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EDITED BY
Vassilios D. Litskas,
Independent Researcher, Lefkosia, Cyprus

REVIEWED BY
Matthew C. LaFevor,
University of Alabama, United States
Ana I. F. Ribeiro-Barros,
University of Lisbon, Portugal

*CORRESPONDENCE
Luis Orozco-Aguilar
luisoroz@catie.ac.cr
Arlene Lopez-Sampson
lopeza@catie.ac.cr

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CacaoFIT: the network of cacao field trials in Latin America and its contribution to sustainable cacao farming in the region

Luis Orozco-Aguilar[1]*, Arlene Lopez-Sampson[2]*, Rolando H. Cerda[2], Fernando Casanoves[2,3], Oscar Ramirez-Argueta[4], Javier Diaz Matute[4], Juan Carlos Suárez Salazar[3], Johanna Rüegg[5], Stephane Saj[5], Joaquin Milz[6], Ulf Schneidewind[6], Argenis Mora Garces[7], Eliana Baez Daza[7], Jairo Rojas Molina[7], Yeirme Jaimes Suarez[7], Genaro A. Agudelo-Castañeda[7], Olivier Deheuvels[8], Enelvi Brito Sosa[9], Jaime Hinojosa Gómez[9], Ramon E. Jaimez[10], Sophya Reyes Espinoza[11], Melanie Bordeaux[11], Carlos Caicedo Vargas[12], Leider Tinoco[12], Geover Peña Monserrate[12], Julian Perez Flores[13], Alfonso Azpeitia Morales[14], Cesar O. Arevalo-Hernandez[15,16], Enrique Arevalo Gardini[15,16], Luis E. Pocasangre[17], Osmary Araque[18], Athina Koutouleas[19], Eufemia Segura Magaña[20], Omar Dominguez[21], Paula Arenas[21], Lorena Sotopinto[22], Marisela Salgado-Mora[23], Antonio Gama-Rodrigues[24], Emanuela Gama-Rodrigues[24], Annelle Holder[25], Gideon Ramtahal[25], Pathmanathan Umaharan[25], Manfred Willy Muller[26], Fernando Texeira Mendes[26] and Eduardo Somarriba[2]

[1]Regional Tropical Agroforestry Consultant, CATIE, Managua, Nicaragua, [2]CATIE, Centro Agronómico Tropical de Investigación y Enseñanza, Turrialba, Cartago, Costa Rica, [3]Universidad de la Amazonia, Programa de Ingeniería Agroecológica, Facultad de Ingeniería, Centro de Investigaciones Amazónicas CIMAZ Macagual, Florencia, Colombia, [4]Fundación Hondureña de Investigación Agrícola (FHIA), Programa de Cacao y Agroforestería, La Masica, Atlántida, Honduras, [5]Department of International Cooperation, Group Resilient Cropping Systems, FiBL, Frick, Switzerland, [6]ECOTOP Foundation, La Paz, Bolivia, [7]Researcher at AGROSAVIA - Corporación colombiana de investigación agropecuaria, Villavicencio, Colombia, [8]Cacaoforest Project, CIRAD-CEDAF, Santo Domingo, Dominican Republic, [9]Departamento del Cacao, Ministerio de Agricultura, Santo Domingo, Dominican Republic, [10]Facultad de Ingenieria, Agronomica, Grupo de Manejo, Nutricíon y Ecofsiologia de Cultivos, Universidad Técnica de Manabí, Portoviejo, Manabí, Ecuador, [11]Fundación NicaFrance, Finca La Cumplida, Matagalpa, Nicaragua, [12]Instituto de Investigaciones Agropecuarias-INIAP, Portoviejo, Manabí, Ecuador, [13]Colegio de Posgraduados, Campus Tabasco, Cárdenas, Tabasco, Mexico, [14]Campo Experimental Huimanguillo, Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, Villahermosa, Mexico, [15]Instituto de Cultivos Tropicales (ICT), Tarapoto, Peru, [16]Universidad Nacional Autónoma de Alto Amazonas (UNAAA), Yurimaguas, Loreto, Perú, [17]EARTH University, Limon, Costa Rica, [18]Laboratorio de Ecofisiología de Cultivos, Universidad de los Andes, Merida, Venezuela, [19]Department of Geosciences and Natural Resource Management, University of Copenhagen, Frederiksberg, Denmark, [20]The Fruits and Cacao Program at CENTA, San Salvador, El Salvador, [21]Researcher at Grupo de Investigación e Innovación de Cacao, FEDECACAO, Santander, Colombia, [22]Colegio de la Frontera Sur, ECOSUR, San Cristobal de las Casas, Chiapas, Mexico, [23]Facultad de Ciencias Agronómicas, Universidad Autónoma de Chiapas, Huehuetán, Chiapas, Mexico, [24]Soils Laboratory, Universidade Estadual do Norte Fluminense Darcy Ribeiro (UENF), Rio de Janeiro, Brazil, [25]Cocoa Research Center, University of West Indies, Saint Agustine, Trinidad and Tobago, [26]CEPLAC/MAPA-Comissão Executiva do Plano da Lavoura Cacaueira/Ministério da Agricultura, Pecuária e Abastecimento, Brasília, Brazil

A network of agronomists, researchers, and practitioners associated with cacao farming provided open access to their independent field trials across Latin America and the Caribbean (LAC). A centralized dataset was assembled using qualitative and quantitative data from 25 experimental field trials (hereafter referred to as "CacaoFIT") spanning several LAC agroecosystems. This dataset was used to document the main traits and agroclimatic attributes of the cacao cultivation model being tested within the CacaoFIT network. By synthesizing data from an entire network of cacao trials, this study aimed to highlight specific design features and management practices that may contribute to better cacao farming sustainability. The CacaoFIT network comprises 200 ha of field trials testing over 150 cacao genotypes and set up under different shade canopy design, management, and research goals. Small-sized trials were common across Mesoamerica, whereas medium to large-size trials were distinct to South America. Cacao trials were 15 years old (on average) and ranged from 3 to 25 years of establishment. Most cacao trials were managed conventionally (i.e., 55%), while 20% were under organic practices, and the remaining 25% presented both conventional and organic management approaches. Most field trials (ca. 60%) planted an average of 10 international clones or national cultivars at high (1,230–1,500 plants ha^{-1}) and medium density (833–1,111 plants ha^{-1}). Mixed shade canopies were the dominant agroforestry model, while timber vs. leguminous shade canopies were also common. The diversity and depth of research domains examined across the CacaoFIT network varied widely. Agronomy and agroforestry topics dominated the research agenda across all trials, followed by environmental services domains. Cacao physiology and financial performance were researched to a lesser extent within the network. Five featured field trials from CacaoFIT offered technical guidelines to inform cacao farming within similar contexts. This collaborative work is a scaffold to encourage public–private partnerships, capacity building, and data sharing amongst cacao researchers across the tropics.

KEYWORDS

agroforestry, cacao trials, on-farm research, perennial crops, sustainability

Introduction

Globally, cocoa cultivation covers over 11 million hectares of land (Fountain, 2022; Hütz-Adams et al., 2022). It is estimated that about 33% of cocoa is cultivated under shade conditions (i.e., agroforestry systems) (Somarriba and López, 2018b). Latin America and the Caribbean (LAC) is the third largest cacao cultivation region worldwide, with 1.2 million ha grown under different cropping systems (ranging from full sun to rustic cacao) (Somarriba and Lachenaud, 2013; Orozco-Aguilar et al., 2021; Daymond et al., 2022). Cacao cultivation in LAC sustains the livelihoods of ~1.7 million small farmers, provides key environmental services, and plays a pivotal role in landscape restoration efforts (Deheuvels et al., 2012; Cerda et al., 2014; Middendorp et al., 2018; Niether et al., 2018; Garcia-Briones et al., 2021; Notaro et al., 2021; Hütz-Adams et al., 2022). Major threats to a thriving cacao industry in LAC are aging cacao plantations and farmers, lack of access to finance for renovation/rehabilitation, reduced availability of high-quality planting material, new pests and disease outbreaks, risk of cadmium contamination, lack of market channels for agroforestry products, soil fertility decline, low crop productivity, and new cero-deforestation regulation (Jacobi et al., 2014; Vaast and Somarriba, 2014; Chavez et al., 2015; Dalberg, 2015; Cilas and Bastide, 2020; Wiegel et al., 2020; Ceccarelli et al., 2021; Solidaridad, 2023; Thomas et al., 2023).

There are two major scenarios of cacao farming and trading models in LAC. In one scenario, smallholder farmers (≤10 ha farmland) grow mostly seed-based and rain-fed cacao plots with low planting density, unknown compatibility of grown cacao varieties, suboptimal shade canopy design, modest pruning, weeding, and harvesting management (Cerda et al., 2014; Somarriba et al., 2018; Garcia-Briones et al., 2021; López-Cruz et al., 2021; Notaro et al., 2021). In the other scenario, medium- and large-size cacao plantations (over 100 ha farmland) grow improved cacao planting material on irrigated plots with a simplified shade canopy, regular fertilization, and timely agricultural management (Hartemink, 2005; Jacobi et al., 2014; Wiegel et al., 2020; Daymond et al., 2022; Hütz-Adams et al., 2022). The former scenario is characterized by poor agronomic performance (with low yields and significant harvest losses due to poor pest and disease control) and low revenue from cacao trading due to limited market access (Leandro-Muñoz et al., 2017; Mazón et al., 2018; Loukos, 2020; Zu Ermgassen et al., 2022). In contrast, the latter scenario features better agronomic performance (i.e., higher yields and fewer losses due to pests and diseases) and has better access to technical advisory and information, which, in turn, leads to greater market access and increased revenue generation (Wessel and Quist-Wessel, 2015; Loukos, 2020; Armengot et al., 2021). Nowadays, technical assistance (in both coverage and frequency) that targets small cacao farmers is missing in most agricultural sectors of LAC. Moreover, the low government budgets to train remote farmers, together with the lack of investment in on-farm research and the low internet access in rural areas, are factors that compromise capacity building and training of key actors along the cocoa value chain (Wiegel et al., 2020; World Cocoa Foundation, 2022).

Under this complex and challenging environment, sustainable cacao farming in LAC requires reality-based public policies, training and financing programs, and evidence-based cultivation models. The novel knowledge being gathered and delivered by the CacaoFIT network in LAC is the foundation for achieving profitable and sustainable cacao farming for both cultivation scenarios in the region. This study compiles knowledge and technical guidelines generated and disseminated by CacaoFIT members and highlights the key role that CacaoFIT could play in agronomy and agroforestry advocacy at the national and regional levels. The aims of this study were (1) to demonstrate the collective capacity of the CacaoFIT in testing cultivation models in LAC, (2) to gather the core research questions addressed in a subset of experimental trials, and (3) to feature the main findings and implications of the CacaoFIT for agroforestry science and practice across LAC and potentially other cacao-growing regions.

Materials and methods

The study is a synthesis made possible by the collective effort of a network of agronomists, foresters, and practitioners associated with cacao farming in either a national or regional research institution and/or a national university within the LAC regions. The methodological approach taken consisted of four steps: (1) ***Gathering general information***: We created a Google form intended to summarize the general information about each research trial. Data collected in these surveys included location and climate features, trial size (ha), age of the trial (year of evaluation), type of planting material grown, experimental design, shade canopy typology, and the overall agronomic management of the trial (Supplementary material 1). The online survey was sent to each participating institution, and one or more researchers were responsible for completing the survey for their respective cocoa plots. After all surveys were submitted, a collated datasheet was created and uploaded to a centralized repository for further analysis and open-access storage (www.erda.dk). (2) ***Featuring trials***: The third step involved the selection of a subset of five experimental trials from Honduras ($n = 1$), Colombia ($n = 2$), Bolivia ($n = 1$), and Brazil ($n = 1$). Data from these five trials were used to develop a fact sheet featuring the main findings and implications for the national cacao sector. The selection criteria of these five featured trials were: (a) willingness to share new and unpublished data, (b) a minimum size of 10 ha, (c) having recorded at least five consecutive years of data, (d) showcasing contrasting environmental and management regimes, and (e) having published at least five scientific papers from the trial. For each featured field trial, we generated descriptive statistics and graphs to show the overall performance and trends devised for five key aspects: agronomy, agroforestry, financial, environmental, and physiological measurements. Data analyzed in each featured trial include (a) crop productivity per system, (b) total system yields (cacao + goods/products), (c) accumulated incidence/severity of pests and diseases, (d) growth curve of shade/timber trees tested, (e) the total cost of establishment and management (when recorded), (f) gross/net income from several combinations of cacao + shade trees (when calculated), and (g) physiological parameter measured. (***3***) ***Description of climatic conditions and shade canopies***; following Somarriba et al. (2023), we described key elements of shade canopy variables in each featured trial, which included tree density, tree cover, species associated, tree phenology, and shade canopy management. The general climatic conditions of each experimental site were classified according to Kottek et al. (2006), and the soil type and properties were described as follows: https://soilgrids.org/. For each featured trial, we provided relevant data on the outreach actions delivered to several cacao actors at national and regional levels. (4) ***Drawing the research agenda***: We built a matrix to document the nature and extent of research agendas across the network. The matrix consists of five research domains, namely agronomy, agroforestry, environmental services, physiology features, and financial performance, with 5–7 sub-research topics each. Each person responsible for the field trial selected the list of research topics being conducted; thus, we mapped the current CacaoFIT research agenda and identified potential research gaps. We provided links to relevant publications or websites to access more detailed information on each featured trial. In this study, both current and completed cocoa trials were mapped, yet we did not document trials led by private actors in LAC. To the best of the authors' knowledge, this is the first attempt to document an entire network of cacao experimental trials across LAC.

Results

Section #1. Description of the cacaofit network in LAC

The CacaoFIT network was managed either by a public research center or university and, to a lesser extent, by non-government actors (such as research foundations or development agencies). The CacaoFIT network consisted of 25 experimental sites on 200 ha across LAC and was set up over four different ecological regions: (a) Equatorial rainforest, which is fully humid, (b) Equatorial monsoon, (c) Equatorial savannah with a dry summer, and (d) Equatorial savannah with a dry winter (Table 1). CacaoFIT was established along four altitudinal strata: low from 0 to 250 m (30% of the trials), medium from 250–500 m (45% of the trials), high from 500 to 750 m (15% of the trials), and very high ≥750 m (15% of plots). Most of the research network was established in locations where cacao farming is rarely water-limited (with the exception of the sites located in Bolivia and El Salvador). ∼70% of the experimental trials in CacaoFIT were in areas with sufficient rain (2,000–2,500 mm year), 20% of the trials were grown in humid locations (2,500–3,000 mm year), and only 10% of the plots were cultivated in dry conditions (≤1,500 mm year) (Table 1). Approximately 70% of the research trials experienced a marked dry season with 2–4 months with less than 100 mm of rain. Temperatures across the CacaoFIT trials ranged from 19°C in the South of Mexico (Chiapas) and the highlands of San Vicente, Santander, Colombia, to 37°C on the Pacific coast of El Salvador.

Experimental trials within the CacaoFIT were found to vary in size (ha), age (years of establishment), management regime

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TABLE 1 Descriptors of the CacaoFIT network in terms of size (ha), establishment date, altitude, rainfall, temperature, and climatic zone.

Country*	Partners**	Area (ha)	Established	Altitude (m)	Rainfall range (mm)	Temperature range (°C)	Climatic zone+	Dry moths	Status
BOL	FiBL-El Ceibo-Farmers	5.5	2008	200–500	1,500–2,000	18–30	As	4	Ongoing
		1.25	2012	200–500	1,500–2,000	18–30	As	4	Ongoing
	FiBL-ECOTOP-Farmers	1.0	2015	200–500	1,500–2,000	18–30	As	4	Ongoing
BRA	UENF-MARS	15	2004	≤200	1,250–1,600	18–30	Af	1	Ended
	UENF-CEPLAC	5	2011	≤200	1,400–1,600	19–32	Af	1	Ended
	UENF-Instituto Sucupira	5	2019	≤200	1,900–2,100	19–31	Af	1	Ongoing
COL	CATIE-Kolfaci-Agrosavia	1.5	2018	200–500	2,500–3,000	26–32	Am	3	Ongoing
	Agrosavia	1.5	2015	200–500	2,000–2,500	20–27	Am	3	Ongoing
	U. de la Amazonia	32.0	2014	200–500	≥3,000	23–30	Am	2	Ongoing
	FEDECACAO	34.8	2000/2020	1,000–1,200	2,000–2,500	20–27	Am	3	Ongoing
CR	CATIE-GIZ-farmers	2.5	1988/1989	≤200	2,500–3,000	26–33	Af	2	Ended
	EARTH University	5.5	2000	≤200	2,500–3,000	24–33	Af	2	Ongoing
	CATIE-Kolfaci-MAG	2.0	2018/2019	≤200	2,000–2,500	24–31	Af	3	Ongoing
ECU	UTM-Manabi+ INIAP	1.5	2015	≤200	≤1,500	25–33	Am	3	Ongoing
	INIAP-CATIE	7.8	2015	≤200	≤1,500	26–34	Aw	2	Ongoing
GUA	CATIE-Kolfaci-ICTA	1.5	2018/2019	200–500	2,000–2,500	26–33	As	4	Ongoing
	Universidad de San Carlos	1.75	1990	≤200	2,000–2,500	23–32	As	3	Ended
HON	FHIA	43	1997	≤200	2,500–3,000	24–35	Af	2	Ongoing
	CATIE-Kolfaci-SAG	1.5	2018	200–500	2,500–3,000	25–34	Af	2	Ongoing
MEX	COLPOS-farmers	1.25	2012	≤200	2,000–2,500	20–33	As	4	Ongoing
	INIFAP-farmers	1.5	2012	200–500	≥3,000	19–35	Af	2	Ended
NIC	CATIE-Kolfaci-INTA	1.5	2018/2019	200–500	2,000–2,500	27–35	As	5	Ongoing
	FNF-ECOM	2.0	2020	500–700	2,000–2,500	26–34	As	5	Ongoing
PAN	GIZ-CATIE-farmers	3.5	1989/1990	≤200	2,500–3,000	24–33	Af	3	Ended
	CATIE-Kolfaci-MIDA	1.25	2018/2019	≤200	2,500–3,000	25–34	Af	3	Ongoing
PER	CATIE-Kolfaci-INIA	2.5	2018	200–500	1,500–2,000	20–33	As	3	Ongoing
	ICT-Farmers	3.3	2004	200–500	1,500–2,000	25–33	As	3	Ongoing
RD	CIRAD-CacaoForest	13.5	2017/2018	≤200	2,000–2,500	26–35	Af	4	Ongoing

(Continued)

TABLE 1 (Continued)

Country*	Partners**	Area (ha)	Established	Altitude (m)	Rainfall range (mm)	Temperature range (°C)	Climatic zone+	Dry moths	Status
	CATIE-Kolfaci-MAG	1.5	2018/2019	≤200	2,000–2,500	27–34	Af	2	Ongoing
SAL	CENTA-MAG	1.5	1992	200–500	≤1500	22–34	Aw	6	Ongoing
T & T	Cocoa Research Center	2.0	2020	≤200	1,500–2,000	23–34	Am	5	Ongoing
VEN	UNI-ANDES	2.5	2005	≤200	1,500–2,000	23–33	As	4	Ended

***Countries:** BOL, Bolivia, BRA, Brazil, COL, Colombia, CR, Costa Rica, ECU, Ecuador, GUA, Guatemala, HON, Honduras, MEX, México, NIC, Nicaragua, PAN, Panamá, PER, Perú; R.D, República Dominicana; SAL, El Salvador; T&T, Trinidad and Tobago, VEN, Venezuela. **+Climatic zones** following Kottek et al. (2006), AF, Equatorial rainforest, fully humid, Am, Equatorial monsoon, As Equatorial savannah with a dry summer and Aw, Equatorial savannah with a dry winter. Sourced from https://koeppen-geiger.vu-wien.ac.at/pdf/Paper_2006.pdf.

****Partners**: FiBL, The Research Institute of Organic Agriculture, Switzerland; El Ceibo, Central de Cooperativas El Ceibo, Alto Beni, La Paz, Bolivia; ECOTOP, an International consultancy firm and foundation specialized in the establishment and training of successional agroforestry systems across the tropics, CATIE: Centro Agronomico Tropical de Investigación y Enseñanza, Costa Rica; EARTH University, Costa Rica; GIZ, Agencia Alemana de Cooperación técnica, FHIA, Fundacion Hondurena de Investigación Agrícola, SAG: Secretaria de Agricultura de Honduras, Agrosavia: Coorporacion Colombiana de Investigacion Agropecuaria, FEDECACAO: Federación de Cacaoteros de Colombia, ICT: Instituto de Cultivo Tropicales-Perú, UTM, Universidad Tecnica de Manabi, Ecuador; INIAP: Instituto de Investigación Agropecuaria, Ecuador; ICTA: Instituto de Ciencia y Tecnología Agricolas, Guatemala; INTA: Instituto Nicaragüense de Tecnología Agropecuaria, Nicaragua; FNF: Fundación NicaFrance, Nicaragua; COLPOS: Colegio de Posgraduados de México; INIFAP: Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, México; ECOM: Grupo Ecom Trading, Nicaragua; MIDA: Ministerio de Desarrollo Agricola, Panama; INIA: Instituto Nacional de Investigacion Agraria, Perú; CIRAD: The French Agricultural Resaerch Center for International Development, France; CENTA: Centro Nacional de Tecnología Agropecuaria, El Salvador; MAG: Ministerio de Agricultura; KoLFACI: Korean-Latin Amerinca Food & Agriculture Cooperation Initiative, Republic of Korea; UNI-ANDES, The University of the Andeans, Venezuela; CRC: Cocoa Research Center, Trinidad & Tobago.

(organic vs. conventional), agroforestry design, overall research goals, and type and frequency of data collection. Trial size and age ranged from 1 to 43 ha and 3 to 25 years, respectively. Small plots were the most frequently used in research (with an average of 1.5 ha in 50% of the trials), ∼35% were medium-sized (from 2.5 to 10.0 ha), and the remaining 15% of the experimental trials were large, with plot sizes ranging from 12 to 35 ha. Small plots were common across Mesoamerica (from Mexico to Panama) and the Caribbean (the Dominican Republic and Trinidad and Tobago), whereas medium- to large-size trials were prominent in Honduras and South America, mainly in Colombia, Peru, and Brazil. More than half (55%) of the research trials documented were aged 10–12 years, ∼30% of research sites were 12–15 years old, and the remaining 20% were older (> 15 years). The two oldest and most active experimental trials were situated in humid-lowland Honduras, led by FHIA (Fundación Hondureña de Investigación Agricola) and dry-lowland El Salvador, managed by CENTA (Centro Nacional de Tecnologia Agropecuaria y Forestal). Cacao trials established by CATIE (Centro Agronómico Tropical de Investigación y Enseñanza) in Costa Rica and Panama in 1988/1989 are no longer active. Cacao experimental trials in Brazil have been established since 2000 in several locations, while most cocoa experimental trials in other South American countries (Peru, Bolivia, Venezuela, and Colombia) were established during the 2005–2010 period. The youngest experimental sites, although small, were those set up by the CATIE-KoLFACI (2018–2019) in eight countries across LAC, the Cacao Forest project (2018–2019) in the Dominican Republic, and the one recently established in 2020 at the Cocoa Research Center experimental station in Trinidad and Tobago.

Five out of the 25 experimental trials mapped in the CacaoFIT network ended their operations (for various reasons, usually linked to financial constraints). Cacao plots that tested seed-based cacao yields under leguminous shade trees (i.e., *Gliricidia sepium, Inga edulis,* and *Erythrina poeppigiana)* vs. timber trees *(e.g., Tabebuia rosea, Terminalia ivorensis,* and *Cordia alliodora*) established in the early 90s in Talamanca, Costa Rica, and Bocas del Toro, Panama, concluded data collection around 2000–2001 when financing ceased (Beer et al., 1998; Somarriba and Beer, 2011) and experimental trials were handed back to local farmers. Another timber-based cacao agroforestry systems trial set up in 2005 in Merida State and managed by the University of Los Andes, Venezuela, ended operations around 2010 due to land invasion and other political reasons (Araque et al., 2012; Jaimez et al., 2013; Mazón et al., 2018; Ávila-Lovera et al., 2016). Maintenance and data collection for the research trials led by CENTA in El Salvador and Universidad de San Carlos in Guatemala are currently facing financial constraints. The research site managed by INIFAP (Instituto Nacional de Investigación Forestal y Agropecuaria) in Mexico ended operation in 2017 after seven years of data collection due to a lack of funding. Research trials set up in 2004 by ICT (Instituto de Cultivos Tropicales) in Peru, although fully functional, ceased the data collection process in 2017 due to funding. Finally, the network of experimental trials led by UENF (Universidade Estadual do Norte Fluminense Darcy Ribeiro) and MARS and UENF and CEPLAC (Comissão Executiva do Plano da Lavoura Cacaueira) in Brazil tested a wide range of cacao + shade tree combinations operated for 10 years (2005–2015) but ended operations once collaboration agreements were over (Gama-Rodrigues et al., 2021).

Surprisingly, only three research trials in the network (FiBL in Bolivia, INIAP in Ecuador, and CRC-Trinidad and Tobago) presented unshaded plots as a control treatment.

Cacao density, planting material, shade canopies, and overall management

Fifteen out of 25 experimental trials from the CacaoFIT network are ongoing and continue doing collaborative research with national and international research institutions or universities. The CacaoFIT network has tested a wide range of planting densities and genetic material. Approximately 150 distinct cacao genotypes/clones were assessed in a mixture of 8–10 clones per plot. Across the network, planting density was classified as low ($<$625 plants ha^{-1}) in 20% of cases, medium (between 625 and 833 plants ha^{-1}) in another 20%, high (1,111 plants ha^{-1}) in another 45%, and very high ($\geq$1,300 plants ha^{-1}) in the remaining trials (Table 2). Most research trials were managed conventionally (i.e., 55%), defined by the use of synthetic inputs, fertilizers, mechanical weeding, etc. Meanwhile, 20% were managed via organic practices defined by the absence of agrochemicals aside from the application of bioproducts and manual weeding practices. The remaining 25% of trials utilized both conventional and organic management for comparison purposes. Additionally, most research trials (80%) performed soil analysis at the beginning of the experiment and continue to do so every two to three years as a means of monitoring changes in physical and chemical soil properties, as well as the effects on enhancing soil biota.

Most trials (ca. 60%) managed both well-known international clones and national cultivars from selection programs; the remaining 30% grew locally selected elite trees, and only 10% grew seed-based cocoa plantations for comparison purposes (mainly in Bolivia, El Salvador, and Peru). Completed trials run by CATIE in Costa Rica and Panama, as well as managing both seed-based cacao plants from controlled pollination and a set of international clones (Somarriba and Beer, 2011). Interestingly, the experimental trial set up by ECOM and Fundación NicaFrance in Nicaragua is currently testing plants derived from somatic embryogenesis. Most experimental trials (90%) were rain-fed, and only five (the ones located along the dry Pacific coast of Ecuador and El Salvador) were irrigated. Mixed shade canopies were dominant across research trials (70%), while timber-based vs. leguminous shade trees were also tested in 20% of the trials (mainly in Colombia and Central America). Timber-based agroforestry systems were dominant in Honduras, while simple shade canopies or full-sun cacao within the CacaoFIT were less common. The research trials set up by UENF + MARS + CEPLAC tested a wide range of cacao-shade tree combinations, including mixed shade, leguminous trees (*Erythrina* sp., *G. sepium*), cacao + coffee (*Coffee canephora*) + teak (*Tectona grandis*), cacao + rubber trees (*Hevea brasilensis*), and other mixtures of cacao with native fruit trees (*Anona muricata*, *Spondias mombin*), timber (*Schizolobium amazonicum, Tabebuia heptaphylla, C. alliodora, Tabebuia heptaphyllam, Bagassa guianensis, C. guianensis*), and palm trees such as Acai (*Euterpe oleracea*), peach palm (*Bactrias gasipaes*), coconut (*Coconut nuficera*), and Brasil nut (*Bertholetia excelsa*). For a full description of these diverse shade canopies, see Gama-Rodrigues et al. (2021).

Nature of the research being conducted across the CacaoFIT network

The diversity and depth of research domains conducted across the CacaoFIT network varied greatly. Agronomy and agroforestry themes dominated the research agenda of all experimental sites. Regarding agronomy, cacao plant growth and vigor, accumulated yields, and the incidence of pests and diseases were the most common research topics. More complex topics, such as the dynamics of pod production and the effects of pruning (frequency and intensity) on yields, had been recently conducted by a handful of research trials. Regarding agroforestry, the topics documented by nearly 75% of the experimental trials were shade tree growth, generation of goods/products from associated trees (annual crops, timber, fruits, firewood, etc.), and the assessment of canopy cover over time (Figure 1). Shading factors and tree phenology (foliage dynamics) were seldom assessed within the CacaoFIT network (Saj et al., 2013; Magne et al., 2014; Schneider et al., 2017; Armengot et al., 2021; Sauvadet et al., 2021).

Regarding the set of environmental/ecosystem services, most research trials (65%) have documented carbon stocks, sequestration rates, and nutrient cycling, whereas topics such as the abundance/habitat of pollinators, local biodiversity, and soil/micro and macro fauna were assessed to a lesser extent. Other research topics, such as rainfall partitioning and litterfall/decomposition rate, were overlooked across CacaoFIT; so far, the trials led by FiBL in Bolivia, Agrosavia in Colombia, and CEPLAC in Brazil were the only ones that were researched and published on these topics. Climate variables (precipitation, temperature, wind speed, and relative humidity) for most research trials (80%) were gathered by in-site or nearby weather stations, while microclimate variables were rarely measured locally. Again, the research trail from FiBL in Bolivia is leading the way concerning microclimate-shade management-yield relationships.

Concerning the physiological features of cacao plants, namely leaf area index, sap flow, chlorophyll fluorescence, gas exchange (CO_2 assimilation, transpiration, and leaf conductance), and water relationships (leaf water potential and osmotic adjustment), only ~40% of the research trials within CacaoFIT have conducted this set of studies. Physiological measurements were commonly taken by experimental trials in Colombia, Bolivia, and Venezuela, which produced several articles in both English and Spanish. Physiology research topics were almost absent in Mesoamerica and the Caribbean, presumably due to a lack of equipment, instruments, and skilled staff (Ramon E. Jaimez, Universidad Tecnica de Manabi, Ecuador, and personal communication). Finally, regarding the financial performance of cacao farming, annual profitability, and cost/benefit analysis were the most common key financial indicators tested in ~70% of the CacaoFIT network. Except for the study conducted by Ramirez et al. (2001), risk analysis and long-term financial modeling are not fully developed themes. Novel topics such as labor, energy demand, food safety, and lifecycle assessments were assessed only by the trial in Bolivia (Armengot

TABLE 2 Management of the CacaoFIT network, including planting density, the origin of planting material, farm systems, and type of shade canopy.

Country*	Partners**	Cacao Density (plants/ha)	Planting material (clones/cultivars)	Soil test	Farm system	Irrigated (yes/no)	Shade canopy
BOL	FiBL-El Ceibo-Farmers	625	International/local selection	Yes	Organic and Conventional	No	Mixed shade, Successional + Full sun
	FiBL-ECOTOP-Farmers	625	International/local selection	Yes	Organic and Conventional	No	Mixed shade, Successional + Full sun
BRA	UENF-MARS	700–2,500	CEPLAC clones	Yes	Conventional	No	Diversified shade + Leguminous trees
	UENF-CEPLAC	1,111	CEPLAC clones	Yes	Conventional	No	Diversified shade + Timber trees
	UENF-Instituto Sucupira	1,250	CEPLAC clones	Yes	Conventional	No	Leguminous trees + Native fruit trees
COL	CATIE-Kolfaci-Agrosavia	1,111	National clones	Yes	Organic and Conventional	Yes/No	Timber trees in simple/double lines
	AGROSAVIA	1,111	National clones/local selection	Yes	Conventional	No	Timber shade trees
	U. de la Amazonia	833	International/national clones	Yes	Conventional	No	Timber shade trees
	FEDECACAO	1,111	National/local clones	No	Organic and Conventional	No	Timber shade trees
CR	CATIE-GIZ-farmers	833	Hybrids, seed-based plants	No	Conventional	No	Leguminous + timber
	EARTH University	1,111	Internacional/CATIE clones	Yes	Organic	No	Leguminous shade + Mussa spp.
	CATIE-Kolfaci-MAG	1,290	CATIE clones	Yes	Organic and Conventional	No	Mixed shade+ trees in the borders.
ECU	UTM-Manabi + CATIE	1,111	National clones/local selection	Yes	Conventional	Yes	Mixed shade/Full sun
	INIAP-Amazonia + CATIE	1,111	EET-103 + EET-96/Local selection	Yes	Organic	No	Timber + Palms + Fruit trees
GUA	CATIE-Kolfaci-DICTA	1,290	CATIE clones	Yes	Organic and Conventional	No	Mixed shade+ trees in the borders
	Univ. San Carlos	888	Hybrids, seed-based plants	No	Organic	No	Mixed shade
HON	FHIA	1,111	International clones	Yes	Conventional	No	Timber shade
	CATIE-Kolfaci-SAG	1,290	International/CATIE clones	No	Organic	No	Mixed shade

(Continued)

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TABLE 2 (Continued)

Country*	Partners**	Cacao Density (plants/ha)	Planting material (clones/cultivars)	Soil test	Farm system	Irrigated (yes/no)	Shade canopy
MEX	COLPOS-farmers	1,111	National and international + criollo selected seeds	Yes	Conventional	No	Mixed shade
	INIFAP-farmers	833	Criollo selected seed and elite trees	No	Organic	No	Mixed shaded + Mussa.
NIC	CATIE-Kolfaci-INTA	1,290	CATIE clones	Yes	Organic and Conventional	No	Mixed shade+ trees in the borders.
	FNF-ECOM	1,111	Plants from somatic embryogenesis	Yes	Conventional	No	Mixed shade + Mussa spp
PAN	GIZ-CATIE-farmers	833	Hybrids, seed-based plants	No	Conventional	No	Leguminous + timber
	CATIE-Kolfaci-MIDA	1,290	CATIE clones	Yes	Organic and Conventional	No	Mixed shade+ trees in the borders.
PERU	CATIE-Kolfaci-INIA	1,290	National clones	Yes	Organic and Conventional	No	Mixed shade/Trees in the borders.
	ICT-Farmers	833	National/local clones	Yes	Organic and Conventional	No	Leguminous shade + Mussa spp.
RD	CIRAD-CacaoForest	625	Selected trees, IDIAF cultivars, and international clones	Yes	Organic	No	Diversified shade.
	CATIE-Kolfaci-MAG	1,290	National clones/local clones	Yes	Organic	No	Mixed shade+ trees in the borders
SAL	CENTA-MAG	833	Selected elite criollo trees/local seeds	Yes	Conventional	Yes	Leguminous trees
T&T	Cocoa Research Center	1,500	Local clones/selected elite trees	Yes	Conventional	Yes	Leguminous shade vs. No shade/full sun
VEN	UNI-ANDES	833	Criollo cultivars: Porcelana, Merideño, Guasare, Lobasare.	Yes	Conventional	Yes	Timber + Leguminous

Countries: *BOL, Bolivia; BRA, Brasil; COL, Colombia, C.R, Costa Rica, ECU, Ecuador, GUA, Guatemala, HON, Honduras, MEX, México, NIC, Nicaragua, PAN, Panamá, PER, Perú; RD, República Dominicana; SAL, El Salvador; T&T, Trinidad and Tobago; VEN, Venezuela.

Partners: **FiBL, The Research Institute of Organic Agriculture, Switzerland; El Ceibo, Central de Cooperativas El Ceibo, Alto Beni, La Paz, Bolivia; ECOTOP, an International consultancy firm and foundation specialized in the establishment and training of successional agroforestry systems across the tropics, CATIE: Centro Agronómico Tropical de Investigación y Enseñanza, Costa Rica; EARTH University, Costa Rica; GIZ, Agencia Alemana de cooperación técnica; FHIA, Fundación Hondureña de Investigación Agrícola, SAG: Secretaria de Agricultura de Honduras, Agrosavia: Corporación Colombiana de Investigación Agropecuaria, FEDECACAO: Federación de Cacaoteros de Colombia, ICT: Instituto de Cultivo Tropicales-Perú, UTM, Universidad Técnica de Manabí, Ecuador; INIAP: Instituto de Investigación Agropecuaria, Ecuador; ICTA: Instituto de Ciencia y Tecnología Agrícolas, Guatemala; INTA: Instituto Nicaragüense de Tecnología Agropecuaria, Nicaragua; FNF: Fundación NicaFrance, Nicaragua; COLPOS: Colegio de Posgraduados de México; INIFAP: Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, México; ECOM: Grupo Ecom Trading, Nicaragua; MIDA: Ministerio de Desarrollo Agrícola, Panamá; INIA: Instituto Nacional de Investigación Agraria, Perú; CIRAD: The French Agricultural Resaerch Center for International Development, France; CENTA: Centro Nacional de Tecnología Agropecuaria, El Salvador; MAG: Ministerio de Agricultura; KoLFACI: Korean-Latin Amerinca Food & AGriculture Cooperation Initiative, Republic of Korea; UNI-ANDES, The University of the Andeans, Venezuela; CRC: Cocoa Research Center, Trinidad & Tobago.

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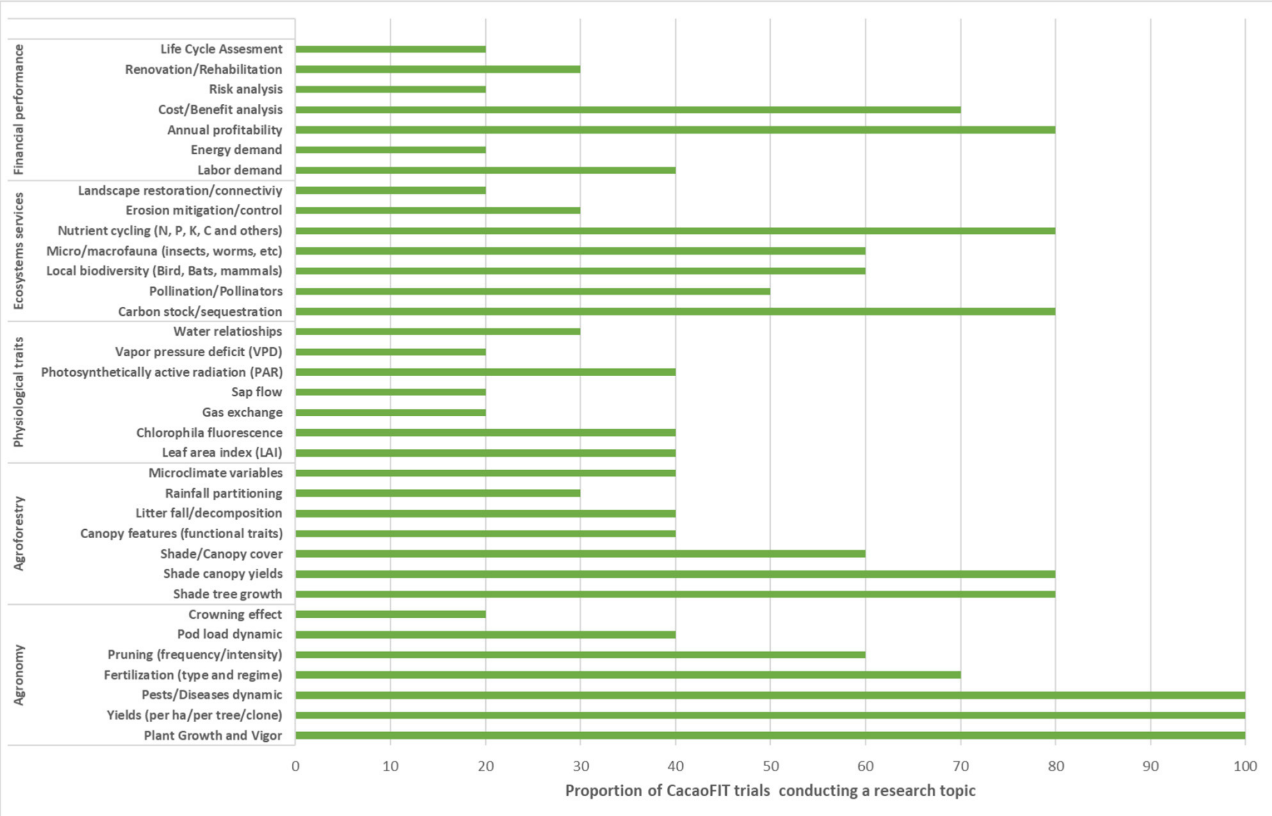

FIGURE 1
Diversity and depth of research domains and topics being conducted across the CacaoFIT network.

et al., 2016; Pérez-Neira et al., 2020, 2023). Establishment and maintenance costs of both conventional and organic management were researched to a lesser extent. In summary, research gaps across the CacaoFIT network were evident and deserved attention.

Section #2. Featured cacao field trials from the CacaoFIT network

Featured trial #1. Native timber-based cacao agroforestry systems in lowland Honduras

In 1986, framed in the cacao and agroforestry research program, FHIA established a network of 36 experimental plots (43 ha in total, ranging in size from 0.5 to 1.5 ha per plot) that combined 12–15 cacao varieties (density=1100 plants ha^{-1}) with 36 timber shade species (29 native species and seven exotic species) aimed at testing the agronomic and agroforestry performance of cacao timber-based agroforestry systems and delivering technical guidelines for cacao farming in humid-lowland Honduras (Figure 2). For over two decades, FHIA and partners have registered monthly data on cocoa yields and by-crops production, costs of agronomic inputs, income from harvested products, and the incidence of pests and diseases. Tree growth parameters (diameter and height) and shade tree phenology features (crown width and shading factors) were recorded annually. Research outcomes generated from this research trial were:

Agronomy outcomes

- The cacao production peak is exhibited between 13–17 years after planting, and attainable yields were in the range of 685 to 2250 kg ha^{-1} year^{-1}, 3X higher than the national average productivity (Figure 3). This finding confirmed that timber-based cacao agroforestry systems produce satisfactory yields comparable to that of leguminous shade trees.
- Over 20 years, frosty rot pot (*Moniliophtora roreri*) + black pod (*Phytohtora palmivora*) incidence ranged from 5 to 18%, demonstrating that the timely removal of infected pods is effective in reducing yield losses (Figure 3). More details are in Ramírez-Argueta et al., 2022. Mineral fertilization (15-15-15, 12 g/plant) applied annually in three equal doses and lime amendments applied yearly at a single dose of 0.5 t ha^{-1} year^{-1} is key to sustaining yields.
- The set of best practices for sustainable cacao yield over time devised from this trial was: (a) cacao pruning must be done twice a year following a 2.5 m plant high threshold, (b) weekly removal of diseased pots during production peaks and fortnightly during low harvest periods, and (c) fertilization and weeding must be performed at least three times a year.

Agroforestry outcomes

- Cacao yields were greater when tree cover and timber basal area were below 40% and 12 m^2, respectively. In line with the competitive allocation of the basal area model suggested by

FIGURE 2
Distribution of the 43 ha of timber-based cacao agroforestry systems across the CEDEC-JAS experimental site in La Masica, Atlántida, Honduras. Photo: FHIA 2020.

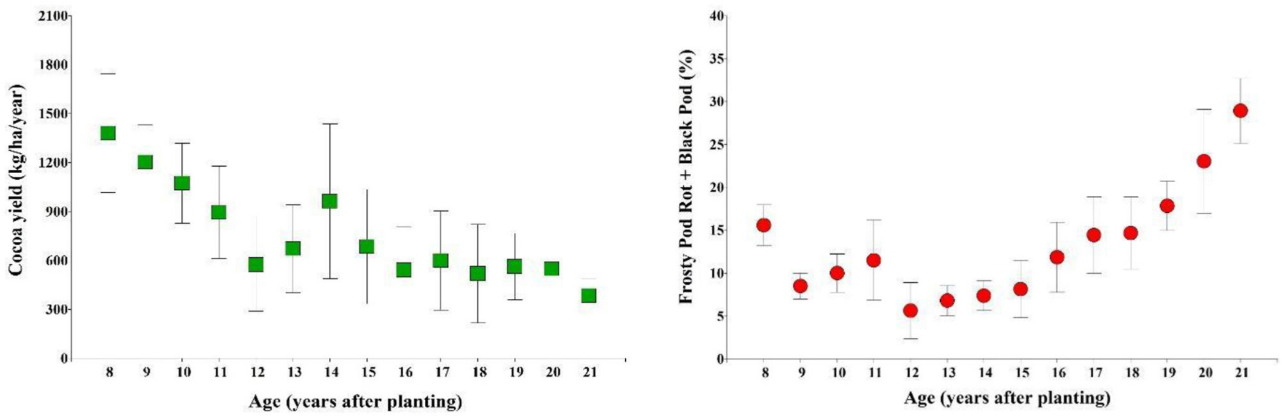

FIGURE 3
Cacao yield (green squares) and incidence of frosty pod rot + black pod (red dots) curves over 20 years in CEDEC-JAS, FHIA, La Masica, Atlantida, Honduras. Mean values and confidence interval across 12 plots.

Somarriba and López (2018a), this is key for the design and management of shaded cacao plots.

- The growth rates of 12 native timber species were promising (Ramírez-Argueta et al., 2022); the mean diameter was 2.4 cm year^{-1}, and the average tree height was 1 m year^{-1} (Figure 4). Most species reached the minimum harvesting diameter (30 cm) at the age of 13–15 years and gained, on average, 4.25 m^3 ha^{-1} year^{-1}. This finding confirmed that native timber species were suitable for cacao cultivation and that timber harvest at shorter timelines was feasible.
- *Dalbergia glomerata*, a native timber species, displayed an inverted phenology pattern: it loses foliage during the rainy season and retains it during the dry season. This unique phenological behavior is of great interest for cacao cultivation in areas with marked dry seasons, suggesting that the species could be incorporated into resilient agroforestry models.

Environmental/Ecosystem Services: Data has not been recorded/published yet.

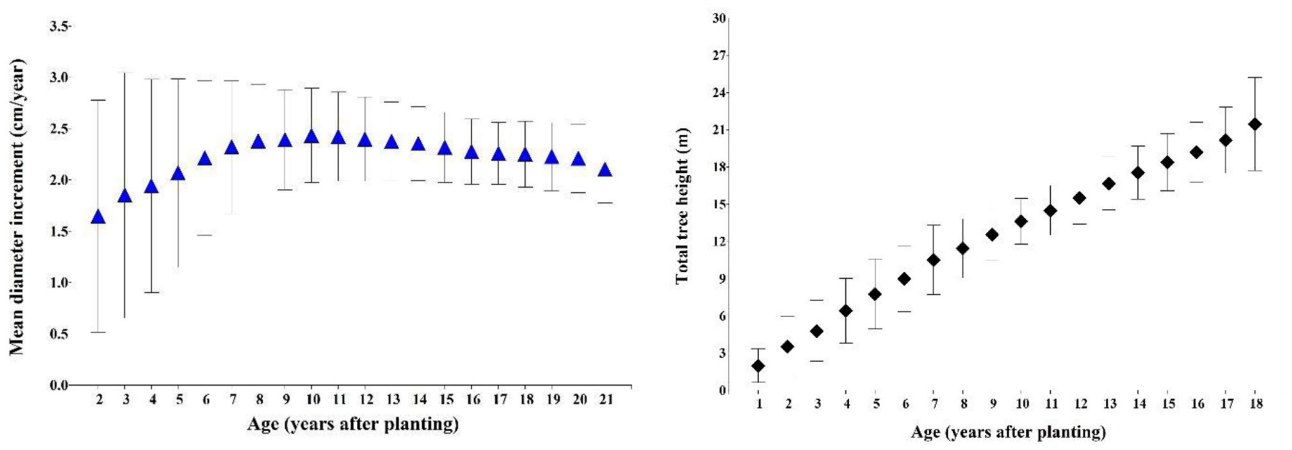

FIGURE 4
Growth rates of diameter (blue triangles) and total height (black diamonds) curves of 12 timber species in CEDEC-JAS, FHIA, La Masica, Atlantida, Honduras. Mean values and confidence intervals are shown.

Financial outcomes

- Total revenues registered were determined by the proportion of income provided by each component of the shaded system: cacao (45%), timber trees (45%), and plantain + *G. sepium* (10%). Thinning of timber trees might provide additional funds to farmers.
- After 22 years, farmers' incomes from timber-shaded cacao plots were in the range of U$1775 ha^{-1} year^{-1} to U$3300 ha^{-1} year^{-1}, depending on cacao and timber local prices.
- Establishment costs ranged from U$2,500–$$3,000 ha^{-1}, while maintenance costs varied from U$700-U$1000 ha^{-1} year^{-1}. Most cacao plots reached a positive economic balance four years (between five and six) after planting when incomes exceeded annual management costs.

Physiological features: Data were not recorded/provided.

Outreach: Over the last decade (2010–2020), a total of 7,993 people from 15 different countries have been trained by the CEDES-JAS staff, including 4,160 farmers, 1,612 students, and 2,220 technicians. Several planting designs for cacao cultivars have been provided to development projects, private investors, and national cacao programs. FHIA is an active member of the Cocoa Board in Honduras, providing technical advocacy and conducting collaborative applied research. Finally, annual technical reports have been published during the last decade (2009–2021) and are available at http://www.fhia.org.hn/html/Programa_de_Cacao_y_Agroforesteria.html.

Featured trial #2. Long-term systems comparison (SysCom) in the Sara Ana center for research and capacity development, Alto Beni, La Paz, Bolivia

Between 2008 and 2010, FiBL, in partnership with El Ceibo and ECOTOP, set up a network of seven ha of research plots aimed at comparing agroforestry systems and monocultures under both organic and conventional management. A fifth treatment included successional or dynamic agroforestry systems with no external inputs. Gross research plot size was 48 m × 48 m (2,304 m^2), while net plots were 24 m × 24 m (576 m^2). For all treatments, cacao and plantains were planted at a low density (625 ha^{-1}) (Figure 5). Since 2009, FiBL and partners have regularly registered data on yields of cocoa and by-crops, labor time, costs of agronomic inputs and income from harvested products/goods, tree growth, pests, and diseases, as well as the phenology of cacao trees, soil fertility, and shade canopy management. Research outcomes derived from the SysCom trial were:

Agronomy outcomes

- In monocultures, cocoa yields were ∼15% higher in conventional systems compared to organic ones (data from 2015 to 2020). This is likely due to the suboptimal amount and timing of nutrient delivery from compost, as well as nutrient competition with cover crops in organic systems. These findings suggest a more consistent organic fertilization plan.
- In agroforestry systems, cocoa yields were equal in organically and conventionally managed systems; however, yields were ∼40% lower than in monocultures. This is due to the slower growth and the limited light availability of cacao plants.
- Cocoa yields in all systems studied were clearly above the yields of many farmers in the region and can be increased up to 6-fold with the choice of locally adapted varieties compared to internationally known varieties (Niether et al., 2017) (Figure 6).
- With the application of good agricultural practices (e.g., frequent harvesting, removing infected cocoa pods, and regular pruning of cacao and shade trees), all cacao production systems experienced low total pest and disease incidence (Armengot et al., 2020).

Agroforestry outcomes

- Agroforestry systems have higher total system yields of all harvested products/goods (cocoa, plantains, bananas, other fruits/tuber crops) compared to monocultures, resulting in a substantially higher nutritional output compared to monocultures (Niether et al., 2020; Sauvadet et al., 2020; Rüegg et al., 2024, in preparation).

FIGURE 5
An aerial image of the SysCom long-term trial, where the five production systems are represented in different colors: conventional monoculture (CM, yellow), organic monoculture (OM, dark blue), conventional agroforestry (CA, light blue), organic agroforestry (OA, white), and successional agroforestry (SA, red) **(**photo by Marco Picucci, FiBL, https://www.fibl.org/en).

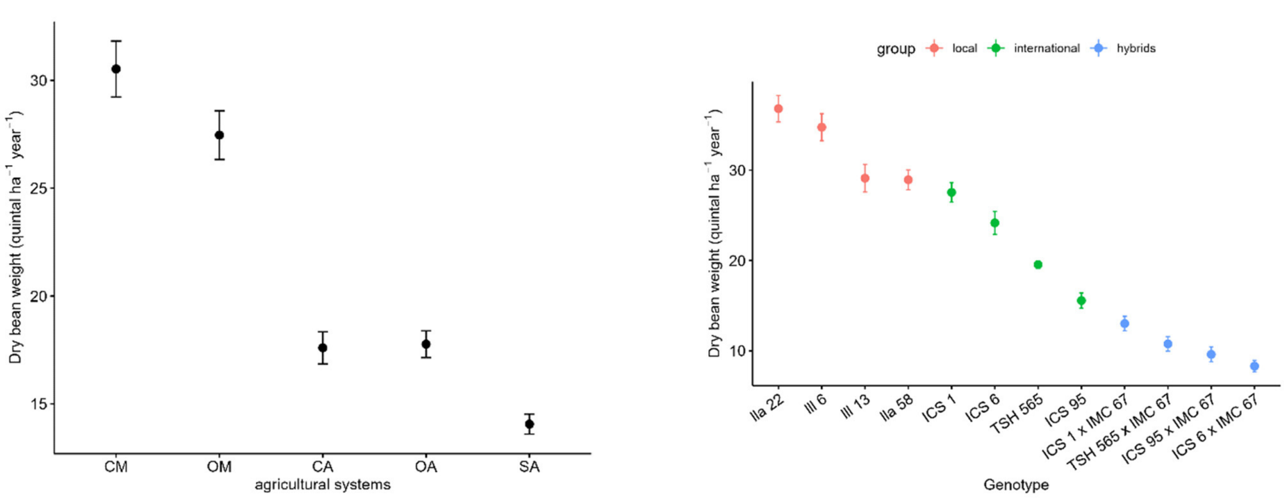

FIGURE 6
Mean cacao yields between 2018 and 2022 for the five agricultural systems **(left)** and genotype group regardless **(right)**. Bars represent standard errors. CM, conventional monoculture; OM, organic monoculture; CA, conventional agroforestry; OA, organic agroforestry; SA, successional agroforestry (Source: FiBL, 2023). Note: 1 quintal = 45 kg or 100 pounds.

- Although the fine roots from cacao and agroforestry trees overlapped and thus might compete, the roots of agroforestry trees explore deeper layers of the soil, with this complementary use of the soil leading to higher system yields and higher biomass production in agroforestry systems as compared to monocultures (Niether et al., 2019).
- Shade cover is dynamic; hence, its management across agricultural systems is key to maintaining satisfactory crop yields and reducing losses due to pest and disease pressure. In this trial, the recommended level of shade cover for acceptable cacao yields was 40%.

Environmental outcomes

- In cacao, conventional and monoculture systems use more energy from non-renewable resources (e.g., fuel and electricity) compared to organic and agroforestry systems (Pérez-Neira et al., 2020). Increasing the complexity of the system, agroforestry vs. monocultures resulted in higher biodiversity and conserved rare and native plant species (Marconi and Armengot, 2020).
- Agroforestry systems sequester up to three times more carbon in their biomass than monocultures (Schneider et al., 2017). At the same time, they buffer the negative effects of temperature peaks and heavy rainfall or drought (Niether et al., 2018). This microclimatic effect is also influenced by the pruning of shade trees (Niether et al., 2018).
- In agroforestry systems, regular pruning of trees, many of which are leguminous, enhances carbon and nitrogen cycling in the soil-plant system (Schneider et al., 2017).

Physiological features: Data has not been provided/published yet.

Outreach: The SuyCom trial supports numerous research and extension activities. To date, over 25 articles have been published in international journals, and ∼45 students from Bolivia and elsewhere completed their academic theses based on the work done in the trial. Sara Ana also offers courses on agroforestry design and management to dozens of farmers and technicians from Bolivia and Latin America. Around 1,000 individuals visit the site each year.

Featured trial #3. Agroforestry models for fine-flavor cacao and value timber in Colombia-Agrosavia

In 2008, Agrosavia established a research trial of 1.5 ha in two localities aimed at comparing the performance of international and local cacao clones shaded by native and exotic timber species. The trial was established under a randomized complete block design with nine treatments (nine cocoa genotypes) in a factorial design with three repetitions. Cacao was planted under abarco (*Cariniana piryformis*) and caucho (*Hevea brasiliensis*) trees in site #1 and under *C piryformis* and teca (*Tectona grandis*) in site #2. The selection of shade tree species responded to local preferences and market potential. Dasometric variables were measured for shade trees, cacao yields, and the incidence of monilia (*Moniliophthora roreri*) by cacao genotype. Data have been recorded for over 10 years per agroforestry combination, which has yielded several scientific and technical publications. Research outcomes devised from the two medium-term trials were:

Agronomy outcomes

- Cacao clones shaded by *C. piryformis* that showed the highest yield were TCS-19 and TCS-13 with 1.8 t ha^{-1} and 1.6 t ha^{-1} dry beans, respectively. Registered yields here were comparable to those of nearby commercial farms. The yields of the other seven cacao clones under *H. brasiliensis* and *T. grandis* were similar among them (0.5 to 0.75 t ha^{-1}) (Figure 7).
- The productivity of cacao genotypes registered in both study sites was 3x higher than the average national yield reported by FEDECACAO (2020).
- Overall, the lowest incidence of monilia (15% on average) was registered in cacao genotypes growing under *C. piryformis*; the least affected cacao genotypes were TCS-19 and TCS-13, with 5% and 8% affectation, respectively (Figure 8). The incidence of monilia registered under the remaining two shade species was similar and ranged from 15% to 25%.
- Cacao pruning twice a year, fortnightly removal of infected pods, and regular fertilization (450 g of N, P and K) $plant^{-1}$ $year^{-1}$ are key to sustaining cacao yields over time.

Agroforestry outcomes

- After 10 years, tree height growth rates were similar among the timber species evaluated. Nevertheless, *H. brasiliensis* grew taller (15.4 m), followed by *T. grandis* (14.5 m) and *C. piryformis* (14.1 m).
- The diameter growth rates of the three species were also similar. After a decade, *C. piryformis* reached 22.5 cm, followed by *T. grandis* (19.8 cm) and *H. brasiliensis* (19.3 cm) (Figure 9).
- Linear plating arrangements in both, instead of squared planting design, have proven to be effective in controlling wind speed, thereby mitigating monilia dispersion across the plantation.

Environmental outcomes

- The contributions of shade tree species to nutrient cycling differed between sites. In the Rionegro site, *C. pyriformis* trees provided 2,484 kg ha^{-1} yr^{-1}, cocoa trees deposited 1,730 kg ha^{-1} $yr^{-1,}$ and teak trees incorporated 1,306 kg ha^{-1} yr^{-1} as pruning residuals. The highest nutrient contribution was made by the cocoa-abarco shaded system (Rojas-Molina et al., 2017; Jaimes-Suárez et al., 2022).
- The carbon stocks of these agroforestry systems also differed between sites. Higher C storage was found in TCS-13 associated with *C. pyriformis* compared to TCS-19 grown under *T. superba*. Cocoa TCS01 under the shade tree *C. pyriformis* might have reduced carbon loss due to decreased respiration in non-photosynthesizing tissues (Carvalho et al., 2023).

Physiological features

- The photosynthetic rates differed among clones, shade tree species, and seasons. In the El Carmen site, cacao clones showed lower photosynthetic efficiency (4.75 µmol m^{-2} s^{-1}, 4.57 µmol m^{-2} s^{-1}) than those growing in the Rionegro site. In Rionegro, cacao genotypes shaded by abarco trees registered a statistically higher photosynthetic efficiency rate (5.39 µmol m^{-2} s^{-1}) as compared to that of cacao clones shaded by teak trees (5.04 µmol m^{-2} s^{-1}).
- At both sites and across clones, photosynthetic efficiency rates were consistently lower during the dry season compared to the rainy season. Clones with higher photosynthetic rates were TCS 19, SCC 53, SCC 83, and TCS 19 with 5.63, 5.09, 5.3, and 4.95 µmol m^{-2} s^{-1}, respectively. For more details, review the work by Agudelo-Castañeda et al. (2018).

FIGURE 7
Frontal view of the cacao + *Cariniana piryformis* (Abarco) agroforestry systems in El Carmen de Chucurí, La Suiza, Santander, Colombia (Photo: Montealegre Bustos et al., 2021).

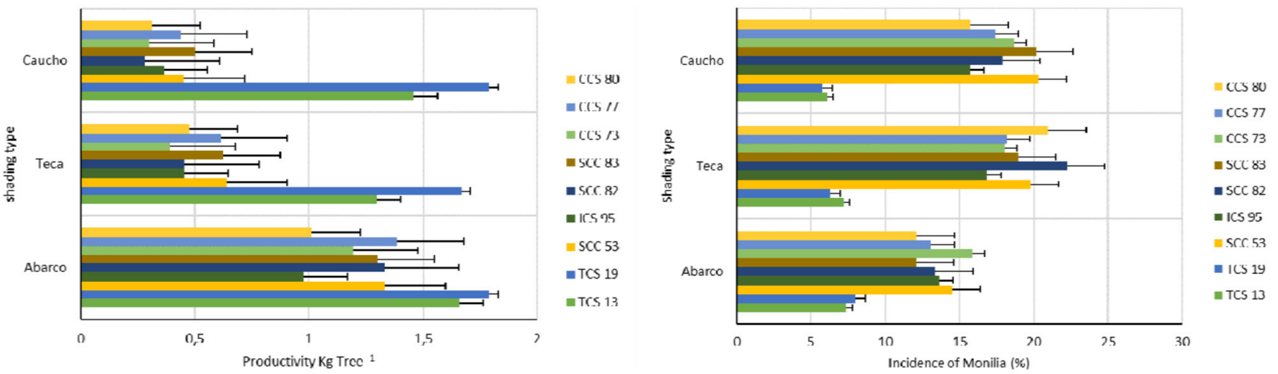

FIGURE 8
Productivity (kg tree^{-1}) and incidence of *M. roreri* of nine cocoa clones grown under timber shade species in the research site, Santander, Colombia (from Agudelo-Castañeda et al., 2023).

- Remarkably, the association between *C. pyriformis* and the TCS01 cocoa genotype rendered higher leaf-level water use efficiency and greater total carbon storage compared to the combination of *T. superba* with TCS19. For more information, see Leite Carvalho et al. (2023).

Financial outcomes: No published yet. See Montealegre Bustos et al. (2021).

Outreach: Between 2017 and 2022, Agrosavia trained ~6,000 people (90% farmers, 6% academics and students from national universities and technical colleges, and 3% extensionists. Training is usually delivered via workshops (42%), professional courses (30%), field discovery days (18%), and other means (10%). Agrosavia is part of the National Agricultural Science and Technology System, which defines policies in the sector and serves to leverage research resources. All scientific and technical publications can be found at https://www.agrosavia.co/biblioteca.

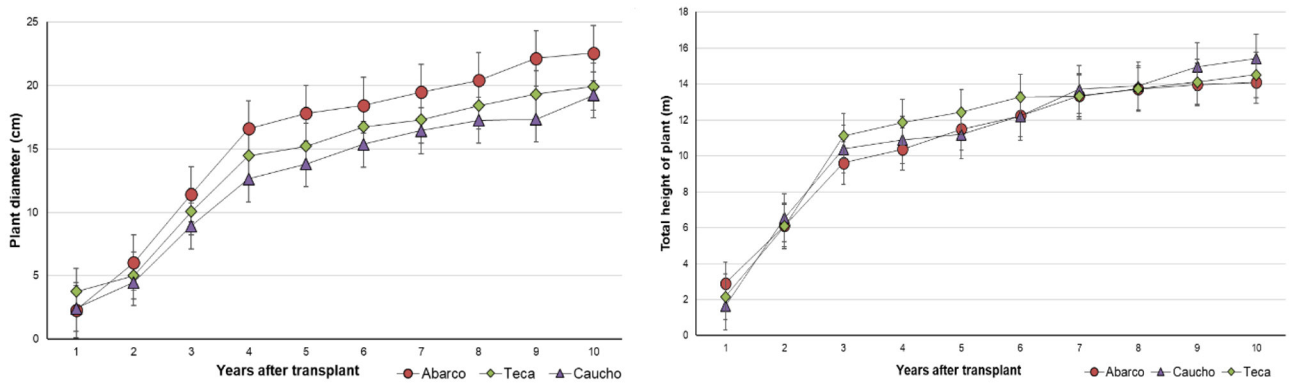

FIGURE 9
Truck diameter (DBH-cm) and total height (m) registered for Abarco (*C. piryformis)*, Teca (*T. grandis*), and Caucho (*H. brasiliensis*) over a 10-year period, Santander, Colombia.

Featured trial #4. Yield and physiological performance of cocoa clones under different agroforestry systems in the Colombian Amazon

In 2014, the University of the Amazonia set up the Macagual Amazon Research Center, Caquetá department, in western Amazonia, comprising 32 ha of cacao-shade tree combinations (AFS) under a randomized complete block design with five replications. In each block, treatments were arranged in strip plots. One strip contained the four AFS, while in the strip perpendicular to the AFS, the clones were randomly planted. The average plot size was 1.5 ha, shaded by several species, including Huito (*Genipa americana*), Caracoli (*Anacardium excelsum)*, Abarco (*Cariniana pyriformis)*, and Capiron de Vega (*Calycophyllum spruceanum*). In each block, shade trees were planted at 12 x 12 (70 trees ha^{-1}), and cacao was planted in a north-south direction at 3.5 × 3.5 m (816 plants ha^{-1}). Shade tree species were selected by local farmers based on leaf traits (leaf size, N fixation), canopy traits (crown size and phenology,) and value. The overall goal of the long-term trial is to evaluate the adaptability of both national and international clones shaded by different AFS and under Amazonian conditions. Data collection was carried out from 2018 to 2022, and key research outcomes from this trial were as follows:

Agronomy outcomes

- Differences have been found regarding agronomic variables at the genotype level; clones CCN-51, FEAR-5, FEC-2, and FGI-4 registered the highest values of pod and seed index.
- During the first two years of production (2018–2020), clones FEAR-5, FGI-4, and FLE-3 yielded ≥25 pods $tree^{-1}$ $year^{-1}$ and clones FEC-2 and EET-8 loaded ≤10 pods per $tree^{-1}$ year $^{-1}$.
- Total yield per clone ranged between 0.40 and 2.40 kg/year/tree. Clones CCN-51, FGI-4, LUK-40, and ICS-60 showed the highest value, while FTA-2, ICS-39, EET08, and LUK-50 were the lowest-yielding clones (Figure 10).
- The incidences of diseases varied widely across clones; monilia affectation ranged between 0 and 80%, while phytophthora ranged between 0 and 70%. The clones less affected by both diseases were FSA-13, TSH-565, ICS 1, IMC 67, ICS 95, and FSA-12 (Figure 11).

Agroforestry outcomes

- Regarding the effects of the agroforestry system on yields, cacao clones growing under *Anacardium excelsum* and *Genipa americana* showed the highest yield (Figure 12).
- Eight years after planting, shade species reached a diameter between 5.6 and 23.4, crown area varied from 3.0 to 66.5 m^2, the total tree height was in the range of 4.2–9.2 m, and commercial tree height was from 2.3 to 4.4 m.
- Above-ground carbon accumulation in the control plot (full sun cacao) reached 6.4 tons compared to 16.7 tons on shaded plots. Soil carbon at 0–10 cm depth reached 24.3 g kg^{-1} in cocoa plots shaded by *G. americana* trees, compared to 18.9 g kg^{-1} in full-sun cocoa plots.
- The contribution of litterfall in shaded plots reached 6.5 Mg ha^{-1}, and the decomposition rate of 50% of the litterfall ranged from 27 to 65 days.

Physiological outcomes

- The performance of the photosynthetic apparatus under full-sun conditions was higher for clone ICS-95, which showed the highest values of Vc_{max} and J_{max} (Suárez Salazar et al., 2021).
- Under the Amazonian region, which is characterized by high cloudiness, the rate of net carbon assimilation, RuBisCO carboxylation, and RuBP regeneration rates were higher in cacao trees under full sun compared to those in shaded conditions. (Suárez Salazar et al., 2018b).
- The microclimatic variables in shaded conditions are significantly modified compared to full-sun cocoa plots (Suárez Salazar et al., 2021), which, in turn, affects sap flow. The maximum sap flow average values were 0.27 ± 0.03 L h^{-1} at daytime and 0.0300 ± 0.0023 L h^{-1} at night.

Environmental outcomes

- In this site, cocoa agroforestry systems were planted on degraded pasture areas, and after three

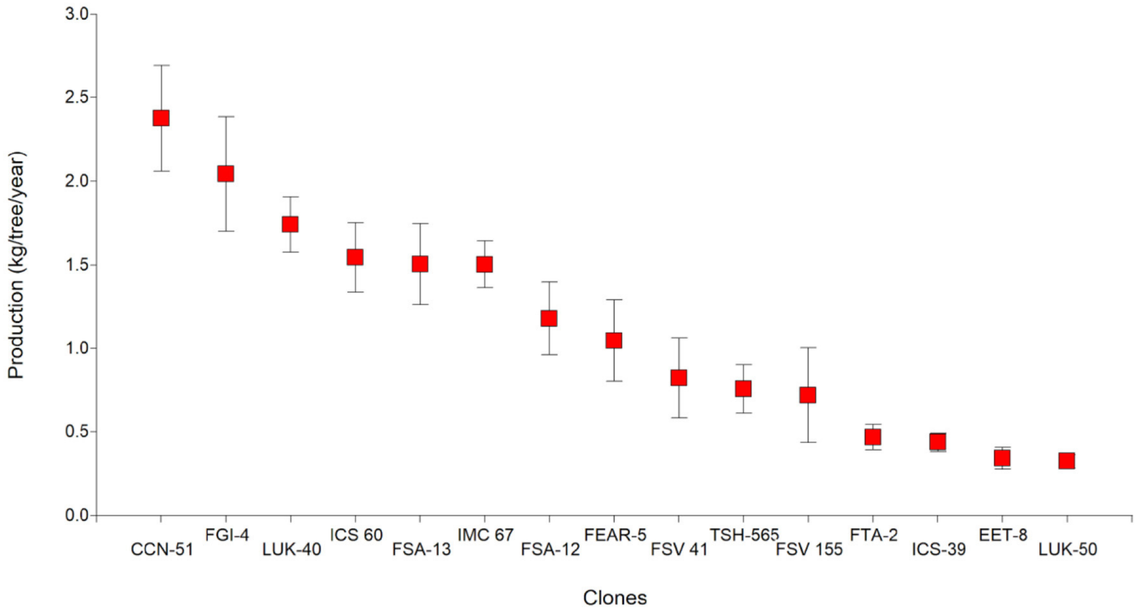

FIGURE 10
Early yield (kg tree^{-1} year^{-1}) of 15 cacao clones being tested under different agroforestry systems in the CIMAZ experimental site, Amazonia, Colombia.

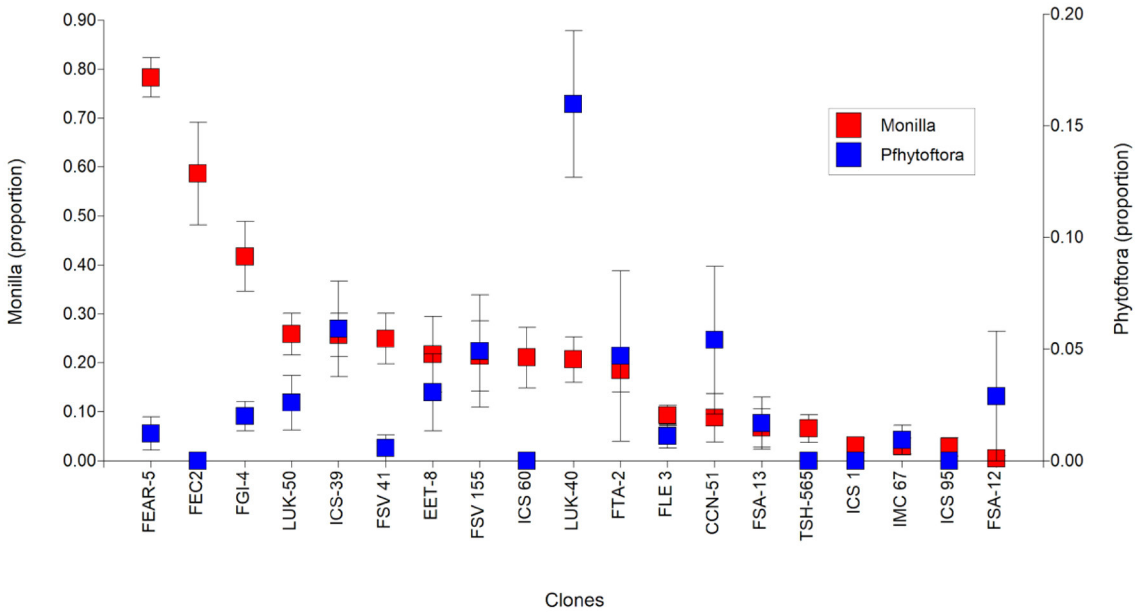

FIGURE 11
Proportion of pods infected by frosty pod rot and black pod among 15 clones being tested in the CIMAZ experimental site, Amazonia, Colombia.

years of evaluation, the GISQ increased from 0.21 to 0.59.

- Macrofauna populations of the Isoptera order increased notably, which, in turn, enhanced the amount of soil aggregates and therefore carbon stability.
- Regarding soil carbon quality, the highest proportion of C_{VL} (very labile carbon, 43.5%) was found under cocoa trees, followed by C_{NL} (non-labile carbon) with 28.2%, and in small proportion, labile carbon (C_L, 15.8%) and less labile carbon (C_{LL}, 12.3%).

Financial outcomes: They have not been recorded/provided yet.

Outreach: The research trial has served as a living lab to conduct applied research, including one doctoral thesis, five master theses, and seven undergraduate research projects. A technical

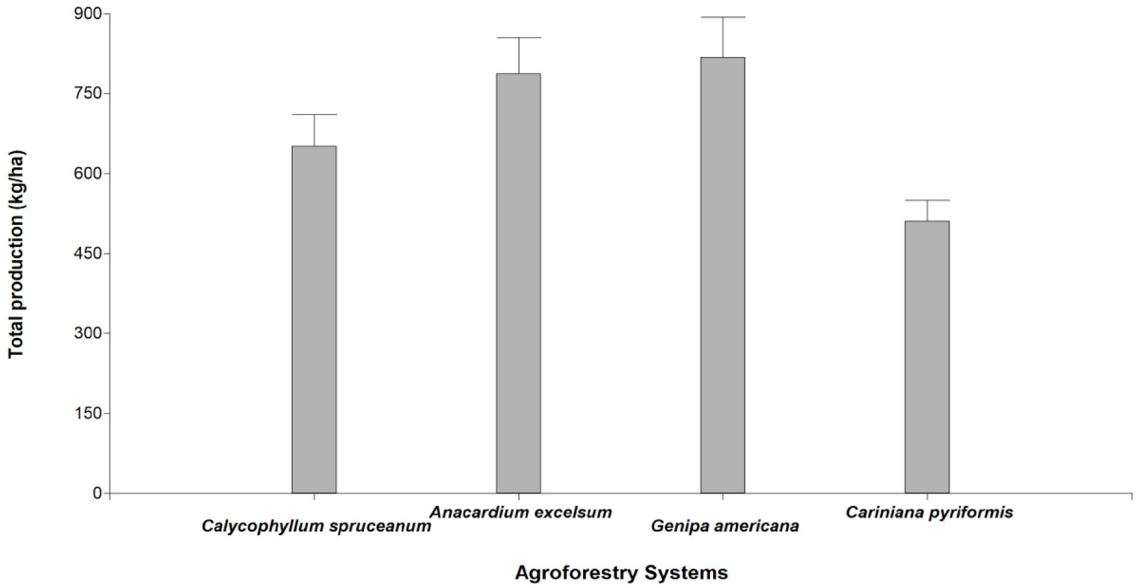

FIGURE 12
Accumulated cacao yields (2018–2022) under four different agroforestry systems in the CIMAZ experimental site, Amazonia, Colombia.

course on shaded cacao cultivation is offered annually, where 200 farmers and students have been trained.

Featured trial #5. Design, production, and environmental value of cacao cultivation models in the Atlantic forest and Amazon biomes in Brazil

Between 2004 and 2010, the CEPLAC Ministry of Agriculture, Livestock, and Food Supply partnered with private actors and organized farmers to implement at least eight different cacao-based agroforestry models across the main production regions in Brazil (MAPA-CEPLAC, 2011) (Figure 13). At the farm level, each cultivation model performed differently in terms of cacao yield, shade canopy products, and, hence, financial revenues to farmers (Table 3). At the landscape level, these cacao cultivation models created an interconnected agroforestry mosaic with natural forests that can be considered climate-smart agriculture, balancing biodiversity protection and commercial production (Schroth et al., 2016a,b). The adoption potential of a given cultivation model is dictated by the productivity and profitability achieved over time. Design features and economic considerations with an emphasis on the yields provided by cacao and the consort of associated shade species are presented elsewhere (Gama-Rodrigues et al., 2021).

The establishment of several cacao-based agroforestry systems by CEPLAC/MAPA considered four key design and management aspects for sustainable agriculture:

a) Technical efficiency: It allows for more efficient control of cacao diseases since crop models implemented use proven practices to increase productivity.
b) Social importance: Given that mechanization is not entirely feasible, cacao farming should use fixed labor while providing long-term sources of income for rural families.
c) Economic sustainability: Projects were usually developed in small modules (≤5 ha) and relied on the family workforce to reduce production costs and withstand price fluctuations.
d) Ecological coherence: Crop models should offer several ecological benefits at the farm and landscape levels, both of which are of great relevance to the primary sector across the Amazon.

Section #3. Learning from the CacaoFIT network

The genetic pool of cacao, cultivation models, and a pallet of agro-environmental information throughout the CacaoFIT network provide fruitful insights to several actors along the value chain. New LAC farmers aiming at simultaneously producing acceptable cacao yields and timber at different time frames might review both FHIA and CATIE trials in humid-lowland Honduras, Costa Rica, and Panama, respectively (Somarriba and Beer, 2011; Ramírez-Argueta et al., 2022). Other meaningful insights from timber-based agroforestry systems are also well documented in Venezuela (Jaimez et al., 2013), Colombia (Agudelo-Castañeda et al., 2018), and Brazil (Gama-Rodrigues et al., 2021), all experimental sites included in this study. Moreover, farmers interested in managing cacao plantations under organic or conventional systems can rely on robust technical and scientific support from the SysCom trial in Alto Beni, Bolivia (SysCom Trial), and several medium-sized trials across Colombia (Agrosavia, Fedecacao, Universidad de la Amazonia), which tested the tree growth of valuable timber species and novel cropping systems, proving suitable for both small and medium-scale farmers.

LAC farmers searching for innovative methods of growing cacao under a diversified shade canopy maybenefit from the insights gained through the CIRAD-led CacaoForest network

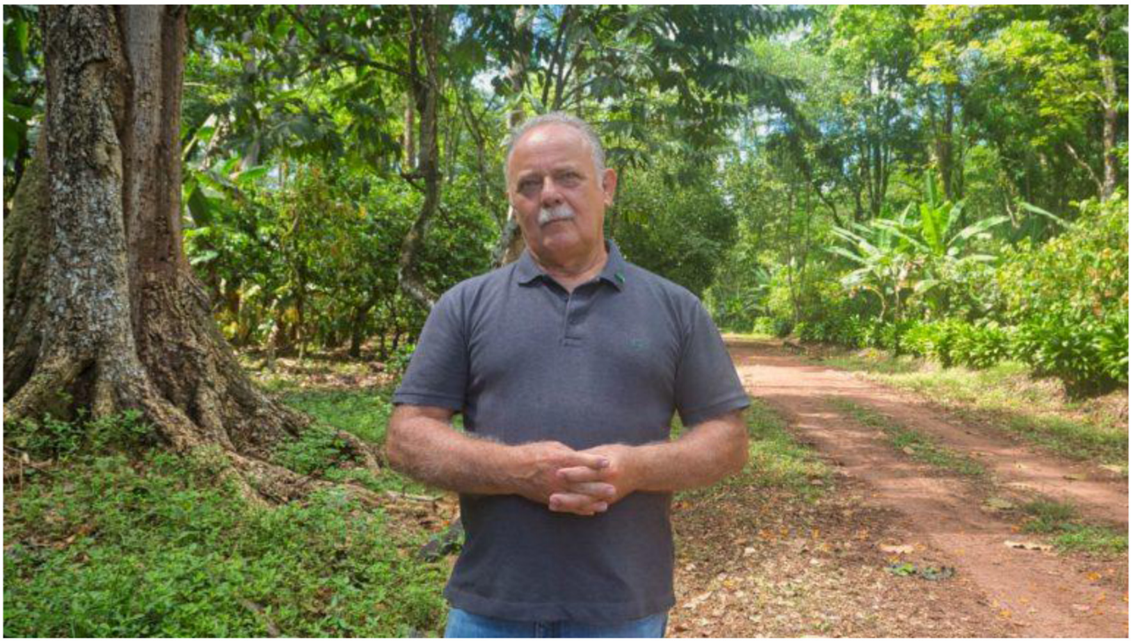

FIGURE 13
Dr. Fernando Texeira Mendes, a researcher at the Executive Commission for Cacao Cultivation Planning (CEPLAC), in the Estação de Recursos Genéticos José Haroldo, in Marituba, Pará, the world's largest cacao genebank, which hosts more than 53,000 cacao plants. Image by Miguel Pinheiro.

TABLE 3 Planted area and main design features of cacao cultivation models tested by CEPLAC-MAPA in the Atlantic and Amazon biomass in Brazil.

Agroforestry models (AFS)	Cultivated area (ha) across the Atlantic and Amazon biomes	Cacao density (plants/ha)	Shade density (trees/ha)	Dominant species	Yields (kg/ha) and timber*
Cacao + Forest Trees	This AFS has been used since 1973 in Rondônia and currently covers ~9,000 ha and 140,000 ha in the state of Para.	1,111	70 and 256 bananas	*Schizolobium amazonicum, Tabebuia heptaphylla, C. alliodora, Bagassa guianensis B. excelsa and S. macrophylla*	1,200/55 m^3 ha^{-1} of timber
Cacao + peach palm + timber	This AFS occupies ~1,245 ha in the states of Mato Grosso and Para.	1,145	575 peach palms + 84 timber trees	*B. gasipaes, C. allidora*	1,170/45 m^3 ha^{-1} of timber
Cacao + coconut palm + yellow mombin	Approximately 100 ha of cacao under this AFS in the State of Amazonas	740	123 coconut and + 25 yellow mombin	*Cocos nucifera* + *Spondias mombin*	1,250/
Cacao + coffee (*C. canephora*) + teak	This AFS occupies nearly 1,765 ha in the states of Amazonas, Mato Grosso, and Spirito Santo.	945 cacao + 1,062 coffee	117 teak	*T. grandis* + *Coffea canephora*	825/25 m^3 ha^{-1} of timber
Cacao + Teak	This AFS currently covers ~3,600 ha in the States of Bahia and Para.	885	258 peach palms and 64 forest trees	*B. gasipaes and T. grandis*	925/180 m^3 ha^{-1} of timber
Cacao + coconut + Andiroba	This model currently covers ~600 ha in the States of Spirito Santo and Rondônia.	833	800 coffee, 33 coconut and 78 andirobas	*C. nucifera* + *C. guianensis*	820
Cacao + Rubber tree	The estimated area under old rubber plantations (>20 years) in Bahia is currently ~11,000 ha	833	830 rubber + 144 madreado trees.	*H. brasilensis* + *G. sepium*	850–1,200
Cacao + Erythrina trees + banana	Currently covers an area of nearly 80,000 ha and was implemented by CEPLAC in the 1960s.	1,111	1111 bananas and 25 Erythrina trees	*Erythrina* sp. + temporal shade provided by *Zea mays* and *Manihot esculenta*	780–900

Sourced from Gama-Rodrigues et al., 2021.
*Yields recorded up to six years after planting. Source: Gama-Rodrigues et al. (2021).

(Notaro et al., 2020, 2021) and the ongoing regional KoLFACI project co-executed by CATIE and several national research institutions (KoLFACI project). Both research networks have yielded meaningful information on diversification strategies, income generation from cacao and agroforestry, and climate-smart agricultural practices. Moreover, farmers planning to renovate or rehabilitate their aging and low-productive cacao fields in a cost-effective manner can review the experience gained by ICT in Peru, where three different renovation pathways (the Improved Native Agroforestry System, the Improved Traditional Agroforestry System, and the Cover Crop System) successfully improved crop yields and soil fertility under organic and conventional regimes (Figure 14). Finally, farmers and investors interested in novel shaded cacao plots could explore the array of agroforestry systems documented across Brazil (Gama-Rodrigues et al., 2021), Mexico (López-Cruz et al., 2021), and Central America (Deheuvels et al., 2012; Cerda et al., 2014).

Development projects such as www.mocca.org, Alianza Cacao El Salvador, Proyecto REVICACAO, private investors including *12T*ree, Ritter Sport-El Cacao, Cacao Oro, and Andean Cocoa, and sectorial platforms, namely SICACAO, ALCACAO, and Climate Smart Cacao, have benefited from the experience documented within the CacaoFIT network. The ICT and Agrosavia research sites generated key inputs and technical guidelines to support nationwide cacao projects (Cocoa Alliance Peru) and Cacao for Peace. Capacity building, dissemination of training materials, sharing findings in forums and seminars, and producing scientific publications were also pivotal in the CacaoFIT network.

The research agenda and outreach from the CacaoFIT network

CacaoFIT's long-term vision is to generate science-based knowledge and technical guidelines for sustainable cacao cultivation across LAC. However, several research gaps were evident from the CacaoFIT research agenda assessment. Agronomy research questions are being addressed by most research trials (specifically linked to cacao growth and yields and the overall incidence of pest and disease under shaded models), while other key topics are under-examined aspects of cacao cultivation. For instance, the dynamic of pod load vs. cacao plant architecture, the effects of pruning regimes (intensity and frequency) on yields (Orozco-Aguilar et al., 2021; Jaimez et al., 2022; Goudsmit et al., 2023) and the allocation of basal area models (Somarriba and López, 2018a) were found to be seldom researched (Nygren et al., 2013; Heming et al., 2022; Schmidt et al., 2022). Exploring the "crowding effects" of cocoa trees and neighboring trees on the per-plant yield will generate more nuanced advice for best practices in planting density (Wibaux et al., 2017; Cilas and Bastide, 2020; Saj et al., 2023). Below-ground interactions such as fine root dynamics, root volume/biomass and exploration profiles were other topics under-researched within the CacaoFIT network.

Agroforestry-related topics such as the effects of shading factors and tree functional traits (Gagliardi et al., 2020, 2021, 2022, 2023; Isaac et al., 2024) on pathogen dynamics (Leandro-Muñoz et al., 2017; Avelino et al., 2020), rainfall partitioning, and microclimate modificationwere still under-researched topics, especially in comparison to coffee agroforestry trials (Padovan et al., 2015; Abdulai et al., 2020). The SysCom trial in Alto Beni, Bolivia, and the CIMAZ research center in Ecuadorian Amazonia were the only research teams exploring such cacao-shade canopy interactions (Niether et al., 2019, 2020; Armengot et al., 2020, 2023; Hernández-Nuñez et al., 2024). The influence of historical weather and microclimate conditions on yields and the dynamics of pests and diseases is an unexplored yet highly pertinent research issue within the CacaoFIT research agenda. Key environmental services at both farm and landscape levels have been studied by several members of the CacaoFIT network, mostly focused on carbon stock and sequestration potential, litter decomposition, and nutrient cycling. However, soil macrofauna, soil moisture/infiltration, pollinator abundance and diversity, and local/migratory birds were studied to a lesser extent (Toledo-Hernández et al., 2020; Ocampo-Ariza et al., 2024). The restoration potential of shaded cacao plots was not a top-ranked topic in the CacaoFIT research agenda (Schroth et al., 2017; Harvey et al., 2021; Fremout et al., 2022; Bennet et al., 2023).

The study of cacao plant physiology and its interactions with associated trees were minimally explored within the CacaoFIT network. Notable research on this topic has been conducted at the experimental site in Merida, Venezuela, and led by the University de Los Andes (Araque et al., 2012; Ávila-Lovera et al., 2016). Nowadays, the experimental trials located at CIMAZ and Agrosavia, both from Colombia, are levering the topic with experimental and modeling work (Suárez Salazar et al., 2018a; Jaimes-Suárez et al., 2022; Carvalho et al., 2023). The remaining CacaoFIT research trials fall short in this regard, presumably due to the lack of instruments, software, and skilled staff. Topics such as rehabilitation or renovation costs and technical guidelines to do so, although needed in the region (Dalberg, 2015; Somarriba and López, 2018b; Riedel et al., 2019), were seldom evaluated. Although key for decision-making and accessing credits, the financial performance of cacao cultivation models was the least researched or published topic within CacaoFIT. This might be a warning call for all CacaoFIT members to agree on a set of key performance indicators to better communicate results to value chain actors. Finally, farmer outreach was strong and dynamic among a few CacaoFIT members, where several actors were trained, technical publications were delivered, and capacity-building spaces were offered. Large-scale dissemination of research findings from the CacaoFIT trial into farmers' hands and university curricula is a much-needed task of this consortium.

The way forward

This dynamic context of cacao cultivation in LAC poses social, economic, and environmental challenges to those in charge of knowledge generation. The delivery of cost-effective technical guidelines for thousands of cocoa farmers is essential.In this study, we documented the novel knowledge generated and published by CacaoFIT members, yet we understand that to properly address the industry challenges, only a coordinated effort by all stakeholders can ensure cocoa profitability and sustainability (Shapiro and Rosenquist, 2004). Here, we identified five key actions to strengthen

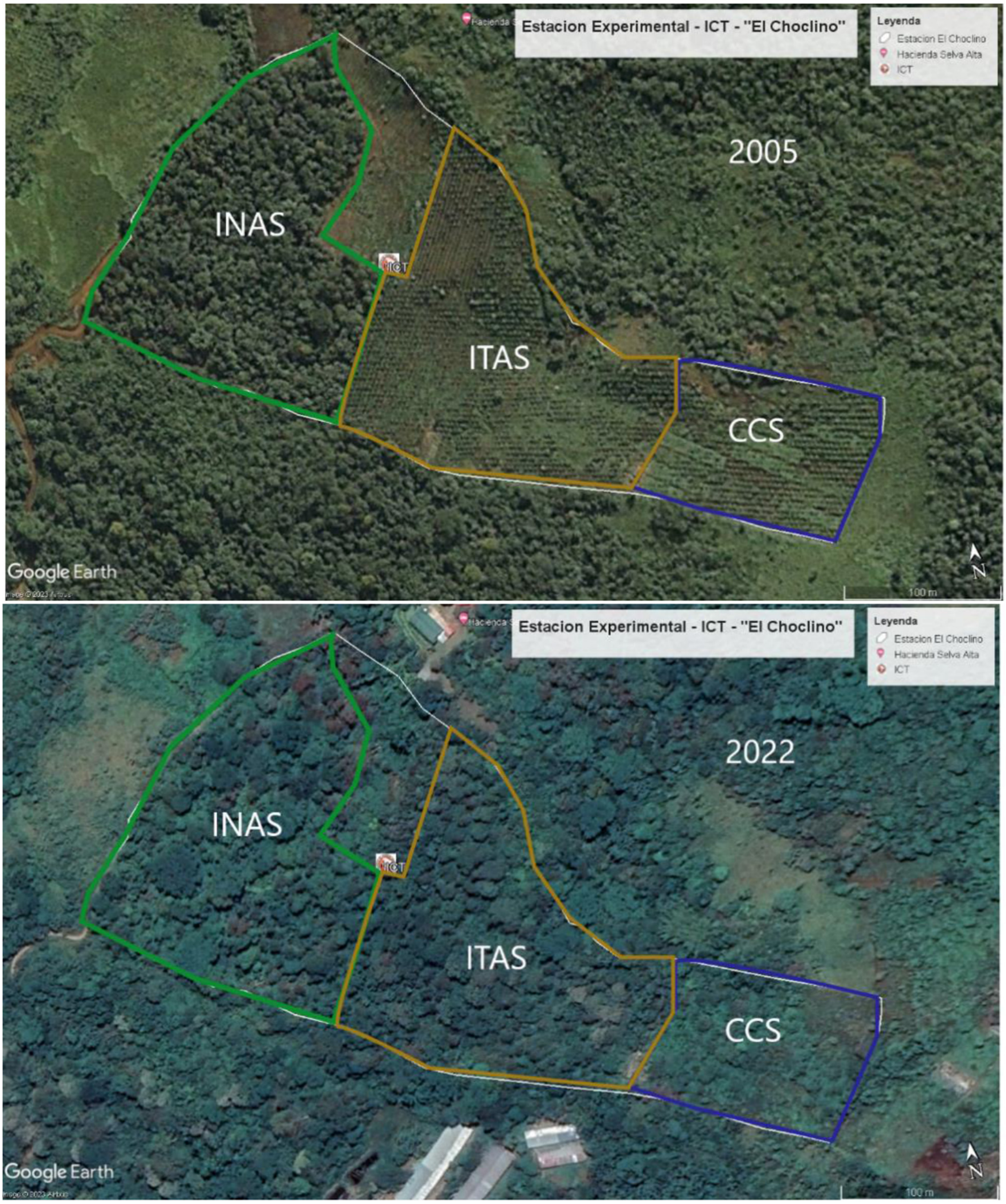

FIGURE 14
Evolution of agroforestry systems established at "El Choclino" research center, ICT, Tarapoto, San Martin, Peru: Improved Native Agroforestry System (INAS), Improved Traditional Agroforestry System (ITAS), and Cover Crops System (CCS) with different cacao genotypes in the Peruvian Amazon. Photo by Arévalo-Hernández et al. (2019).

the research agenda, foster collaboration among the CacaoFIT network, seek alliances between CacaoFIT and third parties, better connect with peers in the global south, and deliver mainstream communication and outreach.

1. **Link and strengthen the research agenda with global research platforms:** CacaoFIT trials and affiliates could be better connected to at least five global research platforms linking cacao farming with sustainability standards: Globalagroforestrynetwork, Agroforesta, Cacaonet, and the Smithsonian Institute. Stronger interaction between CacaoFIT members and international cocoa platforms such as the European Cocoa Association and Nitidae in Africa, INCOCOA, would also be mutually beneficial. Partnering with these platforms might facilitate research protocol sharing, splitting equipment costs, and incorporating software to strengthen research gaps on physiology and the financial performance of shaded cacao.
2. **Collaboration among CacaoFIT members to co-design research projects:** Members of the CacaoFIT network, especially those from South America (e.g., Agrosavia, U. Amazonia, and Fedecacao in Colombia, FiBL-Ecotop in Bolivia, Universidad de Manabi and INIAP in Ecuador, and ICT in Peru), have well-known experimental sites and skilled staff who may collaborate on future research proposals to better respond to national or specific contexts and challenges faced by the cacao sector. Some relevant research funds available are the Fontagro platform, the BID-Lab (https://bidlab.org/es), the Foundation for Food and Agriculture Research (https://foundationfar.org/), the World Cocoa Foundation, ICCO (https://www.icco.org/), and other government-led funds in each country.
3. **Public-private partnerships (PPP):** the existence of major chocolate industry players and private investors in several cacao production countries in LAC is a great opportunity for partnerships and interconnected research missions. Some key actors are Hershey's and Ecom Trading in Mexico (https://www.ecomtrading.com/mexico/), MARS-La Chola in Ecuador (https://www.mars.com/, 12Tree in Guatemala, Panama, Colombia, and the Dominican Republic (https://www.12tree.de/portfolio), Ritter Sport (https://www.ritter-sport.com/el-cacao), and CacaoORO in Nicaragua (https://cacaooro.com/) and Fundo Tamshi in Peru (https://www.tamshicacao.com/home-english), among others. Some topics overlooked in the research agenda of CacaoFIT could be addressed via PPP. These include (a) the survival pod curve for improving yield forecasting methods, (b) links between the length of productive tissue and pruning on tree pod load, (c) breeding new varieties/clones for low cadmium accumulation, (d) screening for new cultivars that are drought and flood-tolerant, and (e) documenting cost-effective strategies for renovation/rehabilitation interventions.
4. **Technical advocacy and training with global South actors**: West and Central Africa (WCA) is currently responsible for 70% of world cocoa production, with an annual output of 3.5 million tons (Hütz-Adams et al., 2022). Over 6 million ha of cocoa are cultivated mainly in open-sun plots or under simple shade canopies (Asare and Anders, 2016; Somarriba et al., 2023). Agroforestry is now widely promoted in cocoa cultivation in WCA to achieve environmental benefits and rural family livelihoods (Asare et al., 2014; Somarriba et al., 2023; Tscharntke et al., 2022; Sonwa et al., 2020). Therefore, the experience accumulated in LAC, and particularly the plethora of cocoa agroforestry systems within the CacaoFIT network, can be used for capacity building and to support the formulation and implementation of sound policies and cacao-agroforestry development projects. Integrating the novel knowledge, technical guidelines, and set of practices devised by CacaoFIT is crucial to achieving the outcomes committed to by global initiatives such as the Cocoa and Forests Initiative.
5. **Pan-institutional communication and outreach for** the production of scientific knowledge from the CacaoFIT network spread over a broad range of topics via scientific papers, technical manuals, fact sheets, and videos. Research outputs need to be organized and disseminated in ways that are most meaningful in supporting sectoral decision-making in both LAC and WCA. Several national and regional cocoa boards, such as Sicacao, Alcacao, APPCacao, Anecacao, and Fedecacao, require data and guidance to better inform the strategic planning of the cocoa industry, certification bodies, and policymakers. Research outcomes from the CacaoFIT network should also be incorporated into the curricula at the university and technical levels to engage youth and women. This will ensure the vitality of the industry with new generations of cacao growers.

Conclusion

CacaoFIT is an active network of medium- to long-term trials acrossLAC that tested several cultivation systems, generated knowledge, validated best practices, and delivered recommendations for farmers, cacao boards, development projects, investors, academia, and decision-makers. Gaps exist in the research agenda of CacaoFIT, mainly concerning cocoa physiology, environmental services, and the financial performance of shaded agroforestry systems. Thus, partnering with academic institutions and private actors in the global south might level up these research topics. CacaoFIT members must better connect to share data, methodologies, and protocols, standardize the data collection process, and formulate joint projects to enhance research outcomes from the network. Greater dissemination of CacaoFIT's research outcomes into academia, formal training, and advocacy by development agencies are required, which, in turn, will motivate public-private cooperation and funding. Finally, the CacaoFIT network has generated ample data and technical guidelines to support agroforestry projects and capacity building in the global south.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

The individual(s) provided their written informed consent for the publication of any identifiable images or data presented in this article.

Author contributions

LO-A: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition, Validation. AL-S: Conceptualization, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, Investigation, Supervision. RC: Writing – original draft, Writing – review & editing. FC: Data curation, Formal analysis, Validation, Writing – original draft, Writing – review & editing. OR-A: Writing – review & editing, Writing – original draft. JD: Writing – review & editing, Writing – original draft. JS: Writing – original draft, Writing – review & editing. JR: Writing – original draft, Writing – review & editing. SS: Writing – original draft, Writing – review & editing. JM: Writing – original draft, Writing – review & editing. US: Writing – original draft, Writing – review & editing. AM: Writing – original draft, Writing – review & editing. JRM: Writing – original draft, Writing – review & editing. YJ: Writing – original draft, Writing – review & editing. EBD: Writing – review & editing, Writing – original draft. GA: Writing – original draft, Writing – review & editing. OD: Writing – original draft, Writing – review & editing. EBS: Writing – original draft, Writing – review & editing. JG: Writing – original draft, Writing – review & editing. RJ: Writing – original draft, Writing – review & editing. MB: Writing – original draft, Writing – review & editing. SR: Writing – original draft, Writing – review & editing. JP: Writing – original draft, Writing – review & editing. AA: Writing – original draft, Writing – review & editing. LS: Writing – original draft, Writing – review & editing. MS-M: Writing – original draft, Writing – review & editing. CA-H: Writing – original draft, Writing – review & editing. EA: Writing – original draft, Writing – review & editing. LP: Writing – original draft, Writing – review & editing. AG-R: Writing – original draft, Writing – review & editing. EG-R: Writing – original draft, Writing – review & editing. AK: Writing – original draft, Writing – review & editing. ESM: Writing – original draft, Writing – review & editing. PU: Writing – original draft, Writing – review & editing. GR: Writing – original draft, Writing – review & editing. AH: Writing – original draft, Writing – review & editing. PA: Writing – original draft, Writing – review & editing. OD: Writing – original draft, Writing – review & editing. OA: Writing – original draft, Writing – review & editing. GP: Writing – original draft, Writing – review & editing. LT: Writing – original draft, Writing – review & editing. CC: Writing – original draft, Writing – review & editing. MW: Writing – original draft, Writing – review & editing. FT: Writing – original draft, Writing – review & editing. ES: Writing – original draft, Writing – review & editing.

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Conflict of interest

LO-A was employed by CATIE as Regional Tropical Agroforestry Consultant. AM, EB, JR, YJ, GA were employed by Agrosavia.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1370275/full#supplementary-material

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