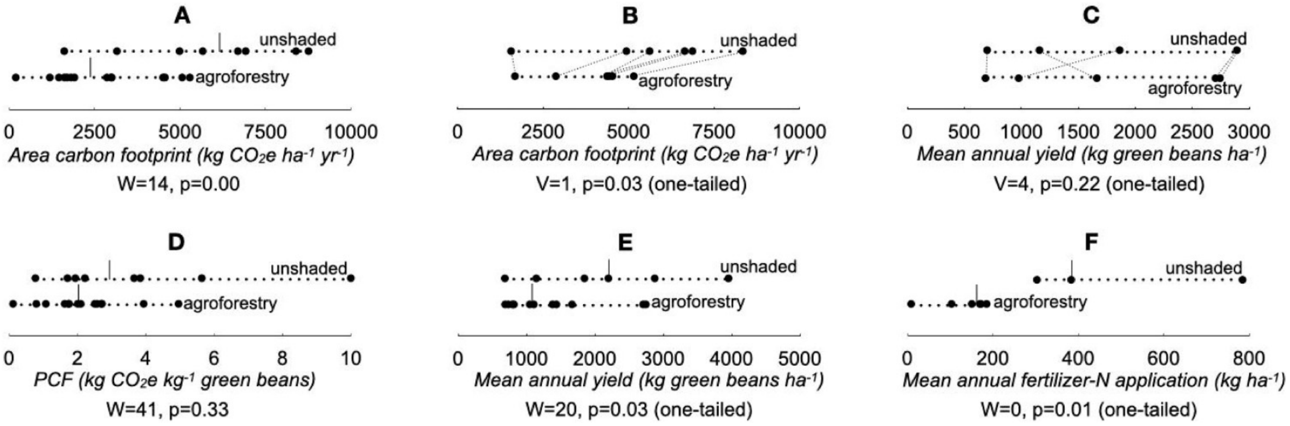
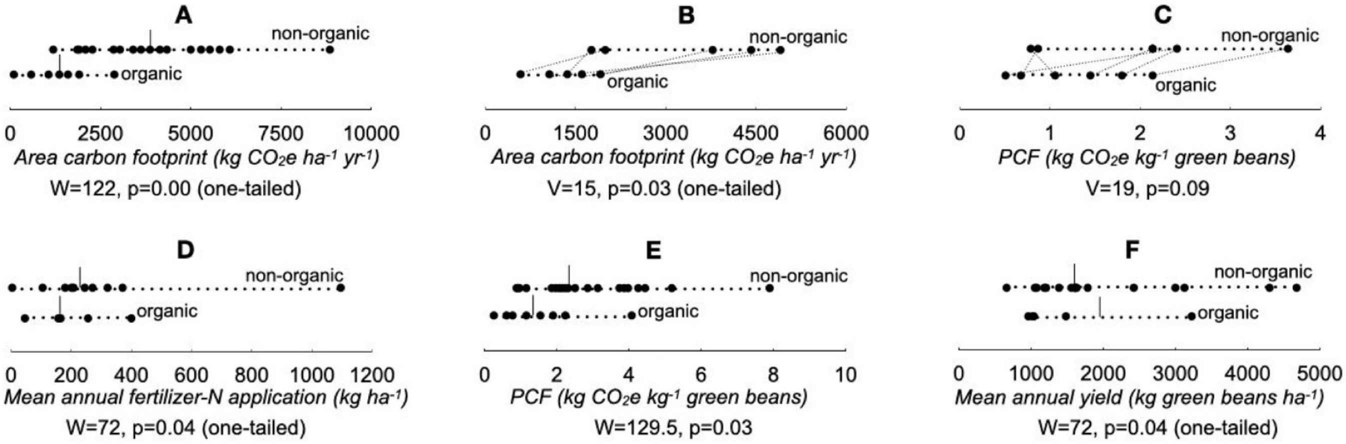


Fig. 3. Comparisons between organic and non-organic arabica and robusta coffee production: (A, B) area carbon footprints, (C, E) product carbon footprint (PCF), (D) fertilizer-N application rates, and (F) yield, with results of Wilcoxon rank-sum (test statistic, *W*, and probability, *p*) and signed-rank tests (test statistic, V, and p). Horizontal dotted lines span ranges of values. Solid circles indicate one or more case values or means. Vertical lines (A, D–F) indicate medians. Angled dotted lines (B, C) link the paired observations used in the signed-rank tests.



$p = 0.83$), but the yield of non-organic agroforestry was higher, with marginal significance ($W = 27$, $p = 0.1$, one-tailed).

3.5. Carbon footprints and land-use change

Land-use change (LUC) was considered in studies 13, 14, and 21. Usva et al. (2020) (study 13) reported that, when emissions due to LUC were included, the PCF estimates in Nicaragua and Honduras were higher by factors of 1.5–2.9, whereas in Brazil the effect was negligible (0.5% increase). In Brazil, the area under cultivation decreased slightly over the study period, while in Honduras and Nicaragua it increased by 4.5% year^{-1} and 2.0% year^{-1}, respectively, partly because of conversion of forest land. Basavalingaiah et al. (2022) (study 14) reported minor increases in ACF (4.6% and 2.8%, respectively, for cases 14.1 and 14.2) when they considered LUC from permanent crop to permanent crop. Enveritas (2023) (study 21) found that inclusion of emissions from LUC increased PCF estimates by 1.1% and 6.7% in Vietnam and Indonesia, respectively.

4. CO$_2$ removal rates in primary production of coffee: findings

4.1. Source publications

The search yielded 16 sources on CDR rates in coffee (15 on arabica and 1 on robusta). All sources are listed in Table 2. The full data set and a list of the papers excluded from consideration following the final screening are listed in the

Table 2. Summary datasets for carbon dioxide removal rate in unshaded and agroforestry production (arabica coffee, except case 21 which is robusta coffee).

Study[a]	Authors; location	Annual CO_2 removal rates (kg ha^{-1})			
		Unshaded		Agroforestry	
		Total	Above-ground	Total	Above-ground
22	Hergoualc'h et al. (2012); Costa Rica, Heredia Province	7954	5476	18 188	14 126
2	Segura and Andrade (2012); Costa Rica, Central Valley and lower elevations	–	–	9880[b]	–
23	Richards and Méndez (2014), El Salvador, Ahuachapán Department	–	–	–	4767[c]
24	Bortolotti da Silva et al. (2013); Brazil, Minas Gerais State	8433	6618	–	–
25	Andrade et al. (2014); Colombia, Tolima Department	–	2310	–	10 890[b]
27	Ehrenbergovará et al. (2016); Peru, Pasco Region	–	–	20 679[b]	–
28	Cerda et al. (2017); Costa Rica, Cartago Province	–	2648	–	5428 [b]
29	Pinoargote et al. (2017); Nicaragua, Jinotega and Matagalpa departments	–	3585	–	13 749
10	Canal Daza and Andrade (2019); Colombia, Tolima Dept.Department	1900	–	18 030	–
31	Zaro et al. (2020); Brazil, Paraná State	6990	6004	16 493	14 399
32	Jurado Riascos et al. (2020); Colombia, Nariño Department	7343	–	9420[b]	–
33	Solis et al. (2020); Peru, San Martín Region	2000	–	17 322[b]	–
34	Goncalvez et al. (2021); Brazil, São Paulo State	–	–	–	8104[b]
35	Notaro et al. (2022); Nicaragua, Matagalpa Department	–	–	–	9736[c]
36	Andrade et al. (2023); Colombia, Tolima Department	–	–	–	12 955[c]
21	Dossa et al. (2008); Togo, Plateaux Region (robusta coffee)	6487	3892	23 128	19 001
	Medians and IQR[d]	6990 ± 3405	3892 ± 2623.5	17 676 ± 3971	11 923 ± 5519.8
	Mean and SD	5872 ± 2752.4	4362 ± 1683.2	16 642 ± 4796.6	11 316 ± 4417.4

Summary datasets for carbon dioxide removal rate in unshaded and agroforestry production (arabica coffee, except case 21)

Note: Arabica coffee, except study 21.

[a] Number assigned for future reference.

[b] Mean of two or more cases.

[c] Shade trees only.

[d] Interquartile range.

supplementary information (tables S5 and S6, respectively). The 16 studies included 46 cases (Table S5). All but one paper describe production in Latin America. Five papers include only agroforestry cases, nine include both unshaded and agroforestry production, and one describes only unshaded production. Four papers consider organic production and four include cases of explicitly non-organic production.

4.2. Mean CO_2 removal rates and planned comparisons

Summary data are presented in Table 2. The median ± IQR total (above- and below-ground) CDR rates were 17 676 ± 3971 and 6990 ± 3405 kg CO_2 ha^{-1} $year^{-1}$ for agroforestry and unshaded production, respectively. The CDR under agroforestry was significantly higher than in unshaded systems (Figs. 4A and 4B). The median ± IQR above-ground CDR rates were 11 923 ± 5520 and 3892 ± 2624 kg CO_2 ha^{-1} for agroforestry and unshaded production, respectively, and differed significantly (Fig. 4C). The typical range of CDR rate in agroforestry production, defined as in Section 2.2.3 and based on all available cases ($n = 17$), was 7865–24 369 kg ha^{-1} $year^{-1}$. The typical range for unshaded production was 1600–8146 kg ha^{-1} $year^{-1}$. In the 11 cases in which authors presented separate total CDR for coffee and shade trees, the latter accounted for a mean of 82.0 ± 0.09% of the CDR rate.

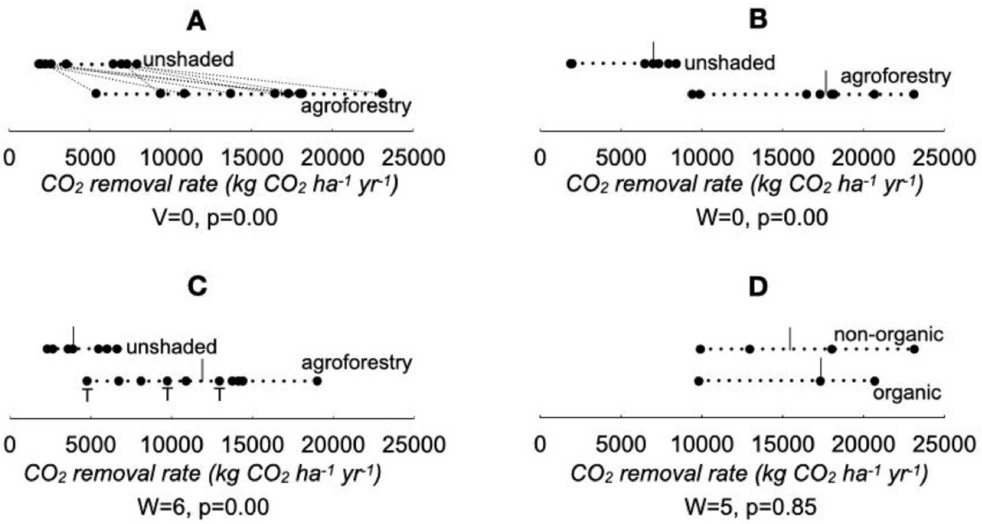
There was no significant difference in CDR rates between organic and non-organic production (Fig. 4D).

5. Synthesis

5.1. Magnitudes of area carbon footprint, product carbon footprint, and CO_2 removal

We have documented median and mean values of area carbon footprint that are of intermediate magnitude compared to benchmark values of other commodity crops. By contrast, median and mean values of product carbon footprint were high in comparison to other crops. However, our results also show that the relatively high PCF values of coffee production are not caused primarily by profligate use of emissions-causing inputs. If this were the case, then ACF of coffee would also be unusually high. Rather, we suggest that the explanation lies in the relatively low harvest index of coffee. That is, the harvested parts (coffee cherries), represent a small biomass in comparison to the total biomass (coffee and, in many cases, shade trees) sustained by the emissions-causing inputs.

Fig. 4. Annual CO_2 removal (CDR) rates in primary production of arabica and robusta coffee, with results of Wilcoxon rank-sum (test statistic, *W*, and probability, *p*) and signed-rank tests (test statistic, *V*, and *p*): (A) agroforestry and unshaded production, paired observations of total (above- and below-ground) or above-ground CDR rates (B) unpaired observations of total CDR rates (above- and below-ground), agroforestry and unshaded production (C) unpaired observations of above-ground CDR rates, agroforestry and unshaded production (D) unpaired observations of total (above- and below-ground) CDR rates in organic and non-organic agroforestry production. Solid circles indicate one or more case values or means. Horizontal dotted lines span ranges of values. Vertical lines (B–D) indicate medians. Angled dotted lines (A) link the paired observations used in the signed-rank test. "T" (C) means "shade trees only"; that is, CDR by coffee plants was not included.



Our results also indicate that primary production of coffee is associated with high levels of removal of atmospheric CO_2. In agroforestry production, particularly, the median mass of CO_2 removed was more than five times greater than the overall mean ACF. However, as outlined above (Section 2.2.2), mass of CO_2 removed through biosequestration is a different metric to mass of CO_2*e*. In the first cycle of production, the additionality of CO_2 removed depends on its magnitude relative to that of the previous land use. Subsequently, presuming that CO_2 removed in the first cycle is released to the atmosphere at the end of the cycle, then subsequent cycles do not contribute further additionality, although they can compensate for the CO_2 released by repeating the CO_2 removal seen in the first cycle. Over a series of cycles summing to 100 years, any CO_2 removal additional to baseline could be interpreted as negative emissions (–CO_2e). This might occur, for example, in the event of a land-use change from unshaded agriculture (including coffee) to coffee agroforestry. In other cases—for example, when forest was the previous land use—there may be no additionality. Despite these uncertainties, the magnitude of the CDR rates reported here is clearly indicative of substantial potential for offsetting emissions.

5.2. Main causes of high emissions

Fertilizer—production, application, or both—was the most common dominant emissions source. Although, in many cases, nitrogenous fertilizers were not singled out in the source papers, they are known to account for most fertilization-related emissions. This is partly because the Haber–Bosch process that is used to produce synthetic N-fertilizers, which produces from 1–10 kg of CO_2e kg^{-1} N manufactured (Walling and Vaneeckhaute 2020), results in emissions that are higher than those for K and P fertilizer manufacture (Hillier et al. 2011). More importantly, the application of N-fertilizers, including organic fertilizers, feeds the nitrification and denitrification soil processes that release N_2O, while K and P fertilizers do not lead directly to soil emissions.

5.3. Differences between production systems and species

We found that both agroforestry and organic production were associated with lower ACFs. Our finding that fertilizer-N application rates have tended to be lower in agroforestry production likely explains the lower carbon footprint of agroforestry. By contrast, fertilizer-N application rates did not differ significantly between organic and non-organic production. It is therefore likely that the lower footprint of organic production is caused by differences in fertilizer-manufacture emissions. Organic-fertilizer manufacture is expected to produce lower emissions than that of synthetic fertilizers, which requires the use of fossil fuels in the Haber–Bosch process (N), in mining (P and K), and in transportation.

We also found that ACF was higher in unshaded arabica agroforestry production than in unshaded robusta production. This finding may also be due to differing nitrogen inputs, possibly motivated or made possible by the higher value of arabica beans. However, the limited data on nitrogen application rate in unshaded robusta production did not allow us to test this hypothesis.

5.4. Representativeness of the source papers

It is likely that the overall mean and median values of carbon footprints that we have presented are underestimates of the true global values, principally because of the over-representation of agroforestry and organic production in the source papers, but also because some studies did not include emissions from fertilizer manufacture. The biases towards organic production and agroforestry may reflect researchers' special interest in their potential for addressing climate-change mitigation and other environmental goals.

Similarly, both agroforestry and organic production were over-represented in the CDR source papers in comparison to their global prevalence. The over-representation of agroforestry does not affect our scope of inference, because we present separate summary statistics for unshaded and agroforestry production. The over-representation of organic production may have resulted in overall underestimation of CDR; although we did not detect any differences in CDR rates between organic and non-organic production, the higher yield of non-organic production should lead to with higher biomass accumulation and therefore higher CDR. Finally, although the Americas are over-represented in the dataset, we consider that the range of production systems included is sufficient to warrant extrapolation of the results to other regions.

6. Implications for the mitigation of the global-warming effects of coffee production

6.1. Need for reducing the global-warming effects of primary production of coffee

Considering the global coffee production area of ≈120 000 km^2 and a mean ACF of the order of 3000 kg $\text{CO}_2\text{e ha}^{-1}\text{ year}^{-1}$, we estimate annual greenhouse-gas emissions from primary production of coffee, excluding land-use change, at around 0.035 Gt CO_2e; that is, greater than the annual emissions of at least 104 countries and territories (European Commission JRC and International Energy Agency 2023).

The magnitude of emissions from coffee justifies the wide interest in mitigating its global-warming effects and suggests the need for a systematic approach to doing so. Our findings, particularly our documentation of the dominance of nitrogen-fertilizer emissions in determining area carbon footprints and the high potential of agroforestry for CO_2 removal, provide a sound basis for such an approach, which we outline below.

6.2. A generalized approach to reducing the global-warming effects of primary production of coffee

6.2.1. Overview

Figure 5 presents the framework of a systematic, generalized approach for reducing the carbon footprint of coffee production. It consists of 10 options for agronomic intervention within three broad categories: improved N management and sourcing, increased coffee productivity, and enhanced biosequestration. These options contribute to both reducing emissions and increasing CO_2 removal, with the objective of achieving carbon neutrality or better (that is, carbon-sink status). Table 3 summarizes the 10 options and their effects. They are more fully described below (Sections 6.2.2–6.2.4).

We present this generalized approach and its components not as a stand-alone proposal but as a complement to broader programs. Because coffee production systems vary widely in age, species composition and management of the plantation, options that seek to reduce global-warming effects must be tailored to local contexts, like other interventions in sustainable coffee (Mithöfer et al. 2017) and agronomic innovations in general (Sinclair and Coe 2019). The feasibility or appropriateness of individual intervention options may also vary with respect to the coffee life-cycle—for example, as part of renovation and rehabilitation (Somarriba et al. 2021), pre-establishment, or during productive life. Other interventions may also be appropriate in some production systems; for example, in irrigated systems, where fossil-fuel emissions may be important. The approach is applicable at the sectoral level (to guide policy and incentives) or at estate, cooperative, farm, or field level (to orient current and future practice in current and new production areas).

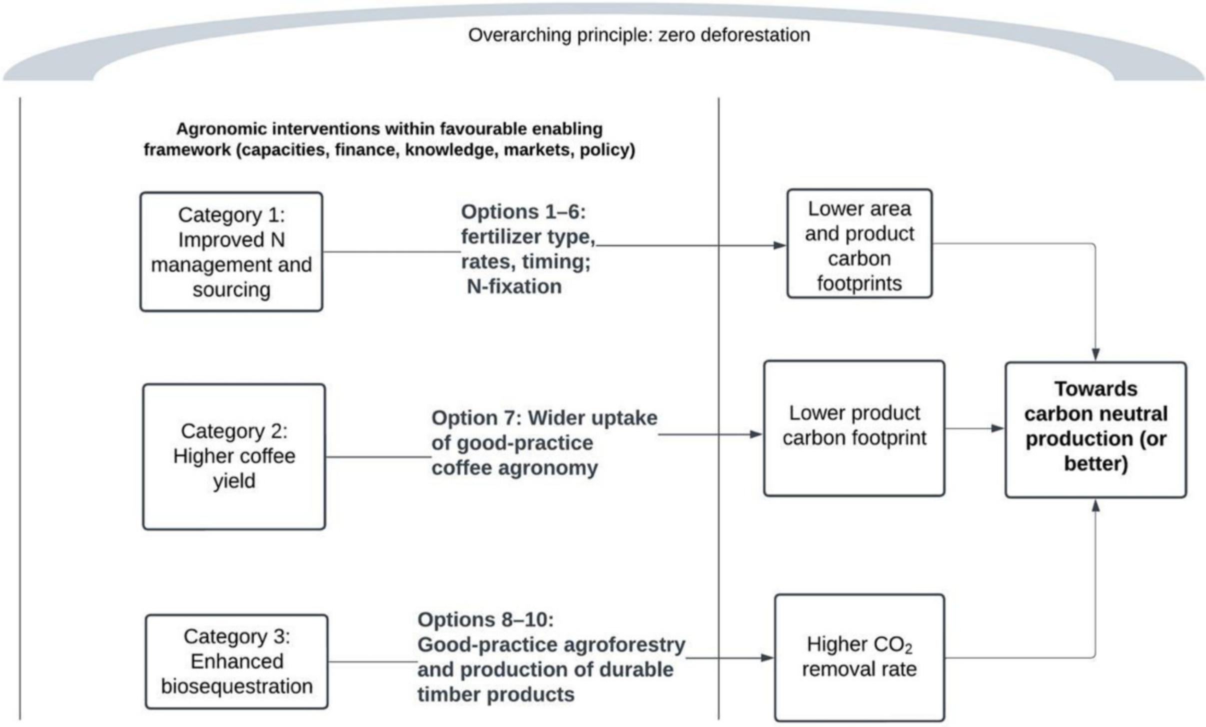
6.2.2. Improved sourcing and management of N (options 1–6)

Improved sourcing and management of N can reduce emissions from both manufacture and application of nitrogenous fertiliser. Here we consider six options that contribute to one or both of these abatement pathways.

Farmers can reduce emissions due to nitrogenous fertilizer production by sourcing a higher proportion of plant N needs from low-emissions sources, including both organic fertilizers (option 1) and N-fixing plants (options 2 and 3). The latter comprise both ground-cover crops and trees (legume species principally, but also *Casuarina* spp.). In the few cases where authors of the source papers separated emissions from fertilizer application from those for fertilizer manufacture, the relative contribution of manufacture varied from around 12%–24% to 50% (Noponen et al. 2012; Usva et al. 2020; Enveritas 2023). This range is indicative of the potential emissions reductions, because many organic N sources have zero or very low manufacturing emissions, while N sourced from biological fixation has no associated manufacturing emissions.

Coffee farmers are known to sometimes apply fertilizer in excess of plant requirements (Cannavo et al. 2013), a practice reported in some of the source papers (Agri-Logic 2020; Ratchawat et al. 2020; Trinh et al. 2020). In such cases, option 4—the reduction of N-fertilizer application rates—should be deployed to abate emissions from both fertilizer manufacture and use. Matching fertilizer quantities to plant needs is the most direct way to reduce application rates—for example, by basing application rates on expected coffee yield,

Fig. 5. A generalized approach to reducing the global-warming effect of primary production of coffee, based on three categories of intervention.



estimated during or immediately after flowering (Jaramillo-Botero et al. 2010; ICAFE 2011).

Options 5 and 6 reduce emissions for a given amount of N applied by addressing the soil processes of nitrification and denitrification that release N_2O. Option 5—synchronization of applications to plant needs—reduces the accumulation of nitrates in excess of plant needs. One way of doing so is to split nitrogen doses over two or more applications, each small enough to be taken up before loss to denitrification or leaching. In many locations, this is standard practice (for example, ICAFE (2011)). The option is not limited to N from synthetic fertilizer; it also applies to inputs from organic fertilizers and N-fixing plants. For example, Rose et al. (2019) found that N_2O emissions in unshaded coffee treatments supplied with N from a cover-crop of pinto peanut (*Arachis pintoi* Krapov. & W.C. Greg.) were half those of treatments supplied with chicken manure. They suggested that build-up of nitrates and associated denitrification were lower under the cover-crop because slash residues were applied regularly throughout the year, while the manure was applied in one large dose associated with a spike in N_2O emissions.

Option 6 comprises use of enhanced-efficiency fertilizers, which include both slow- or controlled-release N fertilizers and stabilized N-fertilizers (Halvorson et al. 2014). The former allow more efficient uptake—a similar effect to option 5 (above). Stabilized fertilizers contain either urease or nitrification inhibitors, which act to reduce N_2O emissions from nitrification and denitrification and to reduce nitrate leaching (Halvorson et al. 2014). For instance, Sarkis et al. (2023) reported that substitution of urea by ammonium nitrate or by urea with the urease inhibitor NBPT reduced N_2O emissions in unshaded coffee by 78.5% and 50.6%, respectively.

The effects of options 1 to 6 are not completely separable. In particular, higher nitrogen-use efficiency, as targeted by options 5–6, should also allow reduced fertilizer-N application rates.

6.2.3. Good-practice coffee agronomic practices for increased coffee yield (option 7)

Because the product carbon footprint is the ratio of emissions to yield, it can be reduced by interventions that increase productivity, providing that the interventions do not cause emissions that outweigh the productivity increase. Intervention option 7 comprises good-practice agronomic options that fulfil this condition. The specific actions that are appropriate in any given location will depend on the factors responsible for yield gaps. These factors are location-specific, but, for example, may include the following: shade management; soil pH; K and P availability; soil-Fe; soil Ca + Mg to K ratio; pathogens; coffee-plant density; pollinator species-richness; and weeding practices (Wang et al. 2015; Bhattarai et al. 2017; Mokondoko et al. 2022). All of these factors can be addressed through specific interventions not associated with high greenhouse-gas emissions. Productivity can also be increased by measures taken before plantation establishment—particularly, the selection of suitable sites and cultivars. We acknowledge that nitrogen is also

Table 3. Summary of intervention options for reducing the global-warming effect of coffee production.

Intervention options	Effects	Notes and caveats
	A. Improved sourcing and management of N	
1. Greater use of organic N-fertilizers	– Reduces or eliminates CO_2 emissions from fertilizer production → lower ACF^a and PCF^b	– Poorly prepared or poorly stored compost may have high methane emissions (San Martin Ruiz et al. 2021) – Nitrification is part of the maturation phase of composting (Cáceres et al. 2018) and will produce N_2O emissions – Assumes that emissions from by-products such as cattle manure are attributable to the primary activity
2. Greater use of (N-fixing) trees	– Reduces CO_2 emissions from fertilizer production→ lower ACF^a and PCF^b – May reduce accumulation of nitrates because of slow decomposition → lower N_2O emissions from denitrification → lower ACF^a and PCF^b – Shade trees (N-fixing or not) may take up nitrates and other nutrients superfluous to crop needs (Babbar and Zak 1995; Tully et al. 2012), reducing leaching and eventual release of N_2O → lower ACF^a and PCF^b	– In poorly designed systems (poor species selection, excessive stocking), shade trees may poach nitrates that would otherwise be taken up by coffee plants – Poor management of shade trees can reduce coffee yield → higher PCF^b – Note that option 2 complements and potentially overlaps with options 8–10
3. Greater use of N-fixing ground-cover plants	– Reduces CO_2 emissions from fertilizer production→ lower ACF^a and PCF^b – May reduce accumulation of nitrates because of slow decomposition → lower N_2O emissions from denitrification → lower ACF^a and PCF^b	– Poorly chosen cover crops may require high labour inputs to prevent smothering of coffee plants
4. Reduction of N-fertilizer quantities	– Reduces or eliminates CO_2 emissions from fertilizer production → lower ACF^a and PCF^b – Reduces N_2O emissions from fertilizer application → lower ACF^a and PCF^b	– Applies to both synthetic and organic fertilizers, although the effect will be greater in the former, due to abatement of emissions from manufacture – In principle, applies also to N from biological fixation, which is subject to the same soil processes as fertilizer-N (Rosenstock et al. 2014)
5. Synchronize N-supply with plant needs	– Higher uptake of N, allowing lower application rates → reduced N_2O emissions from fertilizer application → lower lower ACF^a and PCF^b – Lower accumulation of excess nitrates lower N_2O emissions from denitrification → lower ACF^a and PCF^b	– Applies to all N sources
6. Use of enhanced-efficiency fertilizers	– Reduced N_2O emissions from nitrification → lower ACF^a and PCF^b – Slower release → less accumulation of nitrates→ lower N_2O emissions from denitrification → lower ACF^a and PCF^b	– Enhanced-efficiency fertilizers may be unavailable or inaccessible to resource-poor farmers – Emissions from fertilizer production are not affected
	B. Higher coffee yield	
7. Wider adoption of good-practice coffee agronomy	– Decreased PCF^b due to higher yield	– ACF^a will not decrease unless cropping area contracts – Cropping area may increase due to higher productivity, potentially increasing ACF^a – Applies only to agronomic interventions that are not associated with high emissions (e.g., not N-fertilization), because these would offset the effect on PCF^b of increased yield
	C. Enhancement of biosequestration	
8. Transition to agroforestry production on land currently under unshaded production	– Higher CO_2 removal rates – Lower ACF^a	– Poorly managed agroforestry may reduce productivity – Requires strong technical support to farmers to avoid yield reductions

Table 3. (*concluded*).

Intervention options	Effects	Notes and caveats
9. Wider adoption of good-practice agroforestry	– Higher CO_2 removal rates – Lower ACF[a] and PCF[b]	– Decrease in PCF[b] requires maintenance of yield
10. Wider production of durable products for long-term CO_2 removal	– Higher CO_2 removal rates	– Requires enabling framework for production of high-value products, e.g., credit or subsidies, value-chain strengthening

[a] Area carbon footprint.
[b] Product carbon footprint.

often limiting in agroecosystems (Grahmann et al. 2014), including coffee (Bhattarai et al. 2017), and that increased projected yield itself implies a need for higher N-fertilization (ICAFE 2011). This is one reason why increases in the PCF denominator (due to higher yield) will generally be offset to some degree by increases in the numerator (due to higher emissions).

It is also important to note that when yield increases, even those due to interventions that cause no emissions, lead to lower product carbon footprint, total emissions will not be reduced unless cropping area is also reduced. Further, higher profitability associated with higher yield may incentivize increases in cropping area. Given that demand for coffee is growing (Freitas et al. 2024), higher productivity may simultaneously reduce product carbon footprint while causing higher emissions at sectoral level.

6.2.4. Enhancement of biosequestration (options 8–10)

The median CDR rate under agroforestry that we report above is an order of magnitude greater than the mean and median levels of ACF and three times greater than CDR under unshaded production. Here we suggest three intervention options aimed at harnessing the potential of agroforestry to increase CDR rates. Option 8 (transition to agroforestry production) is directed at areas currently under unshaded production. Options 9 and 10 aim at increasing CDR rates in both current and future agroforestry production.

Option 8 in effect comprises a change of land use from unshaded to agroforestry coffee production. The transition to agroforestry is easiest at or close to the time of plantation establishment. Because of the large difference in CDR rates between shaded and unshaded production, the wider adoption of agroforestry production is a potent means of moving production towards carbon neutrality. However, one important caveat should be considered: if not well executed, the transition to agroforestry may reduce productivity. This is because shade can reduce yield, as shown by both the unpaired analysis presented above and wider experience (Schnabel et al. 2018; Mokondoko et al. 2022). This risk can be eliminated by always implementing option 8 with option 9 (wider adoption of best-practice agroforestry), because careful shade management will avoid the outcome of reduced yield: it is well established that at moderate shade levels (≤30%–40%), yield can be maintained at levels similar to or greater than those of unshaded production (Piato et al. 2020; Haggar et al. 2021; Koutouleas et al. 2022). Nevertheless, farmers without experience in agroforestry management are likely to require technical assistance in making this transition. Specifically, they will need to know what levels of shade will reduce productivity in their locations and what combinations of shade and fertilizer provide the best balance between profitability, their financial and labour resources, and their attitudes to risk.

Shade management by pruning and thinning is an important component of intervention option 9, but the option also extends to other important aspects of agroforestry practice with major effects on CDR rates. These include any actions that aim at securing increased woody biomass accumulation in the tree component, including improved nursery practice, weeding practice, and the choice of appropriate species and seed sources (Guariguata et al. 2008).

Option 10 (durable products for long-term CDR) aims to ensure that some of the carbon that would otherwise be released into the atmosphere at the end of each coffee cycle is instead banked in a longer-term carbon pool; specifically, high-value and durable wood products. Whereas repeated CO_2 removal-and-release over multiple coffee cropping cycles can be effective in maintaining a given mean stock over the 100-year period considered under the GWP_{100} criterion, the CO_2 removed is not cumulative over cropping cycles, precisely because of the release at the end of each cycle. Sequestration of C in long-lived timber products introduces an additional and cumulative component of CO_2 removal to this system.

The potential is considerable. For example, Somarriba (1990) modelled commercial timber yield of *Cordia alliodora* in Costa Rican arabica coffee agroforestry at 6–15 m^3 ha^{-1} $year^{-1}$. Given that wood basic density of *Cordia alliodora* is around 400 kg per m^3 (Greaves and McCarter 1990), this suggests CO_2 removal values of ≈4399–11 000 kg CO_2 ha^{-1} $year^{-1}$. Other tree species suitable for the manufacture of high-value, long-lived timber products can be, and often are, incorporated in coffee fields, including well-known species with easily available planting stock (Harvey et al. 2021). The prospects for production of high-value timber appear particularly strong in robusta, because many widely traded, high-value species are suitable for the lower elevations where it is grown. Even allowing for emissions during harvesting and product manufacturing, low conversion efficiencies in sawmills or late stages, and the difficulty of guaranteeing long-term (≥100 years) product life, the potential for enhancement of CO_2 removal beyond that possible through sequestration in living biomass is clear.

6.3. An overarching consideration: avoidance of deforestation

Our results show that emissions from land-use change, particularly that which involves forest to non-forest land-cover change, can be greater than emissions from coffee management activities. Coffee is almost always produced on land that was once forest, and recent decades have seen continued land-use change from forest to coffee production (Kissinger 2020; Harvey et al. 2021; Chort and Öktem 2024). We are not aware of data on the current extent of coffee-linked deforestation. However, the possibility of climate-induced translocation of coffee production to higher altitudes poses a clear risk of increased emissions (Bozzola et al. 2021; Jawo et al. 2023). The avoidance of further expansion of coffee into forested areas should be seen as a basic overarching consideration in managing the crop's future carbon footprint.

6.4. The importance of enabling frameworks

As we indicate in Fig. 5, the feasibility in specific socio-ecological and production contexts of the 10 interventions depends on the presence of adequate enabling frameworks for them—as, indeed, does the avoidance of deforestation. Where enabling frameworks are deficient in financial, policy, technical, or capacity aspects, additional innovation, and support will be needed. Financial aspects would include the facilitation of access to public and private investment capital or credit, as well as value-chain strengthening for secondary products such as high-value timber. Technical aspects include the supply of planting material of adequate inter- and intraspecific genetic diversity, quality, and quantity. It also includes the generation and synthesis of knowledge through research, including appropriate research into local knowledge. Expansion of coffee agroforestry, as a knowledge–intensive activity, will also require strong technical support networks to assist farmers in the design and implementation of locally adapted practices and systems. Similar approaches are needed to harness the contribution of coffee agroforestry to other international goals such as poverty reduction, climate change adaptation, biodiversity conservation, and landscape restoration, so there is considerable potential for synergies with these other aspects of the international environmental agenda.

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Supplementary material

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