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RESEARCH ARTICLE

Conservation and use of genetic resources of cacao (*Theobroma cacao* L.) by gene banks and nurseries in six Latin American countries

Viviana Ceccarelli · Sphyros Lastra · Rey Gastón Loor Solórzano · Walter Wenceslao Chacón · Mario Nolasco · Ignacio Antonio Sotomayor Cantos · Luis Fernando Plaza Avellán · Diana Aracelly López · Fabian Marcelo Fernández Anchundia · Dominique Dessauw · Luis Orozco-Aguilar · Evert Thomas

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Abstract Cacao (*Theobromacacao* L.) is among the most important cash crops in tropical countries. The existing cacao genetic diversity represents a key resource to ensure the long-term sustainability of cacao cultivation but it remains vastly underused. The objective of this paper is to describe the current state of conservation and use of cacao genetic materials in six countries in South (Peru and Ecuador) and Central America (Nicaragua, Honduras, El Salvador, Guatemala). For each country, we reviewed the regulations for cacao genetic resources, we carried out a survey of 176 gene banks and nurseries, and we performed a review of breeding and selection programs. We found that all countries had poor systems of certification, verification and traceability. Gene banks conserved many local materials in Peru and Ecuador while they mainly conserved international clones in Central

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V. Ceccarelli · S. Lastra · E. Thomas (✉)
Alliance Bioversity International - CIAT, Lima, Peru
e-mail: e.thomas@cgiar.org

R. G. Loor Solórzano · I. A. Sotomayor Cantos · L. F. Plaza Avellán
Instituto Nacional de Investigaciones Agropecuarias (INIAP), Programa Nacional de Cacao Y Café (PNCC), Estación Experimental Tropical Pichilingue (EETP), Mocache, Los Ríos, Ecuador

W. W. Chacón
Consultant in Environmental Management, Quezaltepeque, El Salvador

M. Nolasco
Asociación Red Madre Cacao, Managua, Nicaragua

D. A. López
Instituto Nacional de Investigaciones Agropecuarias (INIAP), Departamento Nacional de Recursos Fitogenéticos (DENAREF), Estación Experimental Tropical Pichilingue (EETP), Mocache, Los Ríos, Ecuador

F. M. Fernández Anchundia
Instituto Nacional de Investigaciones Agropecuarias (INIAP), Programa Nacional de Cacao Y Café (PNCC), Estación Experimental Central Amazónica (EECA), Joya de Los Sachas, Orellana, Ecuador

D. Dessauw
CATIE - Centro Agronómico Tropical de Investigación Y Enseñanza, Turrialba 30501, Costa Rica

D. Dessauw
CIRAD, UMR AGAP Institut, Univ Montpellier, CIRAD, INRAE, Institut Agro, F-34398 Montpellier, France

L. Orozco-Aguilar
Deputy Director for Research and Innovation, Corus International-Lutheran World Relief-MOCCA project, Turrialba, Cartago, Costa Rica

American countries. In all countries except Honduras, more than half of the gene banks did not have any characterization or evaluation data of the conserved materials. Although nurseries in all countries had fair productive capacities, varieties sold were unevenly characterized in Peru, Ecuador and Guatemala, and less than half of the nurseries provided technical assistance to farmers in Ecuador and El Salvador. Breeding and selection programs had not fully used the cacao diversity in these countries. Based on the results, we identified the strengths and weakness, as well as the most appropriate investment areas for each country. A better conservation and use of cacao genetic resources in Latin America would benefit not only these countries but also the whole cacao sector.

Keywords Cacao propagation material · Certification and traceability systems · Clonal gardens · Criollo cacaos · Fine or flavour cacao · Native cacaos

Abbreviations

Peru

CIC	Centro de Inovación del Cacao
ICT	Instituto de Cultivos Tropicales
INDECOPI	Instituto Nacional de Defensa de la Competencia y de la Protección de la Propiedad Intelectual
INIA	Instituto Nacional de Innovación Agraria
SINEACE	Sistema Nacional de Evaluación, Acreditación y Certificación de la Calidad Educativa
SENASA	Servicio Nacional de Sanidad Agraria
UNAS	Universidad Nacional Agraria de la Selva
UNIQ	Universidad Nacional Intercultural de Quillabamba

Ecuador

AGROCALIDAD	La Agencia de Regulación y Control Fito y Zoosanitario
ANECACAO	Asociación Nacional de Exportadores e Industriales de Cacao del Ecuador
ESPOL	Escuela Superior Politécnica del Litoral
INIAP	Instituto Nacional de Investigaciones Agropecuarias

Nicaragua

APEN	Asociación de Productores y Exportadores de Nicaragua
INTA	Instituto Nicaragüense de Tecnología Agropecuaria
IPSA	Instituto de Protección y Sanidad Agropecuaria

Honduras

ASEPRA	Asesoría y Servicios en Producción Agroindustrial
FHIA	Fundación Hondureña de Investigación Agrícola
SENASA	Servicio Nacional de Sanidad e Inocuidad Agroalimentaria
SINASEMH	Sistema Nacional de Semillas de Honduras

El Salvador

CENTA	Centro Nacional de Tecnología Agropecuaria y Forestal
MAG	Ministerio de Agricultura y Ganadería

Guatemala

MAGA	Ministerio de Agricultura, Ganadería y Alimentación
ICTA	Instituto de Ciencia y Tecnología Agropecuarias

International Organizations

CATIE	Centro Agronómico Tropical de Investigación y Enseñanza
CIRAD	Centre de Coopération Internationale en Recherche Agronomique pour le Développement
ICCO	International Cocoa Organization
WCR	World Coffee Research
WCF	World Cocoa Foundation

Introduction

Cacao (*Theobroma cacao* L.) is among the most important tree cash crops in the tropics. Global annual cacao production is around 5 million tons of which 80% is produced in smallholder farms (WCF 2014), corresponding to a total export value of US$9 billion

(ICCO 2020a). In Latin America, which accounts for ~18% of global production, cacao is considered a key crop in development programs to alleviate rural poverty, promote peace in post-conflict regions and replace illicit crops (DEVIDA 2017; Abbott et al. 2018). Compared to African and Asian countries which mainly produce bulk cacao for confectionery industry, Latin America is the dominant global source (~80%) of fine or flavour cacao (CAF 2017). While there is no globally accepted definition, fine or flavour cacao can be differentiated from bulk cacao for its flavour profiles including fruity, floral, herbal, woody, nutty and caramel notes as well as rich and balanced chocolate bases (ICCO 2019). Fine or flavour cacao is sold at a premium price and only represents <5% of the total world market (ICCO 2019), but its market has been growing at a rate of 7–11% per year since 2011 (Vignati and Gómez-García 2020).

Cacao is native to the Amazon rainforest with a putative centre of origin in the Upper Amazon region from Colombia to Peru where the highest levels of genetic diversity occur (Motamayor et al. 2002, 2008; Thomas et al. 2012). Cacao was first domesticated some 5300 years ago by the Moche-Chinchipe-Marañón culture in southern Ecuadorian and northern Peruvian Amazon (Olivera-Núñez 2018; Zarrillo et al. 2018), and was later introduced to Mesoamerica and domesticated by Olmec and Maya societies around 3,000–4,000 years ago (Henderson et al. 2007; Powis et al. 2011). This domestication history has shaped the genetic diversity of the cacao currently cultivated.

Cacao has been traditionally divided into the three groups of Criollo, Forastero and Trinitario (Cheesman 1944), but molecular studies have to date identified ten genetic groups including Nacional (Motamayor et al. 2008). Nacional is a genetic group including Nacional from Ecuador and Blanco de Piura from the northern Peruvian coast (Arevalo-Gardini et al. 2019) and originated from the cacao first domesticated by the Moche-Chinchipe-Marañón culture (Loor Solorzano et al. 2012). The Criollo group refers to the cacao domesticated in Central America by Olmec and Maya societies and was the main variety cultivated during the pre-Columbian and colonial period. Criollo in Central America has a very restricted genetic base as it originated from a few propagation materials introduced from the Amazon and underwent further selection during domestication (Thomas et al. 2012; Cornejo et al. 2018). This selection process led to some of the best quality fine or flavour cacao but also resulted in varieties low in productivity and highly susceptible to pests and diseases. Following severe disease outbreaks in the eighteenth century, most of the Criollo trees in Central America and the Caribbean died, and were replaced by introduced Forastero trees (Pittier 1935; Díaz-Valderrama et al. 2020). The Forastero group includes several diverse but unspecified populations from the Amazon often of lower quality but higher disease resistance and productivity (Cheesman 1944). The Trinitario group originated later by hybridization between Forastero and Criollo individuals in Trinidad resulting in a cacao with intermediate characteristics of quality and vigour compared to the original groups (Motamayor et al. 2003). While traditionally only Nacional, Criollo and Trinitario have been regarded as fine or flavour cacao, and Forastero as bulk cacao, it is now clear that Forastero covers an incredible diversity (Motamayor et al. 2008), including fine flavour varieties such as Chuncho from Peru (Laura et al. 2021).

Cacao´s wide genetic diversity represents a key resource to ensure the long-term sustainability of its cultivation. Key traits of interest include higher productivity, resistance to pests and diseases, organoleptic characteristics (Monteiro et al. 2009) and tolerance to abiotic stress and climate change (Medina and Laliberte 2017; Lahive et al. 2019). In the short term, a better characterization and evaluation of agronomic and organoleptic traits of currently underutilised cacao genetic resources presents a great opportunity to promote the use of superior genotypes in farmers' plantations. In the longer term, genetic diversity can also be used in breeding programs to develop improved varieties. Conserving and exploiting cacao genetic diversity is essential to improve the sustainability and diversification of the sector.

Being the centres of origin and domestication of cacao, South and Central America host a wide genetic diversity of native varieties but this is largely underutilized and threatened by the introduction of a limited set of highly productive non-native genotypes. In Central America, native Criollo has mostly been replaced by introduced varieties of Forastero and Trinitario and has almost disappeared. Currently, cultivated cacao in Central America is mainly based on international clones distributed by CATIE in 1960–2000 and has a narrow genetic diversity

(Orozco-Aguilar et al. 2014). South American countries still have a high diversity of native fine or flavour cacaos such as Nacional in Ecuador and Blanco de Piura and Chuncho in Peru, but these local cultivars have been increasingly replaced by CCN-51, a hybrid developed in Ecuador with high productivity but not regarded as fine or flavour (MINAGRI 2016; Wiegel et al. 2020). Many promising, local genotypes in South and Central America are not conserved in gene banks and have not been used in breeding programs, while much of the diversity maintained in national and local gene banks is underused and lacks appropriate characterization and evaluation data (CacaoNet 2012; Medina and Laliberte 2017). Additional challenges arise along the supply chain, which is characterized by limited technical capabilities and lack of systems to ensure the quality of the genetic materials sold by the nurseries (Wiegel et al. 2020), and by the extensive use by farmers of propagation materials of uncertain quality and genetic identity obtained from their own plots instead of nurseries (INEI 2018; Wiegel et al. 2020).

The objective of this paper is to describe the current state of conservation and use of cacao genetic materials in six countries in South (Peru and Ecuador) and Central America (Nicaragua, Honduras, El Salvador, Guatemala), with the aim of identifying the strengths and weakness of each country as well as the most appropriate needs and opportunities for investment. To this aim, for each of the six countries we: (1) reviewed the current laws and regulations about cacao genetic resources, (2) carried out a survey of Gene Banks and Clonal Gardens (GB/CG) and nurseries, and (3) performed a review of the current research by breeding and selection programs. We provide recommendations to improve the breeding and selection strategies for cacao in the six countries.

Methodology

Study region

Peru and Ecuador are respectively the 8th and 5th top cacao producing countries in the world (Table 1). Being part of the cacao centre of origin, Peru presents a high diversity of native cacaos such as Chuncho and Blanco de Piura. However, since the 1970s, the non-native CCN-51 has been introduced in the country and has been widely promoted for its high productivity by development programs. Currently approximately 56% of the total cacao area in Peru is cultivated with CCN-51 and 44% with native cacaos (MINAGRI 2016). Yet, in recent years there has been a growing interest to redirect the production towards native and fine or flavour cacaos (MINAGRI 2016). Ecuador produces cacao Nacional which makes it the main producer of fine or flavour cacao globally, accounting for 63% of the total world production (ANECACAO 2019). However, CCN-51 has been expanding also in this country (Vicepresidencia del Ecuador 2015). CCN-51 currently covers some 60% of the cacao cultivated area in Ecuador while Nacional covers the remaining 40% (Rey Gastón Loor Solórzano, personal communication). Overall, in Peru, 54% of farmers use propagation material produced on their own farms while only 15% use material from nurseries (INEI 2018). By contrast, in Ecuador most farmers use propagation material from nurseries (Rey Gastón Loor Solórzano, personal communication).

Central American countries produce smaller quantities of cacao. Although they represent one of the two domestication centres and the place where Criollo originated, currently most cultivated cacao derives from seeds of international clones distributed by CATIE in 1960–2000 (Orozco-Aguilar et al. 2014), mainly UF, ICS, IMC, TSH, PMCT, CATIE, and POUND (Morera 1991). Farmers in Nicaragua, Honduras and Guatemala largely use propagation material produced on their own farms instead of materials from nurseries (Wiegel et al. 2020) and only some 6% of the plantations uses pure clones (Orozco-Aguilar et al. 2014).

Nicaragua and Honduras are respectively the 26th and 38th cacao producing countries (Table 1). They sell 60% of the cacao they produce within Central America and export only 40% to Europe and USA (Wiegel et al. 2020). El Salvador and Guatemala are the 44th and 33th cacao producing countries (Table 1) and they mainly import cacao from Nicaragua and Honduras. Currently, El Salvador is not included in the ICCO Annex C of cacao exporting countries due to its low production levels. However, since 2014, the newly funded Alianza Cacao program initiated a U$25 million investment to turn El Salvador into a cacao producing country and has established more than 3000 ha of new cacao plantations involving 3600 new cacao farmers. Within the program, most farmers

Table 1 Overview of cacao sector in the six countries

Country	Peru	Ecuador	Nicaragua	Honduras	El Salvador	Guatemala	Sources
Total production (t/year)	136,000	322,000	7000	1000	370	1300	FAOSTAT (2019) For Ecuador: ICCO (2021) For Guatemala: MINECO (2015)
Total harvested area (ha)	130,000	525,000	12,000	2900	850	4300	FAOSTAT (2019) For Guatemala only: MINECO (2015)
Number of cacao farmers (n)	90,000	120,000	11,000	3700	3900	9100	Peru: MINAGRI (2016) Ecuador: SENPLADES (2019) Nicaragua: MIFIC (2018) Honduras: Pro Honduras (2019) El Salvador: VECO (2017a) Guatemala: VECO (2017b)
Rank among global producing countries	8	5	26	38	44	33	FAOSTAT (2019) For Guatemala only: Rank based on production data from MINECO (2015)
Fine or flavour (% tot export)	75%	75%	80%	–	–	75%	ICCO (2020b)

were provided with propagation materials of international clones sourced from FHIA and CATIE, including UF, ICS, TSH and IMC (Wiegel et al. 2020). Guatemala directs 96% of its cacao production within the country while only 4% is exported internationally (MAGA 2016). All these four countries are planning to increase their production of fine or flavour cacao (Wiegel et al. 2020).

Laws and regulations about cacao genetic material

In each country, we reviewed the national laws and regulations related to cacao genetic material, identified the main regulatory agencies, and assessed the capacity in terms of certification, verification and traceability. *Certification* refers to the regulations related to certify (1) cacao varieties, (2) propagation material, and (3) nurseries and GB/CG and attests that they conform to specified requirements (ISO Guide 2 2014). For cacao varieties, certification confirms that they are uniform, distinct from other varieties, and have undergone proper characterization and evaluation. For propagation material, nurseries and GB/CG, certification confirms the genetic identity and varietal purity of the material produced, its vigour, and the absence of pests and diseases. Certification also includes registries of nurseries and GB/CG, as well as registries of varieties in the country. *Verification* refers to the regulations used to verify whether certified nurseries and GB/CG are complying with the protocols and includes regulations about how and how often the responsible agencies perform inspections (ISO 9000:2015 3.8.12). *Traceability* refers to the regulations related to tracing the origin, production site, handling steps of propagation material, and its location after delivery (ISO 9000:2015 3.6.13).

We scored each country's capacity in terms of certification, verification and traceability of cacao genetic resources using the following scaling approach:

- *High* The country has well-developed systems of certification, verification or traceability. The country has strong and detailed regulations about genetic material specific to cacao which is well enforced by the responsible regulatory agencies across the country.
- *Medium* The country has basic systems of certification, verification or traceability. The country has regulations about genetic material specific to cacao although sometimes these are not correctly

enforced by the responsible regularity agencies across the country.
- *Low* The country has poor systems of certification, verification or traceability. The country has regulations about genetic material, but they are general or not specific to cacao. The regulation is poorly enforced by the responsible regulatory agencies across the country.
- *None* The country completely lacks systems of certification, verification or traceability. There is no regulation nor responsible regulatory agencies.

A detailed description of the four scales for certification, verification and traceability is presented in Table S1. The assessment was based on the results of the review and considering the opinions of consulted experts in each country.

Survey of GB/CG and nurseries

First, we identified all the GB/CG and nurseries in each country through consultation with key informants from the public, private and academic sector, and literature review. Next, between August 2019 and June 2020 we contacted all identified GB/CG and nurseries by email and/or phone to fill out one or both surveys we developed for GB/CG and nurseries (Text S1). We performed field visits to a selection of GB/CG and nurseries in each country to validate the information provided (Table S2). In cases where the primary role of a GB/CG was complemented with nursery operations, or vice versa, respondents were asked to fill out both surveys. In total, we collected 176 survey responses in the six countries from 149 different institutions, representing an average of $\sim$ 50% of the GB/CG and nurseries identified in each country (Figs. 1, 2).

For each country, we summarized the results of the surveys in radargraphs for GB/CG and nurseries separately (Figs. 1, 2). The radagraphs for GB/CG and nurseries are organized across four components: (1) diversity and conservation of cacao genotypes, (2) level of characterization and evaluation of cacao genotypes, (3) infrastructure and maintenance, and (4) productive capacity. Each of these components is represented by two to four descriptors, resulting in a set of 14 descriptors for GB/CG and 11 descriptors for nurseries. Each descriptor is scored on a scale from 0 to 5 according to the categories presented in Tables 2 and 3.

Breeding and selection programs and other research activities

In each country, we reviewed the literature regarding cacao breeding and selection programs. This included peer-reviewed articles, university theses, consultancy reports and catalogues of cacao varieties. In addition, we interviewed key informants and managers from the main cacao research institutes and GB/CG.

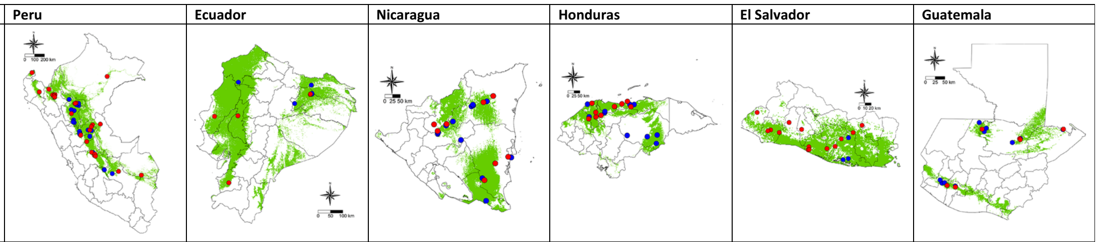
Data analysis

Descriptive statistical analyses were conducted in R version 3.6.2 (R Core Team 2019). For Figs. 1, 2, we produced maps indicating the suitable area for cacao cultivation for each country using the suitability modelling methodology described in Ceccarelli et al. (2021) (Text S2). These maps are for reference only and are used to show the distribution of GB/CG and nurseries across the country compared with the suitable area for cacao cultivation.

Results

Laws and regulations on cacao genetic material

Tables 4 and S3 provide a summary of the assessment of certification, verification and traceability systems in the six country. All countries have low levels of certification, except for Ecuador and Honduras which received high scores. Although all countries have some general regulations for protecting plant breeders' rights and some have created cacao variety registries, enrolling newly developed cacao varieties is not mandatory and no country has a registry including all varieties present in the country. No country has the capacity to certify propagation material and only Ecuador and Honduras have a registry of all nurseries and GB/CG present in the country. Peru, Ecuador, Nicaragua and Honduras have low to medium scores for verification systems, while El Salvador and Guatemala do not have any verification system for cacao genetic resources. Even in countries with medium score for verification, the responsible regulatory agency do not perform periodic visits to the



	Peru	Ecuador	Nicaragua	Honduras	El Salvador	Guatemala
N of GB/CG in the country (n)	45	10	20	22	14	16
N of GB/CG surveyed (n)	23 (52%)	5 (50%)	8 (40%)	9 (41%)	11 (79%)	6 (38%)
Percentage public (%)	39%	30%	15%	9%	29%	19%
Median age (years)	4 (1-33)	20 (3-80)	1 (3-40)	5 (3-11)	4 (3-7)	6 (2-6)
Median area (ha)	1.8 (0.5-10)	8 (0.3-10)	3.5 (0.7-8)	1	1 (0.2-5)	1 (0.5-23)
Main GB/CG in the country	ICT (900 genotypes)	INIAP (> 2000 genotypes across several experimental stations)	INTA El Recreo (159 genotypes)	FHIA (> 100 genotypes)	Universidad de El Salvador (200) CENTA (39 genotypes)	Universidad de San Carlos de Guatemala (20 genotypes)

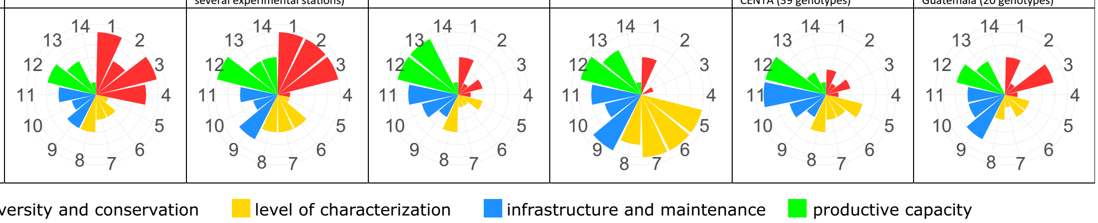
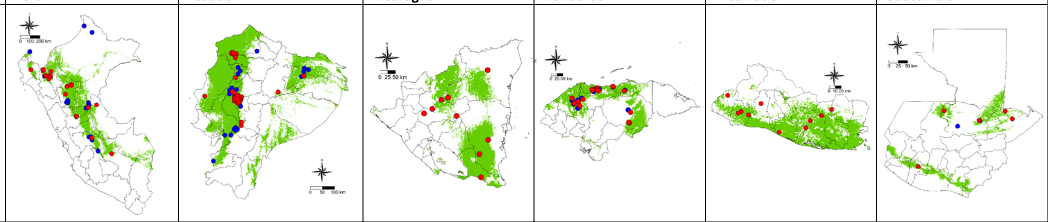


Fig. 1 Descriptive information of the cacao Gene Banks and Clonal Gardens (GB/CG) in the six countries**.** Maps show the distribution of suitable areas for cacao cultivation in green, the locations of gene banks and clonal gardens included in the survey in red and not included in the survey in blue. Descriptors in the radagraphs are divided into four categories and represent: 1 = Median number of genotypes per GB/CG, 2 = Percentage of GB/CG with > 50 genotypes, 3 = Mean percentage of local and national materials per GB/CG, 4 = Percentage of cacao producing departments with at least one GB/CG conserving local genotypes (Diversity and conservation); 5 = Percentage of GB/CG with available database of all conserved genotypes, 6 = Mean characterization of material for the descriptive traits of georeferencing, morphological and genetic characterization, 7 = Mean characterization of material for the use-oriented traits of productivity, sensorial quality and sexual compatibility, 8 = Median number of categories of promising varieties per GB/CG (Level of characterization); 9 = Percentage of GB/CG having a management plan, 10 = Infrastructure index, 11 = Maintenance index (Infrastructure and maintenance); 12 = Percentage of GC/CG with productive capacity, 13 = Median yearly production per GB/CG, 14 = Percentage of GB/CG with projects of genetic improvement or development of new varieties (Productive capacity). The exact values of the descriptors for each country are presented in Table S4a

certified nurseries and GB/C. In all countries, the traceability system is either absent or received a low score.

Survey of GB/CG and nurseries

Figure 1 shows the descriptive statistics and radargraphs for the GB/CG in the six countries. GB/CG across the countries were generally private (< 40% GB/CG public), young (median < 6 years), and small (median < 3.5 ha), except for Ecuador which had older and larger GB/CG (median 20 years and 8 ha). In terms of *diversity and conservation*, GB/CG in Peru and Ecuador conserved higher numbers of genotypes (median 29–147) and mostly representing local and national materials, while GB/CG in Central American countries conserved fewer genotypes (median 6–15) and mainly international and some national materials (Fig. 1 descriptors 1–4, Fig. 3). In terms of *characterization*, in all countries only 20–55% GB/CG had a database with descriptive information of the conserved genotypes and most materials were poorly characterized for descriptive and use-oriented traits, except for Honduras where all the GB/CG had an available database and the characterization level was close to 100% (Fig. 1 descriptors 5–7, Fig. 4). GB/CG conserved a fair number of promising genotypes for high productivity, sensorial quality, pests and diseases resistance, but fewer GB/CG conserved genotypes tolerant to abiotic stresses (Fig. 1 descriptor 8). It is important to mention that, although characterization was missing in many GB/CG in the Central American countries, international clones have often already been characterized by the institutions where they have been



	Peru	Ecuador	Nicaragua	Honduras	El Salvador	Guatemala
N of nurseries in the country (n)	39	554	9	21	10	8
N of nurseries surveyed (n)	19 (49%)	63 (11%)	9 (100%)	7 (33%)	10 (100%)	5 (63%)
Percentage public (%)	46%	5%	11%	5%	0%	13%
Percentage temporary (%)	16%	3%	56%	57%	20%	0%
Median age (years)	4 (1-28)	10 (1-45)	6 (3-40)	6 (3-8)	4 (3-5)	6 (3-10)
Median area (ha)	0.3 (0.001-1)	0.6 (0.02-5)	1 (0.06-15)	0.06 (0.03-1)	0.9 (0.2-5)	1.5 (1-4)
Main nursery in the country	Vivero El Paraiso (960,000) SERVITESA (400,000 plants/year)	Servicios Agricolas RELEV (1,200,000 plants.years)	TRANSPLANTA (3,000,000) and ECOM (1,500,000 plants/year)	ASEPRA (350,000 plants/year)	Finca La Joya (48,000 plants/year)	Kampura (1,000,000 plants/year)
Varieties sold in the nurseries	Several local cultivars and varieties (70% of nurseries), CCN-51 (40%), TSH-95, ICS and other international clones (30%)	CCN-51 (63% of nurseries), EET and EETP (32%), PMA-12 and other international clones (11%)	ICS (100% of nurseries), CATIE (80%), PMCT (60%), IMC (60%), TSH-95 (40%), other international clones (40%)	CATIE (100% of nurseries), ICS (100%), PMCT-58 (83%), UF (67%), CC, TSH and other international clones (50%)	ICS (89% of nurseries), TSH-565 (78%), criollo (33%)	IMC-67 (40% of nurseries), CATIE, ICS, TSH, UF and other international clones (40%), criollo (40%)
Main type of propagation material sold	Grafted plants (84% of nurseries), plants from seeds (79%), seeds (53%), budwood (47%)	Grafted plants (100% of nurseries), plants from seeds (13%)	Grafted plants (100% of nurseries), budwood (56%), seeds (44%), plants from seeds (33%)	Grafted plants (100% of nurseries), cuttings (57%), seeds (43%)	Grafted plants (67% of nurseries), seeds (44%)	Grafted plants (80% of nurseries), seeds (60%), budwood (60%), cuttings (40%)

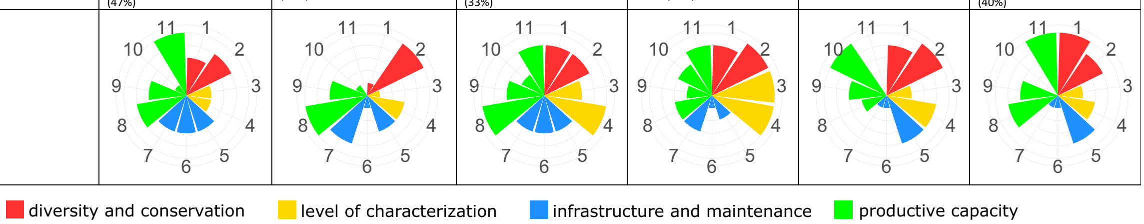


Fig. 2 Descriptive information of the cacao nurseries in the six countries here considered**.** Maps show the distribution of suitable areas for cacao cultivation in green, the locations of nurseries included in the survey in red and not included in the survey in blue. The map of Ecuador only includes 74 nurseries out of the 554 nurseries identified in the country (63 nurseries surveyed + 11 nurseries for which coordinates were available). Descriptors in the radagraphs are divided into four categories and represent: 1 = Median number of varieties per nursery, 2 = Percentage of nurseries using certified genetic material (Diversity and conservation); 3 = Mean characterization of varieties sold for the descriptive traits of morphological and genetic characterization, 4 = Median characterization of varieties sold for the use-oriented traits of productivity, sensorial quality, sexual compatibility, resistance to pests and diseases, and resistance to abiotic stresses (Level of characterization); 5 = Percentage of nurseries following standard protocols, 6 = Infrastructure index, 7 = Maintenance index (Infrastructure and maintenance); 8 = Median yearly production per nursery, 9 = Percentage of cacao producing departments with at least one nursery, 10 = Percentage of self-sufficient nurseries from economic point of view, 11 = Median number of categories of services/assistance offered to costumers (Productive capacity). The exact values of the descriptors for each country are presented in Table S4b

developed (e.g. Phillips-Mora et al. 2013; López et al. 2017). GB/CG in all countries showed an average level of *infrastructure and maintenance*, with Honduras having the highest scores (Fig. 1 descriptors 9–11). In all countries, GB/CG also had a fair *productive capacity* with around 10,000–15,000 plants/year (Fig. 1 descriptors 12–13). Only few GB/CG were involved in activities to develop new varieties, except in Ecuador where 60% of the GB/CG collaborated in some projects (Fig. 1 descriptor 14).

Figure 2 shows the descriptive statistics and radargraphs for the nurseries in the six countries. Ecuador had the highest number of nurseries (554). In the six countries, most nurseries were private (> 85% nurseries), young (median 4–6 years) and small (median < 1.5 ha), except in Ecuador which had older nurseries (median 10 years) and Peru where 46% of the nurseries were public. Peru, Ecuador, El Salvador and Guatemala mostly had permanent nurseries while in Nicaragua and Honduras 56–57% of nurseries were temporary. In terms of *diversity and conservation*, in all countries 80–100% of nurseries used certified materials and sold a median of 5–7 varieties or genotypes, except for Ecuador where most of the nurseries produced only one variety, and Guatemala

Table 2 Descriptors used in the radargraph for the Gene Banks and Clonal Gardens (GB/CG)

		0	1	2	3	4	5
Diversity and conservation							
1	Median number of genotypes per GB/CG	0	1–3	4–9	10–20	21–30	> 30
2	Percentage of GB/CG with > 50 genotypes	0%	1–20%	21–30%	31–40%	41–50%	51–100%
3	Mean percentage of local and national materials per GB/CG	0%	1–30%	31–50%	51–60%	61–80%	81–100%
4	Percentage of cacao producing departments with at least one GB/CG conserving local genotypes	0%	1–30%	31–50%	51–70%	71–90%	91–100%
Level of characterization							
5	Percentage of GB/CG with available database of all conserved genotypes	0%	1–30%	31–50%	51–70%	71–90%	91–100%
6	Mean characterization of material (descriptive: georeference, morphological, genetic)[a]	0%	1–30%	31–50%	51–70%	71–90%	91–100%
7	Mean characterization of material (use–oriented: productivity, sensorial, sexual compatibility)[a]	0%	1–30%	31–50%	51–70%	71–90%	91–100%
8	Median number of categories of promising varieties per GB/CG (8 categories)[b]	0	1	2–3	4	5–6	7–8
Infrastructure and maintenance							
9	Percentage of GB/CG having a management plan	0%	1–30%	31–50%	51–70%	71–90%	91–100%
10	Infrastructure index (0–1 index)[c]	0	0.1–0.4	0.41–0.5	0.51–0.6	0.61–0.7	0.71–1
11	Maintenance index (0–3 index)[d]	0	0.1–1	1.01–1.5	1.51–2	2.01–2.5	2.51–3
Productive capacity							
12	Percentage of GB/CG with productive capacity	0%	1–30%	31–50%	51–70%	71–90%	91–100%
13	Median yearly production per GB/CG (including GB/CG without production)	0	0–5,000	5,000–10,000	10,000–30,000	30,000–80,000	80,000–1,000,000
14	Percentage of GB/CG with projects of genetic improvement or development of new varieties	0%	1–30%	31–50%	51–70%	71–90%	91–100%

[a]This is calculated as the mean value of the median percentages of each of the three characterization classes across the surveyed GB/CG in the country

[b]The 8 categories of promising varieties are: resistance to pests, resistance to diseases, tolerance to drought, tolerance to flooding, tolerance to high or low temperatures, tolerance to degraded, saline, and infertile soils, high productivity, high sensorial quality

[c]Infrastructures are expressed as present = 1 or absent = 0, and are divided into four types: identification (including dashboard, identification signboard, map, signs and tags on field), safety (fence, prevention system to fire, prevention system to flooding, prevention system to phytosanitary risks), general infrastructure (warehouse, water reservoir, furrow or technified irrigation, nursery), postharvest (area and equipment for collection, fermentation and drying, for storage, for processing). The index is calculated as the mean value for the means of the four types of infrastructure

[d]The maintenance activities are pruning, weeding, irrigation, fertilization, and phytosanitary control. The level of maintenance in the last year is expressed as never realized = 0, one or two times = 1, two or three times = 2, five times = 3. The index is calculated as the mean value of the mean maintenance levels across the five activities for the surveyed GB/CG in the country

Table 3 Descriptors used in the radargraph for the nurseries

		0	1	2	3	4	5
Diversity and conservation							
1	Median number of varieties per nursery	0	1	2–3	4–5	6–10	> 10
2	Percentage of nurseries using certified genetic material	0%	1–30%	31–50%	51–70%	71–90%	91–100%
Level of characterization							
3	Mean characterization of varieties sold (descriptive: morphological, genetic) (0–2 index)[a]	0	0.1–0.5	0.51–1	1.01–1.3	1.31–1.5	1.51–2
4	Median characterization of varieties sold (use-oriented: productivity, sensorial, sexual compatibility, resistance to pests and diseases, resistance to abiotic stress) (0–5 index)[b]	0	1	2	3	4	5
Infrastructure and maintenance							
5	Percentage of nurseries following standard protocols	0%	1–30%	31–50%	51–70%	71–90%	91–100%
6	Infrastructure index (0–1 index)[c]	0	0.1–0.4	0.41–0.5	0.51–0.6	0.61–0.7	0.71–1
7	Maintenance index (0–7 index)[d]	0	0.1–2	2.01–3	3.01–5	5.01–6	6.01–7
Productive capacity							
8	Median yearly production per nursery	0	0–5,000	5,000–10,000	10,000–50,000	50,000–80,000	80,000–1,000,000
9	Percentage of cacao producing departments with at least one nursery[e]	0%	1–30%	31–50%	51–70%	71–90%	91–100%
10	Percentage of self-sufficient nurseries from economic point of view	0%	1–30%	31–50%	51–70%	71–90%	91–100%
11	Median number of categories of services/assistance offered to costumers (10 categories)[f]	0	1	2–3	4–5	6–7	8–10

[a]For each of the two categories (morphological, genetic), characterization is expressed as present = 1 or absent = 0. The index is calculated as the mean value across the surveyed nurseries in the country

[b]For each of the five categories (productivity, sensorial, sexual compatibility, resistance to pests and diseases, resistance to abiotic stress), characterization is expressed as present = 1 or absent = 0. The index is calculated as the median value across the surveyed nurseries in the country

[c]Infrastructures are expressed as present = 1 or absent = 0, and are divided into three types: safety (including fence, prevention system to fire, flooding, phytosanitary risks), general infrastructure (warehouse, irrigation system, drainage system, natural or artificial shade), business (business and marketing plan, advertising—written, audiovisual media, website). The index is calculated as the mean value for the means of the three types of infrastructure

[d]The seven activities considered in the production of propagation materials are: sterilization of propagation material, pregermination of seeds, sterilization or solarization of substrate, mechanical control of weeds, chemical control of weeds, chemical control of diseases, fertilization. The index is calculated as the mean number of activities realized across the surveyed nurseries in the country

[e]This is the only descriptor calculated using the locations of all nurseries identified in the countries and not only the nurseries who filled in the survey

[f]The 10 categories of services/assistance are: design of plantation, establishment of plantation, recommendation of varieties according to needs/interests of producer and site condition, recommendation of varieties according to sexual compatibility, renovation and rehabilitation, phytosanitary control, fertilization, pruning, propagation of clones on request, grafting

which had a median of 20 (Fig. 2 descriptor 1–2). Peru and Ecuador mostly sold selected local varieties and CCN-51, while in Central American countries almost 100% of the nurseries sold international clones (Fig. 2). Most nurseries sold grafted plants but seeds, cuttings and other propagation materials were also common (Fig. 2). Nurseries in Honduras had the highest *level of characterization* of the varieties sold, followed by Nicaragua and El Salvador, while Peru, Ecuador and Guatemala showed lower characterization levels (Fig. 2 descriptors 3–4, Fig. 5). Overall, more nurseries had information on the productivity and resistance to pests and diseases of the varieties sold, while few had information on sexual compatibility and genetics (Fig. 5). In terms of *Infrastructure and maintenance*, in El Salvador and Guatemala > 80% of the nurseries followed standardized protocols while this percentage dropped to 33–67% in other countries (Fig. 2 descriptor 5). Nurseries in the six countries had poor to average scores for infrastructure and maintenance (Fig. 2 descriptors 6–7).

Nurseries' *productive capacity* was highest in Ecuador and Nicaragua (median 100,000 plants/year) and lowest in El Salvador (9600 plants/year) (Fig. 2 descriptor 8). In all countries nurseries were unevenly distributed and only 50–67% cacao producing departments had at least one nursery (Fig. 2 descriptor 9). In Nicaragua, the sector was driven by the companies TRANSPLANTA and ECOM which also export to neighbouring countries (production of 1,500,000–3,000,000 plants/year) while in El Salvador most nurseries were small clonal gardens established by Alianza Cacao El Salvador. Most (75–94%) nurseries were economically self-sufficient in Peru and Ecuador compared to 57–67% in Nicaragua, Honduras and Guatemala, but the percentage dropped to 10% in El Salvador (Fig. 2 descriptor 10). Most nurseries reported that they provide technical assistance to farmers for the design and management of cacao plantations in Peru, Nicaragua, Honduras, Guatemala, while assistance was limited in Ecuador and El Salvador (Fig. 2 descriptor 11, Fig. 6). In the case of El Salvador, it is important to mention that although none of the surveyed nurseries offered technical assistance, this had been largely provided to farmers within the programme of Alianza Cacao El Salvador (Wiegel et al. 2020).

Breeding programs, selection programs and other research activities

Tables 5 and S5 provide a summary of the breeding and selection programs across the six countries. Overall, breeding and selection programs varied widely among countries and only Ecuador had a recurrent breeding program for cacao. Programs and research activities in Peru and Ecuador mainly focused on native cacaos while in Central America efforts targeted both international and, in recent years, native genotypes.

Peru does not have a national breeding programme for cacao. Some institutes (UNAM, UNIQ, ICT) have been involved in breeding activities but none of the varieties developed had been released to farmers. On the other hand, in 1990–2000 selection programs identified the highly productive and fine flavour clones CMP (also known as VRAEM) and M-54 whose cultivation has been spreading in the Vraem region and in Cajamarca, respectively (Garcìa 2008, 2010). Over the past years, several actors in Peru including farmer cooperatives, national universities, INIA, ICT, and the Alliance of Bioversity International and CIAT have been involved in projects to select and characterize promising genotypes of native cacaos with fine or flavour traits and high productivity. From our survey with GB/CG and nurseries, we found that around 20% of the institutions involved in selection programs in Peru also distributed the selected varieties to farmers, mainly cooperatives distributing propagation materials to their members.

In Ecuador, INIAP leads the national breeding programme for cacao. Throughout the years, INIAP has developed and distributed to farmers several Nacional cacao varieties called EET with high productivity, resistance to pests and diseases, and high sensorial quality. Apart from INIAP, other local actors and universities have also been involved in selection and characterization programs. Selected varieties have been highly diffused in different regions, such as the so-called "super trees" in the northern Ecuadorian Amazon, PM-12 in the central and northern coast, and JHV-10 in the southern coast. Both in Ecuador and Peru, projects have also focused on identifying genotypes with low cadmium accumulation, in response to the EU regulation No. 488/2014 enforced in 2019 which limits the maximum amount

Table 4 Overview of regulatory agencies and regulations on cacao genetic material in the six countries, and assessment of the level of certification, verification and traceability systems

Country	Official regulatory agencies	Laws and regulations	Certification	Verification	Traceability
Peru	Instituto Nacional de Innovación Agraria (INIA) Servicio Nacional de Sanidad Agraria (SENASA) Sistema Nacional de Evaluación, Acreditación y Certificación de la Calidad Educativa (SINEACE)	Ley General de Semillas (Ley 27,262) y su Reglamento General (DS 006–2012-AG) Reglamento sobre las Plantas de Vivero de Frutales (DS 005–2017-MINAGRI) Normas de Competencia del Productor(a) de Plantones de Cacao (Resolución 078–2020-SINEACE-CDAH-P) Ley sobre las Infracciones a los Derechos de los Obtentores de Variedades Vegetales Protegidas (Ley 28,126) Registro Nacional de Cultivares de Cacao Peruano (Resolución Ministerial 0144/2012-AG)	*Low*	**Medium**	*Low*
Ecuador	AGROCALIDAD Instituto Nacional de Investigaciones Agropecuarias (INIAP)	Ley de Sanidad Vegetal 2004 Reglamento Nacional al Régimen Común sobre Acceso a los Recursos genéticos (Decreto 905) Manual de Procedimientos para el Registro de Viveros y Productores de Material Vegetal de Cacao Nacional Fino de Aroma Sabor Arriba y otras Variedades (Resolución AGROCALIDAD 21–2011) Decreto Ejecutivo que reglamenta la Decisión 345–1993 de la Comisión del Acuerdo de Cartagena sobre el Régimen Común de Protección de los Derechos de los Obtentores de Variedades Vegetales (Decreto Ejecutivo 3708)	**High**	**Medium**	***None***
Nicaragua	Instituto de Protección y Sanidad Agropecuaria (IPSA)	Ley de Producción y Comercio de Semillas (Ley 280) Ley Básica de Salud Animal y Sanidad Vegetal (Ley 291) Norma Técnica Obligatoria Nicaragüense de Certificación de Material Propagativo de Cacao (NTON 11,042–14) Ley de Protección para las Obtenciones Vegetales (Ley 318)	*Low*	*Low*	*Low*
Honduras	Sistema Nacional de Semillas de Honduras (SINASEMH) Servicio Nacional de Sanidad Agropecuaria (SENASA)	Ley de Semillas (Decreto 1046) Acuerdo Marco para la Competitividad de la Cadena Agroalimentaria del Rubro Cacao (Acuerdo 923–13) Reglamento para la Producción, Distribución y Comercialización de Materiales de Propagación de Cacao, Certificación de Viveros y Jardines Clónales (Acuerdo 46–2016) Ley para Protección de Obtenciones Vegetales (Decreto 21–2012)	**High**	**Medium**	***None***

Table 4 continued

Country	Official regulatory agencies	Laws and regulations	Certification	Verification	Traceability
El Salvador	Ministerio de Agricultura y Ganadería (MAG)	Ley de Sanidad Vegetal y Animal (Decreto 524) Ley de Semillas (Decreto 530) Ley de Certificación de Semillas y Plantas (Decreto 229)	*Low*	***None***	***None***
Guatemala	Ministerio de Agricultura, Ganadería y Alimentación (MAGA)	Acuerdo Ministerial 712–2002 para la Producción, Certificación, Importación, Exportación y Comercio de Semillas, Partes de Plantas y Plantas Frutales Certificadas (Acuerdo 712–2002)	*Low*	***None***	***None***

The level of the certification, verification and traceability is classified as none (bold italics), low (italics), medium (bold), high (bold underline)

of cadmium concentration in cacao derivates that can be sold on the EU market.

In Central America, breeding and selection programs have traditionally focused on international clones for high productivity and resistance to pests and diseases. Since the 1980s, several national research centres in the four countries have carried out programs to evaluate international clones from CATIE, but only FHIA and INTA have developed breeding programs. From 2010 to 2015, FHIA bred eight new clones and distributed them to farmers in Honduras (López et al. 2017). FHIA has developed several multiclonal planting arrangements with FHIA and CATIE clones for different regions in Honduras, and has identified and characterized Criollo trees across the country to find new materials for its breeding program (Durán and Dubón 2016; López et al. 2017, 2021a). In Nicaragua, in 2010–2017, INTA released the first cacao variety developed in the country, the INTA-Pacayita, which was bred by crossing local Criollo material with international clones (INTA 2018), and is promoting its distribution to farmers in Nicaragua. El Salvador and Guatemala do not have any active breeding programs. Apart from the recent initiatives from FHIA and INTA, over the past decades, several public and private research institutes and organizations in Central America have started projects to rediscover and characterize ancient Criollo genotypes with the aim of promoting fine or flavour cacao production. However, none of these Criollo genotypes has yet been released commercially or distributed to farms.

Discussion and conclusions

In this study, we analysed the current state of conservation and use of cacao genetic resources in six countries within the centres of origin and domestication of cacao (Motamayor et al. 2008; Thomas et al. 2012; Zarrillo et al. 2018). Overall, there are significant differences between South American countries (Peru and Ecuador) and Central American countries (Nicaragua, Honduras, Guatemala, El Salvador). Peru and Ecuador are within the top ten cacao producing countries in the world, and host a high diversity of native cacaos with a well-established reputation within the fine or flavour cacao market. On the contrary, Central American countries have lower production and export levels. They possess a narrower cacao diversity as native cacaos have been mainly replaced by international clones (Orozco-Aguilar et al. 2014; Wiegel et al. 2020), but they show strong interest to better position themselves on the fine or flavour cacao market.

The systems of certification, verification and especially traceability require more investments in all six countries. While some countries such as Ecuador and Honduras already possess good certification and verification systems, all countries lack proper traceability systems (Table 4, Table S3). All six countries have general regulations for protecting plant breeders' rights for cultivated varieties, but there are no regulations or registries of genotypes or varieties specific for cacao yet. It is important that genotypes or varieties disseminated are clearly identified and

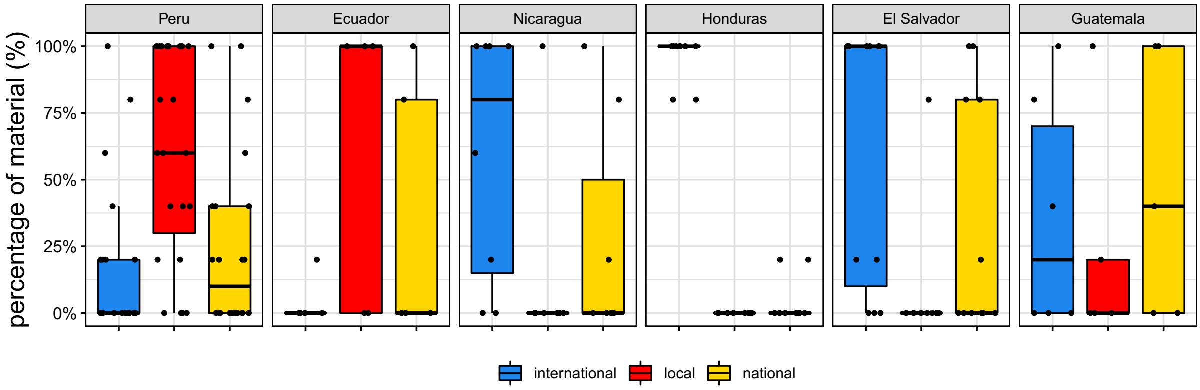


Fig. 3 Origin of materials in the Gene Banks and Clonal Gardens (GB/CG) across the six countries. The boxplots represent the percentages of local (red), national (yellow) and international (blue) materials in GB/CG in the six countries. Black points represent the percentages of the individual GB/CG surveyed. The boxplots for Honduras only show the horizontal bars of the median values because all the individual GB/CG (except two outliers) agree on the same percentages (i.e. 0% local, 0% national, 100% international)

characterized to guarantee producers that planting materials have the desired characteristics (varietal identity, productivity, quality, pests and diseases resistance). Apart from national regulations, it might be useful to promote the creation of a common system for all Latin American producer countries and possibly a global scheme, including protocols for propagating genetic materials and a registry for all existing cacao varieties. Such a scheme is currently missing for cacao, although the Global Network on Cacao Genetic Resources Conservation and Use is coordinating the development of global standards on cacao genetic resources and has developed some guidelines for the safe movement of cacao germplasm across countries (End et al. 2017). The cacao sector could benefit from the experience and protocols from the WCR Verified Program for coffee (WCR 2017)—the first global standard to certify coffee seed producers and nurseries. Such a common scheme for cacao would ensure higher quality materials for farmers and promote exchange of material for breeding and planting across countries.

GB/CG conserve a significant number of genotypes across the countries, but this diversity is unevenly characterized and has been largely underutilised thus far (Fig. 1). Except for Honduras, most GB/CG lack accessible databases and the majority of genotypes are poorly characterized (Fig. 1 descriptors 5–7, Fig. 4). Apart from the main gene banks such as INIAP in Ecuador, FHIA in Honduras and INTA in Nicaragua, most of the other GB/CG surveyed have never participated in activities to develop new genotypes or varieties (Fig. 1 descriptor 14). Further efforts are required to characterize the diversity collected within the GB/CG and to compile the information into accessible databases. GB/CG already conserve several promising genotypes (Fig. 1 descriptor 8) but these should be made more accessible to farmers and research institutes, while new promising genotypes are likely to emerge from more systematic characterization efforts. Characterization of agronomic traits is critical to allow the identification of the most promising genotypes for high productivity, fine or flavour attributes and resistance to pests and diseases that can be directly introduced into farmers' fields or used in breeding programs. Given the vulnerability of cacao to climate change (Medina and Laliberte 2017; Lahive et al. 2019; Ceccarelli et al. 2021), research should also focus on varieties resistant to abiotic stresses such as drought or high temperatures whose identification is currently lacking in most GB/CG. An important gap is information on sexual compatibility, as native cacao in Peru and Ecuador and many international clones are self-incompatible, which requires that different genotypes need to be combined at plantation level (Garcìa 2010; Phillips-Mora et al. 2013; López et al. 2021b). To maximize productivity, this requires information on cross-compatibility levels of different genotype combinations.

Although cacao nurseries in all countries produce fair amounts of propagation materials, there are several areas for improvement for different countries

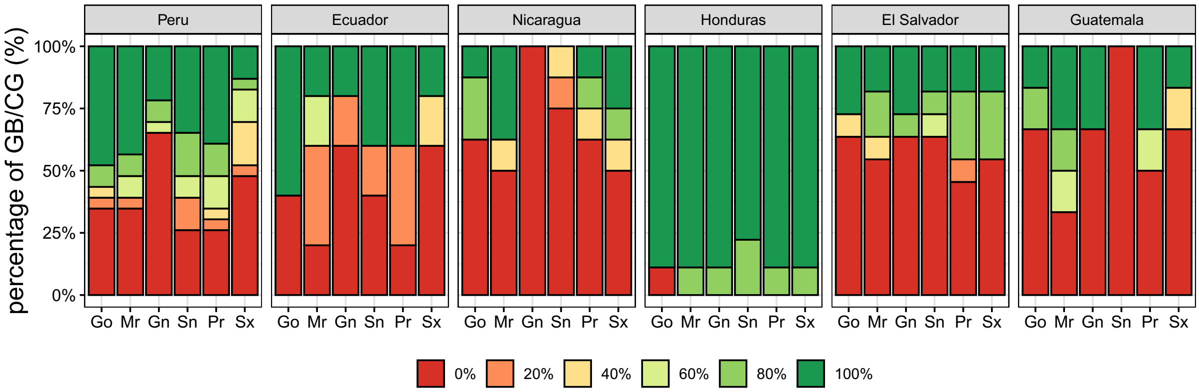


Fig. 4 Characterization of materials in the Gene Banks and Clonal Gardens (GB/CG) across the six countries. The bars represent percentages of materials characterized from 0% (red) to 100% (green) in terms of georeferencing (Go), morphological characterization (Mr), genetic characterization (Gn), sensorial quality (Sn), productive capacity (Pr), and sexual compatibility (Sx)

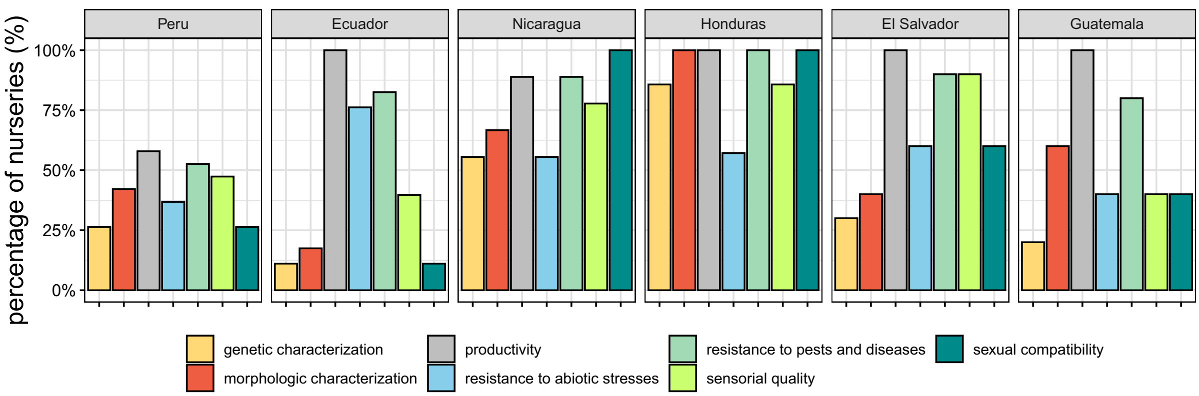


Fig. 5 Characterization of genotypes and varieties sold in nurseries across the six countries. The bargraphs show the percentages of nurseries that have characterization information on the genotypes or varieties they sell for genetic characterization, morphological characterization, productivity (descriptive traits), resistance to abiotic stresses, resistance to pests and diseases, sensorial quality, sexual compatibility (use-oriented traits)

including: (1) ensuring higher characterization of varieties sold (Peru, Ecuador, Guatemala), (2) developing and applying protocols for propagation materials (Peru, Ecuador, Nicaragua, Honduras), (3) investing in infrastructure and better management practices (Ecuador, Honduras, Salvador, Guatemala), and iv) promoting technical assistance to farmers (Ecuador, El Salvador) (Figs. 2, 5, 6). Improving the characterization of the varieties sold and providing tailor-made technical assistance to farmers is essential to ensure that farmers use the right varieties and practices according to the planting site and specific agronomic or sensorial preferences. In all countries, nurseries are unevenly spread across the cacao producing regions and investments may be required to establish new nurseries in departments where they are missing (Fig. 2 descriptor 9). On the other hand, in the past newly created nurseries within the context of projects have often been abandoned after the end of the funding. Therefore, investments and business plans should focus on making the nurseries economically viable in the long term. Considering that many farmers in Peru, Nicaragua, Honduras and Guatemala use materials propagated from their own plots with uncertain quality (INEI 2018; Wiegel et al. 2020), strengthening the nursery systems would be critical to ensure that farmers only use high quality and disease-free materials, to improve overall production, and increase credibility of the fine or flavour sector to international buyers.

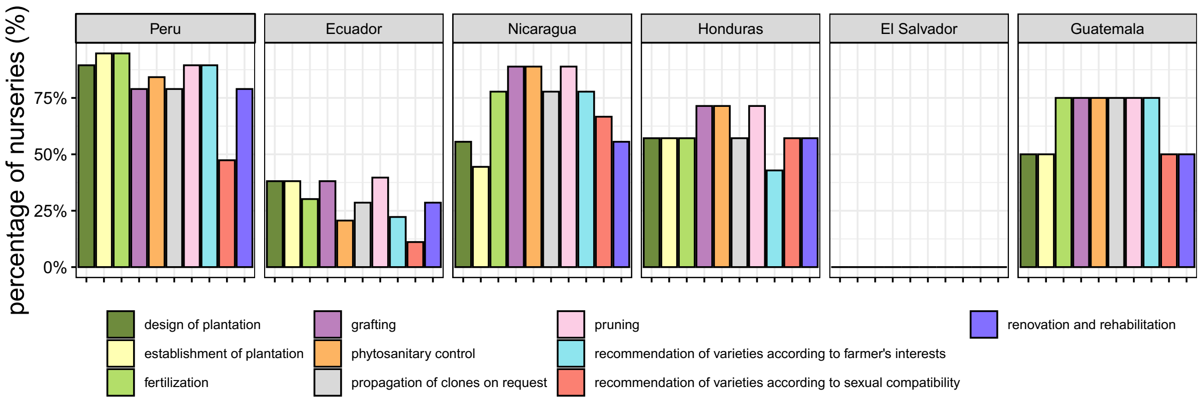


Fig. 6 Technical assistance offered by nurseries across the six countries. The bargraphs show the percentages of nurseries that offer technical assistance to cacao farmers concerning design of plantation, establishment of plantation, fertilization, grafting, phytosanitary control, propagation of clones on request, pruning, recommendation of varieties according to farmers' interests, recommendation of varieties according to sexual compatibility, renovation and rehabilitation. Note that although none of the surveyed nurseries in El Salvador offered technical assistance to cacao farmers, this has been largely provided within the programme of Alianza Cacao El Salvador

One of the competitive advantages of the countries here considered compared to the major cacao producing countries in Africa and Asia is that they host a unique diversity of fine or flavour varieties. Although the fine or flavour market is still small, it is growing fast at a rate of 7–11% per year and Latin American countries are best placed to take advantage of this trend (Vignati and Gómez-García 2020). With their high diversity of native cacaos and well-established reputation, Peru and Ecuador present vast opportunities to scale their fine or flavour market shares. Over the past decades, native cacaos have been replaced in many regions by the highly productive CCN-51, often in the context of development programs (Vicepresidencia del Ecuador 2015; MINAGRI 2016). While the reasons for the promotion of CCN-51 may be legitimate, a stronger focus on native fine or flavour cacaos might offer opportunities for the diversification of production system and value chains (Maas et al. 2020). Selected varieties of Nacional and native cacaos are already distributed to farmers and nurseries in Ecuador and Peru, and the high number of native genotypes conserved in GB/CG in these countries could be further characterized to select genotypes that combine high sensorial quality with high productivity. Furthermore, the recent EU Regulation No. 488/2014 that places a maximum allowable limit to the concentrations of cadmium in cacao beans to be exported in the European market have spurred a search for low accumulating genotypes of native cacaos in Peru and Ecuador (Meter et al. 2019). These regulations especially impact fine or flavour cacao as this is typically used in derivates with high cacao content and cannot be blended to reduce cadmium concentrations which does provide a solution for bulk cacao.

While in Central America cacao genetic resources in farmers' fields, GB/CG and nurseries are dominated by international clones (Orozco-Aguilar et al. 2014; Wiegel et al. 2020; Figs. 1, 2), the recent interest in rediscovering native fine or flavour cacaos may present opportunities to revalue the remaining diversity of national materials. Several research institutes including FHIA and INTA have started projects to rediscover and characterize Criollo trees from famers' fields, but further efforts are required to evaluate and distribute these genotypes to nurseries and farmers so that they can effectively start contributing to national production volumes. Considering that GB/CG in Central America mostly conserve international materials (Fig. 1 descriptor 3, Fig. 3), it is essential to promote the collection of the best local genotypes before they disappear and include them in long-term selection and breeding programs to create new fine or flavour varieties. National materials can be used to develop improved varieties with higher productivity and resistance, possibly by crossing them with international clones. Examples are the INTA-Pacayita developed by INTA (INTA 2018) and CC-137 and ICS-95 developed by CATIE and Imperial Colleges (Phillips-Mora et al. 2013), which are high yielding

Table 5 Summary of breeding programs, selection programs and other research activities in the six countries

	Main breeding programs in the six countries	Are they recurrent programs?	Main varieties generated by the breeding programs	Selection programs and other research activities in the six countries
Peru	ICT, UNAS, UNIQ	No	SHU (2000–2010)	Selection programs resulted in the highly productive and fine flavour clones CMP (known as VRAEM) in the Vraem region and M-54 in Cajamarca
				Several cooperatives, NGOs and national universities have identified and characterized promising genotypes of native and fine flavour cacaos across Peru
				The Alliance of Bioversity International and CIAT together with other actors is identifying genotypes with low cadmium accumulation
Ecuador	INIAP	Yes	EET-19, EET-48, EET-62, EET-95, EET-96 and EET-103 (1970s), EET-544, EET-558, EET-575, EET-576 (2009), EETP-800, EETP-801 (2016)	Several local actors have selected improved varieties such as the "super trees" in the northern Ecuadorian Amazon, PM-12 in the central and northern coast, and JHV-10 in the southern coast
				ESPOL together with INIAP and other organizations are identifying genotypes with low cadmium accumulation
Nicaragua	INTA	No	INTA-Pacayita (2010–2017)	INTA is evaluating international clones from CATIE
				INTA, CIRAD and several national universities promoted projects to identify and rediscover Criollo genotypes
Honduras	FHIA	No	FHIA-168, FHIA-269, FHIA-330, FHIA-662, FHIA-707, FHIA-708, FHAI-738, FHIA-74 (2010–2013)	FHIA has developed several multiclonal planting arrangements with FHIA and CATIE clones for different regions in Honduras according to adaptation to local soil and climatic conditions and sexual compatibility
				FHIA has completed a countrywide identification and characterization of Criollo cacao trees (> 80 genotypes) to find new materials for its breeding program
El Salvador	–	–	–	CENTA, La Carrera Farm, Alianza Cacao El Salvador and other institutes are evaluating the suitability of international clones from CATIE and FHIA for regions in El Salvador
				The government, CENTA, Universidad de El Salvador and Universidad José Matías Delgado have promoted projects to identify Criollo genotypes with fine or flavour traits
				CENTA has selected and evaluated 9 Criollo clones with high productivity and resistance to pests and diseases. The clones are currently tested in experimental plots to be released in 2022

Table 5 continued

	Main breeding programs in the six countries	Are they recurrent programs?	Main varieties generated by the breeding programs	Selection programs and other research activities in the six countries
Guatemala	–	–	–	Bulbuxya Farm and ICTA are evaluating international clones from CATIE Universidad de San Carlos de Guatemala, Universidad del Valle de Guatemala, and the private companies Maya Kakaw and Alta Verapaz have promoted several projects to identify and characterize Criollo genotypes in the country

A detailed list of all the programs and relevant scientific publications is presented in Table S5

and Monilia-resistant clones obtained by crossing Criollo materials with international clones. Considering that only 6% of cultivated cacao comes from international clones of certified varietal purity and most of currently managed varieties were bred during the last three decades from CATIE (Orozco-Aguilar et al. 2014), there is an urgent need to reactivate the national cacao breeding programs in Central America to provide high quality, locally adapted planting material to support the expansion of new areas and conduct renovation/rehabilitation efforts.

In conclusion, this study provides an overview on the current state of conservation and use of cacao genetic resources in Peru, Ecuador, Nicaragua, Honduras, El Salvador, Guatemala. Overall, the main areas for investments in the six countries include: (1) development of a strong system of certification, verification and especially traceability of cacao genetic material in individual countries and for Latin America, (2) better characterization of the materials conserved within the GB/CG and promotion of the best materials in farmers' field and within breeding programs, (3) better characterization of varieties sold in nurseries and improvement of nursery infrastructure, maintenance and technical assistance offered to farmers, (4) promotion of research on native fine or flavour cacaos in Ecuador and Peru, and (5) reactivation of breeding programs using native materials and rediscovery of Criollo cacaos in Central America. In order to support cacao sector in Latin America, we integrated the results from the survey of GB/CG and nurseries from this study into an online tool CacaoDiversity (https://www.cacaodiversity.org/), which provides location-specific information about where to source appropriate propagation material for cacao farms. The tool is currently available for Peru and Ecuador and will be expanded to the other countries in Latin America. Given their role as centre of origin and domestication and the limited diversity of currently cultivated varieties across the world, a better conservation and use of cacao genetic resources in South and Central America would benefit not only these countries but the whole cacao sector globally.

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Availability of data and material Data are provided in supplementary materials.

Declarations

Conflict of interests The authors have no conflicts of interest to declare.

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