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# Carbon footprint of primary production of cacao: a meta-analytical review

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## Abstract

Cacao production occupies ≈120 000 km$^2$ globally. Cacao beans are the most valuable agricultural export of four African countries and of importance in several other tropical countries. Greenhouse-gas emissions from cacao production are therefore of interest, as is the potential of the crop for mitigation of emissions by carbon sequestration. We present a global review of carbon footprints and $CO_2$ removal rates in primary production of cacao. We aim to characterize typical overall values, identify determinants of footprints and removal rates, compare cropping systems, and suggest ways of reducing carbon footprints and increasing $CO_2$ removal rates. The median ± interquartile range carbon footprints of cacao production, excluding any associated deforestation, were 732 ± 1318.5 kg $CO_2$e ha$^{-1}$ (area carbon footprint, ACF) and 1.55 ± 2.703 kg $CO_2$e kg$^{-1}$ dry beans (product carbon footprint, PCF). The typical ranges of ACF and PCF, defined as those from the first to the eighth decile, were 26–1691 kg $CO_2$e ha$^{-1}$ year$^{-1}$ and 0.05–3.74 kg $CO_2$e kg$^{-1}$ dry beans, respectively. Nitrogenous fertilizers and harvest residues were the most important emissions sources. The ACF of agroforestry production was significantly lower than that of unshaded production, as were yields. The PCF of agroforestry systems did not differ significantly from unshaded systems. The mean ACF and PCFs of organic production were significantly lower than those of nonorganic production. $CO_2$ removal rates were considerably larger than carbon emissions (ACF values), particularly for agroforestry production (median ± interquartile range of 3445 ± 1952 kg $CO_2$ ha$^{-1}$ year$^{-1}$ and 10 237 ± 4178 kg $CO_2$ ha$^{-1}$ year$^{-1}$ for unshaded and agroforestry production, respectively). $CO_2$ removal rates in organic and nonorganic production did not differ significantly. We present a generalized approach for reducing the overall global-warming effect of cacao production, consisting of 12 specific intervention options within an overarching principle of zero deforestation. Improved management of harvest residues, wider use of agroforestry production, and use of organic nitrogen sources are central to enhancing the interventions. Implementation of 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, *Theobroma cacao*, cocoa, greenhouse gas

## 1. Introduction

### 1.1. Background and justification

Crop production caused ≈4% of global greenhouse gas emissions between 2007 and 2016, excluding associated land-use change (Jia et al. 2019). Reducing these emissions requires action not only in the highest emitting sectors (rice and other cereals) but also in the production of the many other crops that, as a group, cover ≈50% of global cropland (FAO 2023). Cacao (*Theobroma cacao* L.) is one such crop. It is the sixth largest-area perennial crop globally, occupying ≈120 000 km$^2$, and is the largest-area perennial crop in Côte d'Ivoire, Ghana, Ecuador, and Cameroon—four of the five main producing countries (FAOSTAT 2023; ICCO 2024). As such, the greenhouse-gas emissions from cacao production are of concern, as recognized by corporate and other actors in the cacao sector (World Cocoa Foundation 2020; Fountain and Huetz-Adams 2023; Mars 2023; Quantis and World Cocoa Foundation 2025). Furthermore, seven countries have prioritized climate-change mitigation actions in cacao in their nationally determined contributions under the Paris Agreement (Climate Watch 2024).

Cacao is a quintessential tropical wet forest crop (Smith et al. 1992). Historically, its production has been associated with extensive deforestation (Ruf and Schroth 2004) within cycles of boom-and-bust that continue to this day (Ruf and Galo 2024). Nevertheless, millions of farmers worldwide are engaged in cacao production under certification schemes that prohibit further deforestation. This includes, for example, 1.21 million farmers with Rainforest Alliance certification, who in 2023 were responsible for 51% of world cacao bean production (Rainforest Alliance 2024).

The present study aims at strengthening the climate-change mitigation effects of cocoa production by providing a detailed analysis of the carbon emissions and removals that stem from the management of cocoa plantations. Specifically, we review published values of the carbon footprint and atmospheric $CO_2$ removal rates (CDR) of cacao production. The carbon footprint and CDR are measures, respectively, of the greenhouse-gas emissions produced and the $CO_2$ removed by an activity (BSI 2008). To our knowledge, this is the first global analysis of these values in cacao. This information is valuable because it informs strategies and actions to reduce the crop's effects on global warming, which we also address.

Our focus is on agronomic practice in existing cacao plantations, with a view to improving future practice. As such, the carbon footprint of ongoing deforestation and the sociopolitical, rather than agronomic, interventions needed to address it are outside the scope of the present article and are not directly relevant to our objectives. Nevertheless, where authors reported carbon footprint from historical deforestation, we have collated the estimates in question.

### 1.2. Carbon footprints and $CO_2$ removal rates

Researchers of climate-change mitigation in agriculture have reported both the area carbon footprint (ACF) and the product carbon footprint (PCF) as measures of the carbon footprint of agricultural production. ACF is the mass of greenhouse-gas emissions in $CO_2$ equivalents ($CO_2$e) per unit area of cultivation, usually measured in kg $CO_2$e 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 $CO_2$e 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 such as ecoinvent (ecoinvent 2024). As in other sectors, emissions of non-$CO_2$ greenhouse gases are expressed as $CO_2$ equivalents ($CO_2$e)—i.e., in terms of the mass of $CO_2$ that would produce the same global-warming effect over the standard time horizon of 100 years (CFA and Quantis 2022). In agriculture, this is noteworthy because its emissions, unlike emissions from other sectors, are dominated by $CH_4$ and $N_2O$ rather than $CO_2$, which overall is the main contributor to global warming (Shukla et al. 2019).

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 $CO_2$ using the ratio of the molecular mass of $CO_2$ to the atomic mass of C (i.e., 44/12). The CDR is of particular interest here because an estimated 31% of cacao is grown in agroforestry systems (Somarriba and López-Sampson 2018)—i.e., in the shade of other trees. Because shade trees also remove atmospheric $CO_2$, average removal rates in cacao are therefore potentially higher than those of crops grown exclusively in unshaded conditions.

A given rate of $CO_2$ removed from the atmosphere through biosequestration is not necessarily (or probably) equivalent to a negative $CO_2$e emission rate of the same mass. This is partly because $CO_2$e measures the global-warming effect, over the 100-year time period, of a greenhouse-gas emission (relative, i.e., to the same mass of $CO_2$). In addition, the neutralization potential (CFA and Quantis 2022) of a given mass of $CO_2$ removed—i.e., the degree to which it corresponds to the same mass of $CO_2$e—depends also on its additionality, relative to a base scenario, and its reversibility (i.e., 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).

### 1.3. Approach, scope, and aims

In our analysis, we identified the typical ranges of carbon footprints and CDR rates in cacao production using meta-analysis. We also compared agroforestry to unshaded production and organic to nonorganic production. We acknowledge that deforestation and subsequent access to nutrient-enriched soils (forest rent) has, in effect, often been an integral part of the primary production of cacao. However, as noted above, here we focus on the agricultural phase from planting to harvesting—i.e., excluding the effects of land-use change. In the final section, we draw on our results to outline a systematic approach to climate-change mitigation in the agricultural phase of cacao 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 and low-emissions production.

## 2. Meta-analysis procedure

### 2.1. Carbon footprint

#### 2.1.1. Search methods and variables

To identify papers with data on the carbon footprint of cacao, we searched titles, abstracts, and keywords on the Scopus bibliographic database (search expression: ["carbon footprint" OR "C footprint" OR "C-footprint" OR "life cycle analysis" OR "life cycle assessment" OR "LCA" OR emission*] AND [cacao OR cocoa OR "Theobroma cacao"]). We screened titles to eliminate irrelevant articles and then excluded those without empirical estimates of the carbon footprint of primary production.

#### 2.1.2. Data extraction

We collated or calculated estimates of the following variables from each article: area carbon footprint (kg $CO_2$e ha$^{-1}$ year$^{-1}$), product carbon footprint (kg $CO_2$e kg$^{-1}$ dry beans), yield (kg dry beans ha$^{-1}$ year$^{-1}$), and fertilizer-N application rates (kg N ha$^{-1}$ year$^{-1}$). Many studies omitted either ACF or yield, and a few omitted PCF. In such cases, we calculated val-

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ues of the omitted variable, using the equation ACF = PCF × Yield.

We chose 1 kg of dry beans as the common functional unit because dry beans are the most traded form of the product. We converted other functional units, such as fresh pods, cocoa powder, and chocolate bars, to the common unit (see results tables). Consistent with our system boundary (the agricultural phase from planting to harvesting, excluding prior land-use change), we adjusted carbon footprints that included emission sources from post-farmgate value-chain stages, such as off-farm processing, by subtracting the corresponding $CO_2$e emissions from the total emissions. If N application rates were not stated, we calculated them from fertilizer formulas and application rates, if provided. If application rates of organic fertilizers were provided without specification of N content, we estimated it using published information (see supplementary information Table S1).

We classified production systems as agroforestry or unshaded, and organic or nonorganic, where possible. We considered production to be organic if no synthetic inputs were used, regardless of certification status. Some studies included emissions caused by land-use change. We omitted these from our calculations but present them separately in the results section.

#### 2.1.3. Analysis

We constructed a summary dataset consisting of estimates of area carbon footprint, product carbon footprint, and yield. The individual values 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 $N + 1$ ($N$ was the number of sites—usually farms—on which estimates were based, varying from 1 to 5945). For completeness, we also calculated the simple arithmetic grand mean and SD.

We defined "typical values" of carbon footprint as those 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 area carbon footprint, product carbon footprint, 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 nonparametric 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, unless cases within studies 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 application rates to be lower in agroforestry production, principally because unshaded production requires higher fertilization. We also expected yields to be lower in both agroforestry and organic production than in conventional (sun production, nonorganic) production. For these categories (agroforestry or unshaded, organic or nonorganic), 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. Search methods and variables

To identify papers with data on $CO_2$ removal rates in cacao, 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 same 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. Studies in which cacao was planted under remnant forest trees were included if the authors reported shade-tree carbon sequestration rates or $CO_2$ removal rates.

#### 2.2.2. Data extraction

We collated or calculated from the selected articles estimates of above-ground $CO_2$ removal rates (divided into crop, shade trees, and other noncrop pools) and CDR in roots. When only carbon values were given, we converted them to mass of $CO_2$ using the stoichiometric ratio (44/12). We did not calculate CDR rates 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).

#### 2.2.3. Analysis

We constructed datasets of means and medians of $CO_2$ removal rates separately for unshaded production and agroforestry production. We calculated mean values for studies that presented more than one agroforestry or unshaded case. To characterize ranges of typical values of CDR rate, we defined "typical" as observed values from the first to the ninth decile—i.e., the middle 80%.

We compared organic and nonorganic 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 cacao: findings

## 3.1. Source publications and representativeness

The search yielded 20 sources with information on the carbon footprints of cacao production. All are listed in Table 1, which comprises the summary dataset. The full dataset and a list of papers excluded from consideration following the final screening are included in the supplementary information (Tables S1 and S2, respectively). Thirteen of the selected papers describe production in Latin America, three in Southeast Asia, and four in West Africa. The production systems represented include agroforestry, unshaded, organic, and nonorganic production, ranging from low-input production under pre-existing forest to unshaded, irrigated plantations. The 20 studies include 51 cases (Table S1).

African countries were responsible for 69% of world cacao bean production in 2022 (FAOSTAT 2023). In this sense, Africa is under-represented in the source articles, with 20% of the articles versus 65% from Latin America. However, in mitigation of this bias, 12 of the 20 studies were from Côte d'Ivoire, Ghana, Ecuador, Brazil, and Indonesia—five of the seven highest-producing countries in 2021–23, accounting for 74% of global production (ICCO 2024). Of the 44 cases to which we could assign a value, 66% (29) describe agroforestry production, indicating that, in comparison to global production patterns, agroforestry production is over-represented in the cases described in the source articles. Similarly, the proportion of cases that describe organic production (22%) is much larger than the global proportion of organic production, which in 2020 was estimated at 4.0% (FiBL Survey 2023).

## 3.2. Summary statistics and comparison with benchmark values

We present medians and other summary statistics in Table 1. The medians are more informative than the means as measures of central tendency in the dataset because the estimates of carbon footprint were strongly right-skewed (Sokal and Rohlf 1995). The typical ranges of values of ACF and PCF were 26–1691 kg $CO_2$e $ha^{-1}$ $year^{-1}$ and 0.05–3.74 kg $CO_2$e $kg^{-1}$ dry beans, respectively.

Authors presented emissions data disaggregated by emission source in 38 of the 51 cases. Fertilizers (application or both application and production) were the dominant emission source in 15 cases, whereas the decomposition of cacao husks was the dominant emissions source in 14 cases. In the remaining 8 cases, fuel for farm machinery (3 cases) or tools and machinery (manufacture or operation, or both) (5 cases) were the dominant emissions sources (Table S1).

Higher fertilizer-N application was associated with higher area carbon footprints (linear regression: $F_{df=1,11} = 9.04$, $R^2 = 0.45$, one-tailed $p = 0.01$, Fig. S1), but no significant relationship between product carbon footprint and N-application was found (linear regression, $F_{df=1,20} = 0.56$, $p = 0.46$).

For benchmarking purposes, we have listed broadly representative carbon footprint values for 12 of the environmentally significant commodity crops described by Clay (2004) (supplementary information, Table S3). The median area carbon footprint and product carbon footprint of these crops were 3927 kg $CO_2$e $ha^{-1}$ $year^{-1}$ and 0.36 kg $CO_2$e $kg^{-1}$ of product, respectively. These values indicate that the area carbon footprint of the agricultural phase in cacao, excluding land-use change, has in general been low in comparison with benchmark values, whereas the product carbon footprint has been relatively high.

## 3.3. Characteristics of cases outside the range of typical values

In four cases of agroforestry production (study 2, nonorganic agroforestry in Colombia; study 13, nonorganic and organic agroforestry in Brazil), the area carbon footprint and product carbon footprint were much greater than the upper bounds of the typical ranges (i.e., $\gg$1691 kg $CO_2$e $ha^{-1}$ $year^{-1}$ and $\gg$3.74 kg $CO_2$e $kg^{-1}$, respectively) (Table S2). In each case, the high values were caused largely or almost totally (78%–99%) by $CH_4$ emissions from the decomposition of cacao pod husks left on site.

The area carbon footprints in cases 8.3, 12, 18.2, 19.5, and 19.10 were also higher than the typical range. Cases 8.3, 18.2, and 19.10 describe relatively high-intensity production, while, in cases 12 and 19.5, pod husks were the main emissions source. Case 18.2 also had product carbon footprint above the typical range, as did case 10.1, which describes a juvenile plantation with low productivity, and cases 19.7, 19.12, 19.13, and 19.14, in which case either cacao husks or high N application, combined with low yield, were responsible.

Four cases, all examples of organic agroforestry, had carbon footprint values below the typical range of both PCF and ACF (cases 7, 11.1, 16, and 19.11). Yield was low in three of these cases (11.1, 16, and 19.11; 360, 434, and 100 kg $ha^{-1}$ $year^{-1}$, respectively).

## 3.4. Comparisons of carbon footprints between production systems

The agroforestry practices described in the source articles vary considerably both within and between studies. They vary from traditional cacao agroforest (for example, Schroth et al. (2016) (study 4)) to simple mixtures with one or two shade species (for example, Utomo et al. (2016) (study 5)) (Table S2 includes descriptions). The median area carbon footprint of agroforestry production was 24.5% that of unshaded production ($W = 51.5$, $p$-value $= 0.05$, Fig. 1A), while the median product carbon footprint of agroforestry production was 31.3% that of unshaded production ($W = 60$, $p$-value $= 0.09$, Fig. 1B) (studies 2 and 13 were not considered in this comparison, because the very high carbon footprints reported are due to residue-management practices that are not specific to agroforestry (see Section 3.3).

The median cacao yield under agroforestry was 48% that of unshaded production; the distributions differed signifi-

**Table 1.** The summary carbon footprint dataset, with study descriptions, estimates of area carbon footprint (ACF), product carbon footprint (PCF), yield, and fertilizer-N application rates (FN), and summary statistics for ACF, PCF, yield, and FN.

| No.[a] | Authors | Location[b] and (number of observations)[c] | Production systems | ACF kg $CO_2$e ha$^{-1}$ year$^{-1}$ | PCF kg $CO_2$e kg$^{-1}$ dry beans | Yield kg dry beans ha$^{-1}$ year$^{-1}$ | FN kg N ha$^{-1}$ year$^{-1}$ |
|---|---|---|---|---|---|---|---|
| 1 | Ntiamoah and Afrane (2008) | Ghana; nationwide (–) | Nonorganic | – | 0.05 | – | – |
| 2 | Ortiz-Rodríguez et al. (2016) | Colombia; Antioquía, Arauca, North of Santander, and Santander departments (60) | Nonorganic “conventional production” (2.1), agroforestry[d] (2.2) | 7877 | 8.45 | 909 | 45 |
| 3 | Pérez Neira (2016) | Ecuador; nationwide (6) | Unshaded “traditional” and “technified” production | 865 | 0.98 | 850 | 24 |
| 4 | Schroth et al. (2016) | Brazil; southern Bahia state (26) | Cabruca[e] agroforestry, nonorganic | 99 | 0.36 | 275 | – |
| 5 | Utomo et al. (2016) | Indonesia; East Java Province (5) | Nonorganic agroforestry | – | 0.39 | – | – |
| 6 | Raschio et al. (2018) | Peru; San Martín Region (1892) | Unshaded, nonorganic production | 732 | 1.15 | 1111 | 118 |
| 7 | Recanati et al. (2018) | Peru (–) | Organic agroforestry | 0 | 0 | – | 0 |
| 8 | Ivanova et al. (2020) | Peru; Ucayali Region (–) | Organic and nonorganic, mostly unshaded | 1418 | 1.12 | 1000 | 75 |
| 9 | Pérez-Neira et al. (2020) | Ecuador; Guayas Province (30) | Organic and nonorganic, agroforestry and unshaded | 682 | 0.72 | 829 | 19 |
| 10 | Armengot et al. (2021) | Bolivia; La Paz Department (1) | Organic and nonorganic, agroforestry and unshaded | 428 | 2.35 | 171 | – |
| 11 | Caicedo-Vargas et al. (2022) | Ecuador; Napo, Orellana, and Sucumbios provinces (90) | Organic and nonorganic agroforestry | 69 | 0.11 | 405 | – |
| 12 | Epquin Rojas (2022) | Peru, Amazonas Region (5) | Nonorganic agroforestry | 1731 | 2.89 | 600 | – |
| 13 | Hernandes et al. (2022) | Brazil, Pará State (9) | Nonorganic (13.1) and organic agroforestry (13.2) | 8492 | 10.17 | 835 | – |
| 14 | Parra-Paitan and Verburg (2022) | Ghana, High Forest Zone (–) | Nonorganic agroforestry and unshaded production | 26 | 0.06 | 472 | 0 |
| 15 | Romero et al. (2022) | Peru, Ucayali Region (–) | Organic, unshaded production | 427 | 0.45 | 1164 | 33 |
| 16 | Vervuurt et al. (2022) | Côte d’Ivoire, Divo Department (372) | Organic agroforestry production | 0.434 | 0.001 | 434 | 0 |
| 17 | Avadi (2023) | Ecuador, nationwide (5945) | Unshaded, organic and nonorganic production | 982 | 2.81 | 341 | 13 |
| 18 | Miharza et al. (2023) | Indonesia, West Sulawesi Province (20) | Nonorganic agroforestry | 1423 | 3.33 | 456 | 33 |
| 19 | Hawkins et al. (2024) | Ghana, Eastern Region (106) | Unshaded and agroforestry production | 1145 | 3.44 | 414 | 0–618 |
| 20 | Khang et al. (2024) | Vietnam, Central Highlands (48) | Unshaded production | – | 4.24 | – | – |
| | | Summary statistics | | | | | |
| | Median ± IQR[f] | | | 732 ± 1318.5 | 1.55 ± 2.703 | 536 ± 453.6 | 30 ± 34.2 |
| | Weighted mean ± SD | | | 1374.4 ± 2286.45 | 2.05 ± 2.565 | 641.0 ± 295.12 | 4.67 ± 18.195 |
| | Mean ± SD | | | 1553 ± 2557.0 | 2.16 ± 2.809 | 635 ± 303.3 | 30 ± 34.2 |

**Note:** Table S1 includes additional notes on the derivation of estimates.
[a]Number assigned for future reference.
[b]Country and first-tier geopolitical subdivision.
[c]Number of farms or distinct sites sampled. We counted an experiment as one observation.
[d]The authors distinguished “conventional management” (2.1) from “agroforestry management (2.2)”. However, both included 150 (unspecified) units ha$^{-1}$ of permanent shade.
[e]A type of cacao agroforestry used in Brazil, in which cacao is cultivated under native forest trees.
[f]Interquartile range.

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**Fig. 1.** Comparisons between agroforestry production and unshaded production of cacao, with results of Wilcoxon rank-sum tests: (A) area carbon footprint, (B) product carbon footprint, (C) yield, (D) annual N-fertilization. Solid circles indicate one or more case values or means, dotted lines span ranges of values. Vertical lines indicate medians.

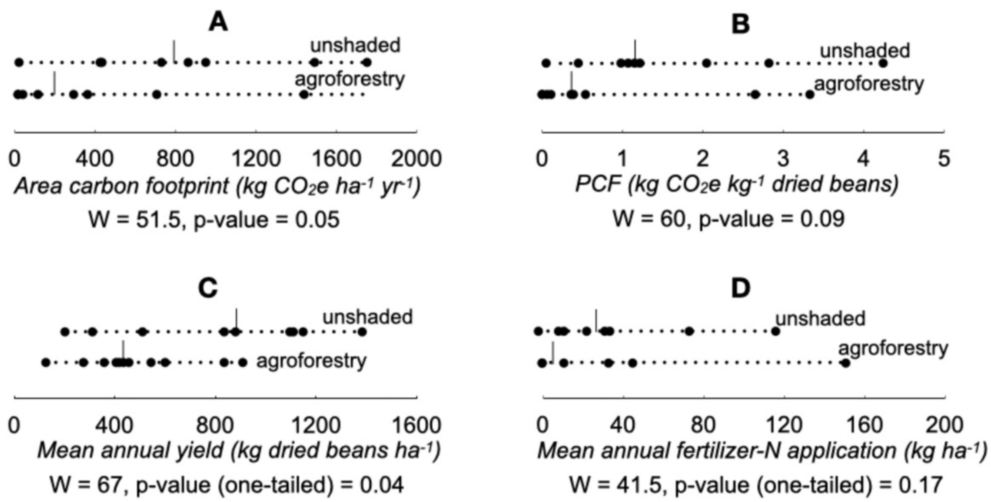
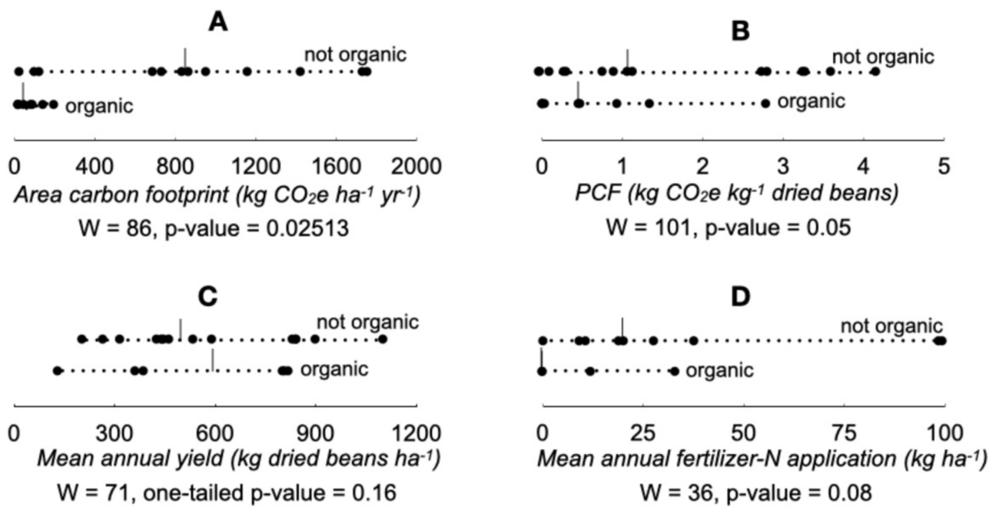



**Fig. 2.** Comparisons between organic and nonorganic cacao production: (A) area carbon footprints, (B) product carbon footprint, (C) yield, (D) annual fertilizer-N application, with results of Wilcoxon rank-sum tests. Solid circles indicate one or more case values or means. Horizontal dotted lines span range of values. Vertical lines indicate medians.




cantly at ($W = 67$, $p$-value $= 0.04$) (Fig. 1C). The median fertilizer rate in unshaded production systems (28.5 kg ha$^{-1}$ year$^{-1}$) did not differ significantly from the application rate in agroforestry (5.4 kg ha$^{-1}$ year$^{-1}$) (Fig. 1D) ($W = 41.5$, $p$-value $= 0.17$).

Insufficient data were available for paired comparisons of PCF, yield, and nitrogen application rates. In ACF ($n = 4$ pairs), the median of unshaded production was more than three times that of agroforestry production, but the difference was not significant ($V = 6$, $p$-value $= 0.1814$).

The median ACF and PCF of organic production were respectively 18.5% and 37.0% those of organic production; the differences were significant in both unpaired (Figs. 2A and 2B) and paired comparisons (ACF: $V = 10$, $p = 0.09$, 6 pairs. PCF: $V = 21$, $p = 0.03$, 6 pairs). The median yield of organic production was 80.6% that of nonorganic, but yield did not differ significantly in either unpaired (Fig. 2C) or paired comparisons ($V = 14$, $p = 0.56$, six pairs). The median N application rates were 0 and 24 kg ha$^{-1}$ year$^{-1}$, in organic and nonorganic production, respectively, a difference significant at $p = 0.04$ (unpaired comparison, Fig. 2D); insufficient pairs were available for the paired comparison.

## 3.5. Carbon footprints and land-use change

The effect of land-use change on carbon footprint was considered in eight cases; in six of these, the change involved deforestation to establish new cocoa production areas (Table 2). The median area carbon footprints with and without land-use change were 12 257 and 250 kg $CO_2$e ha$^{-1}$, respectively, while the median product carbon footprints were 15.55 and 0.31 kg $CO_2$e kg$^{-1}$ dry beans.

**Table 2.** Carbon footprint of cacao production with and without inclusion of emissions due to land-use change (LUC).

| Case | Case description | Area carbon footprint (kg $CO^2e$ $ha^{-1}$ $year^{-1}$) | | Product carbon footprint (kg $CO_2e$ $kg^{-1}$ dry beans) | |
|---|---|---|---|---|---|
| | | Excluding LUC | Including LUC | Excluding LUC | Including LUC |
| 6.1 | Smallholder cocoa/banana production in San Martin, Peru | 732 | 1241 | 1.15 | 2.1 |
| 8.1 | Traditional nonorganic smallholder production, Peruvian Amazon | 119 | 17 290 | 0.17 | 24.7 |
| 8.2 | Organic smallholder production, Peruvian Amazon | 1494 | 17 680 | 0.93 | 22.1 |
| 8.3 | "Technified", nonorganic smallholder production, Peruvian Amazon | 381 | 20 550 | 2.30 | 13.7 |
| 14.1 | Cacao agroforestry, Ghana | 24 | 7214 | 0.06 | 17.2 |
| 14.2 | Full-sun cacao, Ghana | 24 | 7219 | 0.05 | 13.7 |
| 15.1 | Smallholder organic monoculture production, Peruvian Amazon | 427 | 22 925 | 0.45 | 24.4 |
| 16.1 | Low-intensity agroforestry in Côte d'Ivoire | 0.434 | 1302 | 0.001 | 3.0 |
| | Medians | 250 | 12 255 | 0.31 | 15.45 |
| | Interquartile range | 503 | 12 661 | 0.93 | 11.65 |

**Note:** Land-use change was from forest to cacao, except possibly for cases 14.1 and 14.2; in these cases, the previous land use was not stated but, based on the magnitude of the LUC carbon footprint, can be assumed to have entailed deforestation.

# 4. $CO_2$ removal rates in primary production cacao: findings

## 4.1. Source publications

The search yielded 14 sources on CDR rates in cacao (Table 3). The full dataset and a list of the papers excluded from consideration following the final screening are listed in the supplementary information (Tables S4 and S5, respectively). The 13 papers include 29 cases (Table S4). Six describe production in Africa, six describe production in Latin America, and one from Indonesia. Twenty cases describe agroforestry production. Seven cases describe unshaded production. Six cases and eight cases describe organic and nonorganic production, respectively.

Africa was under-represented in the source articles, with 46% of the articles, but less so than in the case of the carbon footprint articles. Seven of the 14 studies were from one of the top five producing countries in 2021–2023. Both agroforestry production (21 of 29 cases) and organic production (7 of the 26 cases to which we could assign a value) were overrepresented in comparison to their global prevalence.

## 4.2. Summary statistics and planned comparisons

The median ± IQR total removal rates in unshaded and agroforestry production were 3445 ± 1952 and 10 237 ± 4178 kg $CO_2$ $ha^{-1}$ $year^{-1}$, respectively (Table 3). The removal rates in unshaded and agroforestry production differed significantly (total: Fig. 3A; above-ground: Fig. 3B). The typical range of total CDR in agroforestry production was 4863–13 906 kg $ha^{-1}$ $year^{-1}$, while the typical range in unshaded production was 590–6713 kg $ha^{-1}$ $year^{-1}$.

$CO_2$ removal rates in organic and nonorganic agroforestry production did not differ significantly (Fig. 3C). The number of observations was insufficient to compare organic and nonorganic unshaded production.

Kim et al. (2016) (for eight types of agroforestry practice: home gardens, intercropping, live fences, parklands, riparian buffers, perennial-crop systems, shelterbelts, and silvopasture) and Bernal et al. (2018) (for forest landscape restoration using agroforestry) provide useful benchmark values. The former reported average biomass carbon sequestration rate of 5.0 Mg $ha^{-1}$ $year^{-1}$ (i.e., 18 333 kg $CO_2$ $ha^{-1}$ $year^{-1}$). The latter reported above-ground CDR in the first 20 years of agroforestry-based forest landscape restoration in the range of 10 800–15 600 kg $CO_2$ $ha^{-1}$ $year^{-1}$. The typical ranges of values that we report for agroforestry are consistent with these benchmark values.

# 5. Synthesis

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

We have shown that median and mean values of area carbon footprint of cacao production have typically been low compared to agricultural benchmark values, while median and mean values of product carbon footprint have typically been higher than benchmark values. Consistent with the system boundary—i.e., the agricultural phase from planting to harvesting—these findings do not consider emissions due to land-use change. The contrasting results for area carbon footprint and product carbon footprint show that the high PCF values were not caused by unusually high emissions-causing inputs. If this were the case, then both ACF and PCF would be high. Rather, we suggest that the high PCF is explained by the relatively low harvest index of cacao; the biomass of cacao beans is much smaller than the total biomass (cacao trees and, in many cases, shade trees) sustained by the emissions-causing inputs.

**Table 3.** Summary datasets for carbon dioxide removal rate in unshaded production and agroforestry production with pre-existing and contemporary shade trees.

| Study[a] | Authors; location | Annual $CO_2$ removal rates ($CO_2$ $ha^{-1}$ $year^{-1}$) | | | |
|---|---|---|---|---|---|
| | | Unshaded | | Agroforestry | |
| | | Total | Above-ground | Total | Above-ground |
| 19 | Hawkins et al. (2024); Ghana, Eastern Region | 3260[b,c] | – | 5417 | – |
| 21 | 1 Somarriba et al.; Nicaragua | – | – | 8074 | 6051 |
| | 2 Somarriba et al. (2013); Honduras | – | – | 11 215 | 8067 |
| | 3 Somarriba et al. (2013); Guatemala, Alta Verapaz | – | – | 10 777 | 7982 |
| | 4 Somarriba et al. (2013); Costa Rica | – | – | 10 705 | 7760 |
| | 5 Somarriba et al. (2013); Panama | – | – | 10 237 | 7729 |
| | 6 Somarriba et al. (2013); Guatemala, south coast | – | – | 10 821 | 8631 |
| 22 | Saj et al. (2013); Cameroon, Centre Region; | – | – | 4494[c] | – |
| 23 | Jacobi et al. (2014); Bolivia, Alto Beni Municipality[c] | 12 044 | 8974 | 21 183[c] | 16 018[c] |
| 24 | Jadán et al. (2015); Ecuador, Napo Province | 843 | 697 | 9442 | 7438 |
| 25 | Mohammed et al. (2016); Ghana, E. Region and W. Region | – | 3851 | – | – |
| 26 | Abou Rajab et al. (2016); Indonesia, Central Sulawesi | 2026 | 1486 | 8096[c] | 6559[c] |
| 27 | N'Gbala et al. (2017); Côte d'Ivoire, Centre-West Region | 3857 | 3279 | – | – |
| 28 | Schneidewind et al. (2019); Bolivia, Alto Beni Municipality[b] | 4429[c] | 3970[c] | 15 526[c] | 13 761[c] |
| 29 | Nadège et al. (2019); Cameroon, Centre Region | – | – | 11 476 | 9166 |
| 30 | Nijmeijer et al. (2019); Cameroon, Centre Region | – | – | 5606 | |
| 16 | Vervuurt et al. (2022); Côte d'Ivoire, Divo Dept. | – | – | 3833 | – |
| 31 | Mena-Mosquera and Andrade (2021); Colombia, Chocó Dept. | – | – | – | 4858 |
| 32 | Goñas et al. (2022); Peru, Amazonas Region | – | – | – | 3339 |
| | Medians | 3558 | 3566 | 10 237 | 7760 |
| | Interquartile range | 1952.5 | 2365 | 4178 | 2326 |
| | Mean | 4409 | 3710 | 7793 | 8258 |
| | Standard deviation | 3957.6 | 2898.5 | 4446.1 | 3370.1 |

[a]Number assigned for future reference.
[b]Based on cases 19.4 and 19.5.
[c]La Paz Department.
[d]Mean of two or more cases.

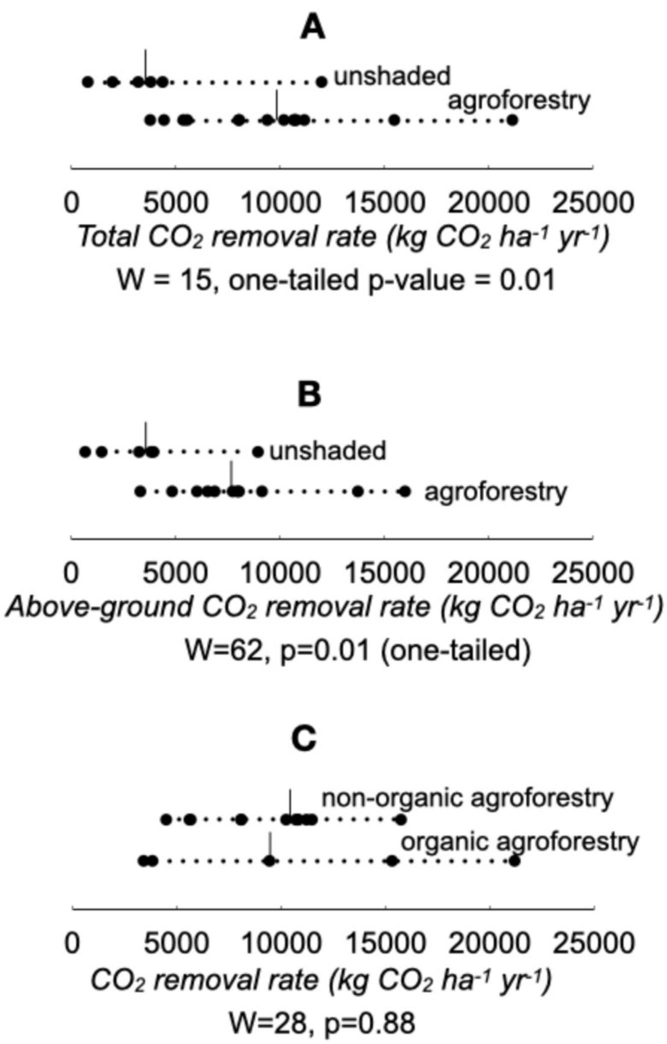
Our results also indicate that primary production of cacao has been associated with high rates of removal of atmospheric $CO_2$. In agroforestry production, the median annual mass of $CO_2$ removed was 14 times greater than the overall median area carbon footprint. However, as outlined above (Section 1.3), the 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 at the end of the previous cycle by repeating the $CO_2$ removal seen in the first cycle. Over a series of cycles summing to 100 years, any $CO_2$ additional to baseline could be interpreted as negative emissions (–$CO_2$e). This might occur, for example, in the event of a land-use change from unshaded agriculture (including cacao) to cacao 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

The production and application of fertilizers was most commonly the 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 $CO_2$e $kg^{-1}$ of manufactured N (Walling and Vaneeckhaute 2020), results in emissions factors 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 greenhouse gas emissions from soil.

In several studies, methane emissions from anaerobic decomposition of discarded husks were also an important source of emissions. This is consistent with recent guidance. In three of four cases in studies 2 and 13, the area carbon footprint values were >8000 kg $CO_2$e $ha^{-1}$ $year^{-1}$, i.e., five to seven times greater than the upper bound of the typical range. In part, this results from the high ratio (≈10:1) of the mass of fresh cacao husks to dry beans (Hougni et

**Fig. 3.** Annual carbon dioxide removal (CDR) rates in primary production of cacao, with results of rank-sum tests: (A) agroforestry and unshaded production total (above- and below-ground) CDR rates, (B) agroforestry and unshaded production, above-ground CDR rates, and (C) total CDR rates in organic and nonorganic agroforestry production. Solid circles indicate one or more case values or means. Horizontal dotted lines span range of values. Vertical lines indicate medians.




al. 2021); even a moderate yield of 400 kg ha$^{-1}$ dry beans generates around 4000 kg ha$^{-1}$ year$^{-1}$ of discarded husks. Neither Ortiz-Rodríguez et al. (2016) (study 2) nor Hernandes et al. (2022) (study 13) specified how residues were treated. However, the methane correction factors of 0.4–0.5 used in their emissions calculations correspond to those for shallow-buried or heaped residues (Pipatti et al. 2006). Piling of husks is widespread—for example, in Africa (Hougni et al. 2021), Brazil (Miccolis, personal communication, 1 April 2024[1]), and Peru (Epquin Rojas 2022). Extension materials often ignore husk disposal (Compañía Nacional de Chocolate (Colombia) 2013; Sobrinho Maranho et al. 2017; FHIA Honduras 2018; Soto et al. 2022) or even recommend piling on site (Brazil. Ministério de Agricultura, Pecuária e Abastecimento 2020). We therefore consider it likely that husk-piling is common enough for methane emissions from harvest residues to be a significant emissions source in primary production of cacao.

[1] Andrew Miccolis, Brazil Director, CIFOR-ICRAF.

### 5.3. Differences between production systems

We found that agroforestry had lower area carbon footprints than unshaded production, and that organic production had a lower area carbon footprint than nonorganic production.

Two factors explain the lower carbon footprint of organic production. First, manufacture of organic fertilizer is expected to produce lower emissions than that of synthetic fertilizers, which are dependent on the use of fossil fuels in the Haber-Bosch process (N), in mining (P and K), and in transportation. Second, our findings suggest that organic production has tended to have lower fertilizer-N application rates, although this is not inherently a characteristic of organic production.

Fertilizer-N application rates were also lower in agroforestry than in unshaded production, although not significantly so. However, other factors may also have contributed to the lower area carbon footprints observed in agroforestry production—for example, an overall lower intensity of production, including lower consumption of fossil fuels by weeding and irrigation machinery.

### 5.4. Representativeness of the source papers

It is possible that the overall median and mean values of carbon footprints that we have presented are underestimates of the true global values, mainly 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 and transport.

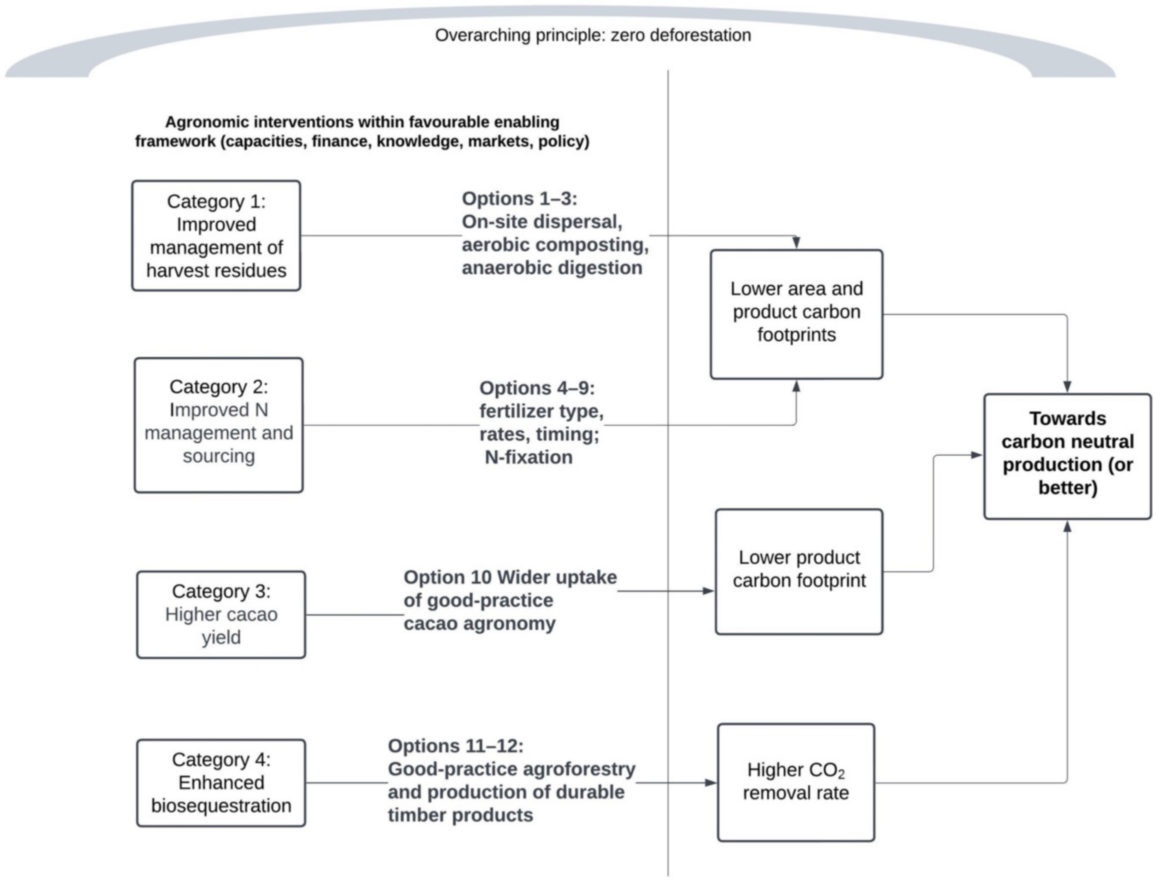
In $CO_2$ removal, the over-representation of organic production in the source articles is unlikely to affect our findings, as we did not detect any differences in removal rates between organic and nonorganic production. The over-representation of agroforestry has no effect on our analysis because we present separate summary statistics for unshaded and agroforestry production.

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

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

Based on its global cropping area of ≈120 000 km$^2$ and mean area carbon footprint of ≈1400 kg $CO_2$e ha$^{-1}$ year$^{-1}$, we estimate annual greenhouse-gas emissions from primary production of cacao, without including emissions from land-use change, to be ≈0.017Gt—greater than the annual individual emissions of at least 81 countries (European Commission JRC and International Energy Agency 2023). This scale of emissions justifies the wide interest in reducing the emissions from cacao production and suggests the need for a sys-

**Fig. 4.** Generalized approach to reducing the global-warming effect of primary production of cacao.




tematic approach to climate mitigation in the sector. Our findings, particularly our documentation of the importance of emissions from harvest residues and 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 cacao

### 6.2.1. Overview

Figure 4 shows the overall framework of the approach. It consists of 12 options for agronomic intervention within four broad categories: improved management of harvest residues, improved N management and sourcing, increased cacao productivity, and enhanced biosequestration. These options, which are summarized in Table 4, contribute to both reducing emissions and increasing $CO_2$ removal, with the objective of enabling transitions towards carbon neutrality. The options are more fully described below (Sections 6.2.2–6.2.5).

The approach is applicable at the sectoral level, to guide policy and incentives, or at estate, cooperative, farm, and field level, to orient current and future practice in current and new production areas. It should be understood as a complement to broader programmes, not as a stand-alone proposal, and as a menu rather a recipe. Cacao production systems vary greatly, and interventions that seek to reduce their global-warming effects must therefore be tailored to local practice and contexts, like other interventions in sustainable cacao (Hoffmann et al. 2020) and like agronomic innovations in general (Sinclair and Coe 2019). The suitability of individual intervention options may also vary with respect to the cacao life-cycle—e.g., 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 (Pérez Neira 2016). Finally, because of the very high emissions associated with deforestation, it is important to stress that such agronomic interventions can secure overall carbon neutrality of production only in plantations established without deforestation or in older plantations in which emissions due to land-use change have already been accounted for.

### 6.2.2. Improved management of harvest residues

Options 1–3 target the reduction of methane emissions from discarded cacao pod husks. They entail either the avoidance of anaerobic decomposition or its management.

Option 1, the simplest of the three, is the on-site dispersal of husks. This is the practice described briefly by

**Table 4.** Summary of intervention options for reducing the global-warming effect of cacao production.

| Intervention options | Effects | Notes and caveats |
|---|---|---|
| | A Improved management of harvest residues | |
| 1. Disperse pod husks on site | Reduces methane emissions by promoting aerobic decomposition of husks → lower ACF[a] and PCF[b] | – Retention of pods on site may increase disease risk |
| 2. Aerobic composting of husks | Reduces methane emissions by promoting aerobic decomposition of husks → lower ACF[a] and PCF[b] | – Poorly prepared or poorly stored compost may have high methane emissions because of anaerobic conditions (San Martin Ruiz et al. 2021) may require technical support in composting techniques<br>– Compost can be used in option 4 |
| 3. Anaerobic digestion of husks | Reduces methane emissions → lower ACF[a] and PCF[b] | – Biodigestate can be used in option 4<br>– Requires availability of large- or small-scale digestors and technical support |
| | B Improved sourcing and management of N | |
| 4. Greater use of organic N-fertilizers | 1 Reduces $CO_2$ emissions from fertilizer production → lower ACF[a] and PCF[b] | – Poorly prepared compost may have high methane emissions (San Martin Ruiz et al. 2021)<br>– Nitrification is part of the maturation phase of composting (Cáceres et al. 2018) and will produce $N_2O$ emissions<br>– Assumes that emissions from by-products such as cattle manure are attributable to the primary activity |
| 5. Greater use of (N-fixing) trees | 1 Reduces $CO_2$ emissions from fertilizer production→ lower ACF[a] and PCF[b]<br>2 May reduce accumulation of nitrates because of slow decomposition→lower $N_2O$ emissions from denitrification→lower ACF[a] and PCF[b]<br>3 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 cacao plants<br>– Poor management of shade trees can reduce cacao yield→higher PCF[b]<br>– Note that option 2 complements and potentially overlaps with options 8–10 |
| 6. Greater use of N-fixing ground-cover plants | 1 Reduces $CO_2$ emissions from fertilizer production→ lower ACF[a] and PCF[b]<br>2 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 cacao plants |
| 7. Reduction of N-fertilizer quantities | 1 Reduces or eliminates $CO_2$ emissions from fertilizer production → lower ACF[a] and PCF[b]<br>2 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<br>– In principle, applies also to N from biological fixation, which is subject to the same soil processes as fertilizer-N (Rosenstock et al. 2014) |
| 8. Synchronize N-supply with plant needs | 1 Higher uptake of N, allowing lower application rates → reduced $N_2O$ emissions from fertilizer application → lower lower ACF[a] and PCF[b]<br>2 Lower accumulation of excess nitrates lower $N_2O$ emissions from denitrification→lower ACF[a] and PCF[b] | – Applies to all N sources |
| 9. Use of enhanced-efficiency fertilizers | 1 Reduced $N_2O$ emissions from nitrification→lower ACF[a] and PCF[b]<br>2 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<br>– Emissions from fertilizer production are not affected |

**Table 4.** (*concluded*).

| Intervention options | Effects | Notes and caveats |
|---|---|---|
| | C Higher cacao yield | |
| 10. Wider adoption of good-practice cacao agronomy | 1 Decreased PCF[b] due to higher yield | – ACF[a] will not decrease unless cropping area contracts<br>– Cropping area may increase due to higher productivity, potentially increasing ACF[a]<br>– 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 |
| | D Enhancement of biosequestration | |
| 11 Wider adoption of good-practice agroforestry, including on land currently under unshaded production | 1 Higher $CO_2$ removal rates<br>2 Lower ACF[a] and PCF[b] | – Poorly managed agroforestry may reduce productivity<br>– Requires strong technical support to farmers to avoid yield reductions<br>– Achievement of lower PCF[b] requires maintenance of yield |
| 12 Wider production of durable products for long-term $CO_2$ removal | 1 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.

Romero et al. (2022) (study 22); husks were dispersed over the cacao plantation, mostly during the driest period of the year, and consequently were assumed to decompose aerobically, without methane emissions. A slightly more laborious approach, in which small groups of discarded husks are distributed throughout the plantation and then sprayed or sprinkled with a 15% urea solution to speed decomposition, is recommended in the Dominican Republic (Dominican Republic. Ministerio de Medio Ambiente y Recursos Naturales 2021). The scattering of the husks, or at least their disposal in small piles, ensures oxygen availability. This option is suitable for farmers with insufficient time or resources to adopt more intensive procedures, providing that the phytosanitary risks of leaving husks on-site can also be minimized.

Option 2 is the composting of husks, as recommended by Amponsah-Doku et al. (2022) and in some extension materials (Couto et al. 2011; Nestlé Brasil 2016; PNG Cocoa and Coconut Institute 2017; Ghana Cocoa Board 2018; Dominican Republic. Ministerio de Medio Ambiente y Recursos Naturales 2021; Murrieta Medina and Palma Moscoso, undated). Well-constructed and regularly turned (aerated) compost heaps should greatly reduce methane emissions. However, caution should be used in advocating composting if technical assistance is limited or if farmers lack either awareness of the importance of aerating the heap or the time to carry out the required activities. In such circumstances, decomposition in the compost heap may resemble that in husk piles.

Option 3 is the use of cacao husks as cosubstrates in managed anaerobic systems such as biodigestors, in which the emitted methane is captured and recycled as biogas (Da Cruz Ferraz Dutra et al. 2023). Such approaches may be most feasible for large companies and well-organized cooperatives.

### 6.2.3. Improved sourcing and management of N

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

Options 4–6 seek to reduce emissions due to nitrogenous fertilizer production by sourcing a higher proportion of plant N needs from low-emissions sources, such as organic fertilizers (option 4), N-fixing cover crops (option 5), and N-fixing trees (option 6). 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 24% to 61% (Ivanova et al. (2020); cases 8.2, organic production, and 8.3, "semi-technified" nonorganic production). 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.

Option 7, the reduction of fertilizer-N application rates, is the most direct means of reducing emissions from both manufacture and use of fertilizers. Several factors lead to the risk of over-fertilization in cacao. First, the crop's nitrogen requirements are relatively low (Snoeck et al. 2016), due to both efficient nutrient cycling (van Vliet and Giller 2017) and low nutrient exports (Hartemink 2005). Second, wider use and higher doses of fertilizers are key elements of efforts to increase global cacao production without further deforestation (Hoffmann et al. 2020; Avane et al. 2022). Third, major knowledge gaps exist regarding the nutrient requirements of cocoa, such that farm-level recommendations often have a weak scientific basis (Van Vliet and Giller 2017). Such knowledge gaps carry a risk of over-fertilization. Skilled technical advice might mitigate this risk, but technical support is often weak or unavailable (Jacobi et al. 2015; Brasil. Ministério de Agricultura e Pecuária 2023; Fasakin et al. 2023; Lloren et al. 2023).

There is some evidence of over-fertilization in the source articles. Three cases of unshaded production—cases 2.2, 6, and 8.3—describe fertilizer-N rates 2.5–5 times greater than the median value. Yield was also high, but in, for example, case 6, the yield of 1111 kg ha$^{-1}$ would correspond to N exports of around 40 kg (Hartemink 2005), versus N application rate of 118 kg ha$^{-1}$. Without more detailed information, we cannot be sure that in any of these three cases fertilization was excessive. However, in general we are sceptical that farmers who can afford fertilizers will always limit their use to profit-maximizing levels. Furthermore, while risk-averse farmers may tend to under-fertilize (Begho et al. 2022), risk aversion may lead to over-application when knowledge gaps exist (Isik and Khanna 2003).

Case 18.2 (cacao with gliricidia) (Miharza et al. 2023) exemplifies another risk: given their often precarious livelihoods, it is unrealistic to assume that farmers will always maintain their plantations in conditions optimal for responding to fertilization. The authors reported a lack of response to the relatively high fertilizer application (49 kg ha$^{-1}$ year$^{-1}$) and noted that factors including poor management affected the response.

Nevertheless, while option 7 is the most direct approach to reducing N-fertilizer emissions, it is probably not the most widely applicable. This is because reduction of N-fertilization may often be inappropriate. The fertilization rates reported in the source articles are already rather low. Moreover, in many countries large numbers of farmers do not use fertilizers (Ali et al. 2018; Danso-Abbeam and Baiyegunhi 2019; Ruf 2021) due in part to their high cost (Hoffmann et al. 2020; Ruf 2021; van Vliet et al. 2021). We suggest that, where locally applicable research results are not available, N-fertilization rates should be based on prior local experience of farmers, technicians, and researchers and on the need to replenish exported nutrients. They should also reflect wider relevant research results, such as the generally lower response of shaded cacao to increases in fertilization rate, which suggests the need for caution in attempting to boost production of cacao agroforestry through higher fertilization rates.

Options 8 and 9 reduce emissions for a given amount of N applied by addressing the soil processes—nitrification and denitrification—that release $N_2O$. Option 8—synchronization of applications to plant needs—aims at reducing the accumulation in the soil of nitrates in excess of plant needs. One way of doing so is to split N doses over two or more applications, each small enough to be taken up before loss to denitrification or leaching. In many locations, this is already standard practice (for example, Conseil du Café-Cacao (2015), Nestlé Brasil (2016)). The option is not limited to N from synthetic fertilizer; it also applies to inputs from organic fertilizers and N-fixing plants.

Option 9 comprises the use of enhanced-efficiency fertilizers, which include both slow- or controlled-release N-fertilizers and stabilized N-fertilizers (Halvorson et al. 2014). The former allows more efficient uptake—a similar effect to option 8 (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). Stabilized fertilizers can have a marked effect on emissions. For instance, in coffee, Sarkis et al. (2023) reported that substitution of urea by ammonium nitrate or by urea with the urease inhibitor NBPT reduced $N_2O$ emissions by 78.5% and 50.6%, respectively.

The effects of options 4 to 9 are not completely separable. In particular, higher N-use efficiency, as secured by options 8–9, should also allow reduced fertilizer-N application rates.

### 6.2.4. Good-practice cacao agronomic practices for increased cacao yield

Because the product carbon footprint is the ratio of emissions to yield, it can, unlike area carbon footprint, be reduced by interventions that increase productivity, provided that the interventions do not cause emissions that outweigh the productivity increase. Option 10 comprises good agronomic practices that fulfil this condition. The specific actions that are appropriate in any given situation will depend on the factors responsible for yield gaps. These factors are location-specific but may include poor shade management, pathogens, low cacao-plant density, low pollination, and use of over-generalized fertilization prescriptions (Amponsah-Doku et al. 2022; Asante et al. 2022; Toledo-Hernández et al. 2020, 2023). These 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.

An important caveat should be noted: when increased yield leads to a lower product carbon footprint, the total emissions from a farm or territory will not be reduced unless the cropping area is also reduced. Further, if increased yield is associated with higher profitability, then cropping area may increase. Given that demand for cacao is growing and is expected to continue growing (Suh and Molua 2022), higher productivity could cause higher emissions at sectoral level, even while lowering the product carbon footprint.

### 6.2.5. Enhancement of biosequestration

In addition to proposing options to reduce the carbon footprint of cocoa, we also propose options to enhance carbon removals within cacao plantations. The median CDR rate under agroforestry that we report above is an order of magnitude greater than the median and mean area carbon footprint and around three times greater than CDR under unshaded production. We suggest three intervention options aimed at harnessing the evident potential of agroforestry to increase CDR rates.

Option 10 (transition to agroforestry production) is directed at areas currently under unshaded production. In effect, it represents a change of land use—i.e., from unshaded to agroforestry cacao production. The transition to agroforestry is most easily accomplished around the time of plantation establishment.

Because of the large difference in CDR rates between unshaded and shaded production, option 10 is a potent means of increasing CDR rates. However, one important caveat should be considered: if not well executed, the transition to agroforestry may reduce productivity. This is because, at high shade levels, light becomes limiting to yield, as suggested by the results of our unpaired analysis. This risk can be eliminated by always implementing option 10 with option 11 (wider adoption of best agroforestry practices), because careful shade management will avoid the outcome of reduced yield. It is well established that well-managed agroforestry production need not be less productive than unshaded production with comparable levels of inputs and management intensity. Mattalia et al. (2022) for example, found that yield in simple cacao agroforestry systems ($\leq$3 shade species) was closely similar to that in unshaded systems, while Blaser et al. (2018) found that productivity was not affected at shade levels up to $\approx$30%. Technical assistance in support of climate-friendly interventions must therefore ensure that farmers can make evidence-based decisions about which practices best serve their objectives and circumstances. 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.

Option 11 includes not only shade management by thinning and pruning but also other important aspects of agroforestry practice with major effects on $CO_2$ removal rates. These include any actions that aim at securing increased woody biomass accumulation in the tree component, including improved nursery practices, weeding practices, and the choice of appropriate species and seed sources (Guariguata et al. 2008).

Option 12 (durable wood products for long-term $CO_2$ removal) aims to ensure that some of the carbon that would otherwise be released into the atmosphere at the end of each cacao cycle is instead banked in a longer-term carbon pool—specifically, durable, high-value wood products. Whereas repeated $CO_2$ removal-and-release over multiple cacao 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. Banking of carbon 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 et al. (2014) summarized timber yields of *Cordia alliodora* (a timber species) in cacao in Costa Rica at 4.4–10.3 $m^3$ $ha^{-1}$ $year^{-1}$ (mean $\pm$ SD tree density was 48 $\pm$ 47 trees $ha^{-1}$). Given that the basic wood density of *C. allliodora* is around 400 kg per $m^3$ (Greaves and McCarter 1990), this yield range suggests potential long-term $CO_2$ removal potential of around 8067–18 883 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 cacao fields, including well-known species with easily available planting stock (dos Reis et al. 2019; Mazón et al. 2018; Mussak and Laarman 1989; Ramírez-Argueta et al. 2022; Villanueva-González et al. 2024). Even allowing for emissions during harvesting and product manufacturing, low conversion efficiencies in sawmills or late stages, and the difficulty of guaranteeing long-term ($\geq$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-nonforest land-cover change, are very likely to be much greater than emissions from cacao management activities. Cacao cultivation has been linked to deforestation for centuries (Ruf and Schroth 2004) and remains an ongoing cause of deforestation (Orozco-Aguilar et al. 2021; Ashiagbor et al. 2022; Kalischek et al. 2023). Further, there is no guarantee that intensification of cacao production will prevent expansion into forested areas (Ruf 2021; Lock and Alexander 2023). For this reason, although our focus is on how to reduce emissions and enhance carbon removal within existing cacao plantations, we consider that the avoidance of further expansion of cacao into forested areas should be seen as a basic overarching consideration in managing the crop's future carbon footprint. At deforestation frontiers, interventions will need to be accompanied by measures specifically designed to prevent the expansion of otherwise sustainable cacao production in forest land; without such measures, other efforts to reduce carbon footprint may be counterproductive. In general, policy and development innovations that address the root causes of deforestation will be needed. The detail of such interventions is outside the scope of this study and is likely to be highly specific to national and subnational contexts. However, we note that sophisticated approaches to elucidating the often complex causes of deforestation, such as DriveNet (Robiglio et al. 2023), are increasingly available.

### 6.4. The importance of enabling frameworks

As we indicate in Fig. 4, the feasibility in specific social and production contexts of the 12 interventions depends on the presence of adequate enabling frameworks—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 to promote the implementation of climate-smart practices, as well as value-chain strengthening for secondary products such as high-value timber. Technical aspects include the supply of planting material of adequate diversity, quality, and quantity. It also includes the generation and synthesis of knowledge through research, including appropriate research into local knowledge. Expansion of cacao 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 cacao 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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### Data availability

The data on which the analyses are based are included in the supplementary material.

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## Supplementary material

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