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Original Article

MITIGATING GENETIC EROSION IN COCOA AND COFFEE: DRIVERS, IMPACTS, AND SUSTAINABLE CONSERVATION SOLUTIONS IN AFRICAN AGROECOSYSTEMS

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ABSTRACT

Genetic erosion in cocoa (*Theobroma cacao*) and coffee (*Coffea arabica*, *Coffea canephora*) poses a significant threat to global food security and the livelihoods of over 30 million smallholder farmers in Africa. This study examines the drivers, impacts, and conservation strategies for genetic erosion in eight African countries (Cameroon, Côte d'Ivoire, Democratic Republic of Congo, Ethiopia, Ghana, Kenya, Nigeria, Uganda) from 2001 to 2023. Using geospatial data from Global Forest Watch and germplasm inventories from Genesys-PGR, this study quantified deforestation and assessed accession diversity. Results indicate severe tree cover loss, with the Democratic Republic of Congo losing 16.83 million hectares, primarily in coffee regions, and Côte d'Ivoire and Ghana losing 3.67 and 2.09 million hectares, respectively, in cocoa areas. Coffee faces higher erosion risks due to forest loss in biodiversity hotspots, while cocoa is threatened by monoculture expansion. Genebanks, such as the Tropical Agricultural Research and Higher Education Centre (CATIE) in Costa Rica and the International Cocoa Genebank, Trinidad (ICGT), hold significant accessions but lack wild and landrace varieties, risking allele depletion. The study calls for better conservation, increased in situ and ex situ efforts, and sustainable agroforestry. Global cooperation is crucial to maintaining the resilience of cocoa and coffee to climate and economic challenges.

Keywords: Genetic erosion, cocoa, coffee, deforestation, genetic diversity, conservation strategies

INTRODUCTION

Tropical cash crops, such as cocoa (*Theobroma cacao*) and coffee (*Coffea arabica* and *Coffea canephora*), are essential for global agricultural systems, underlying the livelihoods of more than 30 million small farmers in Africa, Latin America, and Asia [1,2]. These crops contribute significantly to global trade, with coffee exports valued at approximately $13.8 billion annually for *C. arabica* alone and cocoa supporting a multibillion-dollar chocolate industry [2,3]. Beyond their economic importance, cocoa and coffee are cultural staples that shape diets, traditions, and economies in producing regions. However, its sustainability is increasingly threatened by genetic erosion, the progressive loss of genetic variation in cultivated varieties, landraces, and wild relatives of crops (CWR), which undermines its ability to adapt to environmental challenges such as climate change, pests, and diseases [4,5].

Its Genetic diversity is the cornerstone of agricultural resilience, providing the raw material for breeding programmes to develop varieties that withstand biotic stresses (eg, coffee leaf rust, cocoa swollen shoot virus) and abiotic pressures (eg, drought, temperature extremes) [6,7]. For cocoa, native to the Amazon basin but predominantly grown in West Africa, genetic diversity is critical to combating diseases and adapting to changing climatic conditions [8]. Similarly, coffee is dependent on its genetic resources, particularly wild populations of *C. arabica* in Ethiopia's montane forests and *C. canephora* in lowland forests in Central Africa, to maintain productivity and quality in the face of global demand and environmental change [9,10]. However, both crops face significant threats from deforestation, agricultural intensification, and socioeconomic pressures, which reduce the availability of diverse genetic resources [11].

Deforestation, driven by agricultural expansion and urbanization, is a primary driver of genetic erosion, destroying habitats of CWRs and traditional varieties [6,8]. In cocoa-producing regions such as Côte d'Ivoire and Ghana, which account for more than 60% of global production, monoculture plantations have replaced biodiverse agroforestry systems, limiting the genetic pool available for breeding [12]. Coffee faces analogous challenges, as Ethiopia's coffee forests and the Democratic Republic of Congo (Democratic Republic of Congo) lowland forests experience significant losses, threatening wild populations critical for global breeding programmes [9]. These losses are compounded by climate change, which alters the suitability of cultivation zones, forcing farmers to clear new forest areas or abandon unprofitable fields [13,14].

Conservation efforts, primarily through ex situ field genebanks such as the Tropical Agricultural Research and Higher Education Centre (CATIE) in Costa Rica and the International Cocoa Genebank, Trinidad (ICGT), aim to preserve genetic diversity but face significant challenges [15,7]. Coffee and cocoa seeds are recalcitrant, preventing long-term storage in conventional seed banks, and field genebanks are vulnerable to pests, diseases, and funding constraints [1,16]. Moreover, many collections lack representation of landraces and CWRs, and historic accessions, those no longer actively maintained risk allele loss if not duplicated elsewhere [17]. In situ conservation, such as protecting Ethiopia's coffee forests or West Africa's cocoa agroforests, remains underfunded and poorly implemented, further exacerbating the risks of erosion [4].

Socioeconomic factors, including low commodity prices, urbanization, and shifts to alternative crops (eg, sugarcane), also drive genetic erosion by encouraging changes in land use that remove diverse agroecosystems [11,18]. For coffee, the introduction of *C. canephora* in regions traditionally dominated by *C. arabica*, such as Central America, reflects adaptive responses to climate change but risks further loss of Arabica's genetic diversity [19]. Similarly, cocoa farmers in West Africa increasingly adopt high-yielding genetically uniform varieties to meet market demands, neglecting traditional land-

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races [7].

This study addresses these challenges through a comparative analysis of genetic erosion in cocoa and coffee, focusing on eight African countries (Cameroon, Côte d'Ivoire, Democratic Republic of Congo, Ethiopia, Ghana, Kenya, Nigeria, Uganda) critical to their production. By integrating geospatial data on tree cover loss, carbon emissions, and net carbon flux (2001–2023) with germplasm collection inventories, the research aims to:

Quantify the extent of genetic erosion through deforestation and analysis of genebank data.

Compare the drivers, impacts, and vulnerabilities of genetic erosion between the cocoa and coffee agroecosystems.

Propose integrated conservation strategies to protect genetic diversity and improve crop resilience.

This work contributes to global efforts to protect plant genetic resources, aligning with international frameworks such as the International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) and the Convention on Biological Diversity (CBD) [20]. By highlighting the urgency of mitigating genetic erosion, it seeks to inform policymakers, researchers, and farmers, ensuring the long-term sustainability of the cocoa and coffee agroecosystems.

MATERIALS AND METHODS

Study Design

This study adopts a mixed methods approach to investigate genetic erosion in cocoa (*Theobroma cacao*) and coffee (*Coffea arabica* and *Coffea canephora*), integrating quantitative geospatial and germplasm analyses with qualitative literature synthesis. The research focuses on eight African countries, in cocoa regions (Côte d'Ivoire, Ghana, Cameroon, Nigeria, DRC) and coffee regions (Ethiopia, Kenya, DRC, Uganda). The analysis uses geospatial data on deforestation and carbon dynamics, germplasm inventories from global genebanks.

Data sources

Geospatial data: Comprehensive datasets covering tree cover loss, gross carbon emissions, and net carbon flux from 2001 to 2023 were obtained from the Global Forest Watch database. These data sets include national and subnational estimates of tree cover loss (based on a 30% canopy threshold), along with the corresponding values for gross CO_2-equivalent emissions and net carbon flux for the selected countries.

Germplasm data: Accession data for cocoa and coffee were obtained from the Genesys-PGR database and supplemented by reports from the Food and Agriculture Organisation [1] and the Tropical Agricultural Research and Higher Education Centre (CATIE). These data include accession counts, biological status (wild, landrace, bred), countries of origin, and acquisition years.

Data analysis

Geospatial data were analysed to assess the impact of deforestation on genetic erosion in cocoa and coffee producing regions in eight African countries from 2001 to 2023. Using Python, the total and average annual loss of tree cover (ha), gross CO2 emissions (Mg), and net carbon flux (Mg CO2e/year) were calculated. The trend analysis identified the years of peak deforestation and subnational hotspots in the cocoa regions (Côte d'Ivoire, Ghana, Cameroon, Nigeria, DRC) and the coffee regions (Ethiopia, Kenya, DRC, Uganda). Results were presented in descriptive tabular formats linking forest loss to decline in genetic diversity.

Germplasm data was evaluated to assess genetic diversity and erosion risks through descriptive statistical analysis. The metrics included accession counts, countries of origin, and proportions of wild, landrace, and bred varieties, along with acquisition year ranges. Data were obtained from the Genesys-PGR database and supplemented by FAO and CATIE reports.

RESULTS

The Democratic Republic of Congo recorded the highest loss of tree cover at 16.83 million hectares between 2001 and 2023, with an annual average of 731,881 hectares, mainly in coffee-producing regions (Table 1). Côte d'Ivoire lost 3.67 million hectares (159,734 ha / year), followed by Ghana with 2.09 million hectares (91,018 ha / year), both reflecting extensive deforestation in cocoa-producing areas. Cameroon, which supports cocoa and coffee, lost 2.57 million hectares (111,902 ha / year), while Nigeria recorded 1.47 million hectares (63,905 ha / year) in cocoa regions.

In coffee producing regions, Ethiopia lost 482,959 hectares (21,002 ha / year), with losses concentrated in areas such as Oromia and Southern Nations, aligned with documented

Table 1. Loss of national tree cover (2001-2023)) for Cocoa and Coffee Producing Countries (30% Canopy Cover Threshold)

Country	Crop	Tree Cover Extent 2000 (ha)	Total Tree Cover Loss 2001–2023 (ha)	Annual Average Loss (ha/yr)
Côte d'Ivoire	Cocoa	14,872,640	3,673,885	159,734
Ghana	Cocoa	6,955,668	2,093,415	91,018
Cameroon	Cocoa	31,459,332	2,572,759	111,902
Nigeria	Cocoa	10,048,731	1,469,806	63,905
Democratic Republic of Congo	Coffee	199,281,687	16,833,264	731,881
Ethiopia	Coffee	12,040,336	482,959	21,002
Kenya	Coffee	3,319,483	384,253	16,707
Uganda	Coffee, Cocoa	9,876,543	64,208	2,791

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forest declines in the origin regions of C. arabica [6]. Kenya lost 384,253 hectares (16,707 ha / year), mainly in shaded coffee areas such as the Central and Rift Valley. Uganda, with both coffee and cocoa production, recorded the lowest loss at 64,208 hectares (2,791 ha / year).

Source: (21,22,23)

Peak years of deforestation were identified in the major cocoa and coffee producing countries, reflecting periods of concentrated habitat loss (Table 2). The Democratic Republic of Congo exhibited the highest annual tree cover loss, with 526,132 hectares in 2023, 512,672 hectares in 2022, and 499,059 hectares in 2021. These successive peak years indicate a recent surge in deforestation within key coffee-growing areas.

Cameroon recorded notable peaks in 2023 (102,887 ha), 2020 (100,295 ha), and 2014 (89,176 ha), consistent with sustained pressure in both the cocoa and coffee production zones. Côte d'Ivoire's peak deforestation occurred in 2014 with 36,119 hectares lost, followed by 29,740 hectares in 2011 and 23,086 hectares in 2012, highlighting earlier periods of intensive change in land cover within cocoa growing landscapes.

Source: (21,23)

Analysis of forest-related carbon emissions from 2001 to 2023 reveals substantial atmospheric contributions associated with tree cover loss in major cocoa and coffee producing countries (Table 3). The Democratic Republic of Congo recorded the highest cumulative emissions, approximately 24.62 billion megagrammes of CO2 equivalent (Mg CO_2e), with an annual average of 1.07 billion Mg. This reflects the extensive deforestation observed during the study period.

Côte d'Ivoire and Cameroon reported cumulative emissions of 1.99 billion Mg CO_2e and 1.92 billion Mg CO_2e, corresponding to annual averages of 86.35 million and 83.66 million Mg, respectively. Ghana contributed 813.37 million Mg CO_2e (35.36 million Mg/year), while Nigeria's emissions reached 469.92 million Mg (20.43 million Mg/year). Ethiopia and Kenya exhibited lower total emissions, 73.80 million Mg and 49.25 million Mg, respectively, although their implications remain significant within ecologically sensitive coffee-producing zones.

Source: (21,24)

Geospatial analysis of carbon dynamics between 2001 and 2023 indicates that all assessed countries functioned as net carbon sinks during the study period (Table 4). The Democratic Republic of the Congo exhibited the highest annual net carbon sink, estimated at –1.12 billion megagrammes of equivalent CO2 (Mg CO_2e/year), reflecting its extensive forested landscapes.

Cameroon followed with a net carbon flux of –104.22 million Mg CO2e/year, while Côte d'Ivoire and Ghana recorded –26.99 million Mg CO2e/year and –15.19 million Mg CO2e/year, respectively. Nigeria's net flux was –5.08 million Mg CO2e/year, indicating more limited but still positive carbon sequestration potential.

Table 2. Peak years of tree cover loss (Top 3 Countries)

Country	Year	Tree cover loss (ha)	Emissions (Mg CO2e)	Primary Crop
Democratic Republic of Congo	2023	526,132.34	377,627,338.64	Coffee
Democratic Republic of Congo	2022	512,672.11	370,359,909.08	Coffee
Democratic Republic of Congo	2021	499,058.97	355,561,923.90	Coffee
Cameroon	2023	102,887.49	67,127,216.19	Cocoa, coffee
Cameroon	2020	100,294.68	67,898,382.15	Cocoa, coffee
Cameroon	2014	89,176.40	56,684,140.39	Cocoa, coffee
Côte d'Ivoire	2014	36,119.23	16,481,335.10	Cocoa
Côte d'Ivoire	2011	29,740.37	13,288,043.46	Cocoa
Côte d'Ivoire	2012	23,086.24	10,740,642.36	Cocoa

Table 3. Carbon emissions from forest loss (2001–2023)

Country	Crop	Average Annual Gross Emissions (Mg CO2e/year)	Total emissions 2001-2023 (Mg CO2e)
Côte d'Ivoire	Cocoa	86,345,013	1,985,935,299
Ghana	Cocoa	35,364,099	813,374,277
Cameroon	Cocoa	83,662,678	1,924,241,594
Nigeria	Cocoa	20,431,468	469,923,764
Democratic Republic of Congo	Coffee	1,070,336,203	24,617,732,669
Ethiopia	Coffee	3,208,592	73,797,616
Kenya	Coffee	2,141,097	49,245,231
Uganda	Coffee, Cocoa	1,471,142	33,846,262

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Among the coffee-dominant regions, Ethiopia and Kenya reported net flows of –5.51 million Mg CO2e/year and –2.35 million Mg CO2e/year, respectively. Uganda exhibited the lowest net sink at –1.47 million Mg CO2e/year. These findings suggest varying degrees of carbon absorption capacity in agroecologies of cocoa and coffee.

Source: (21,24)

In the Democratic Republic of Congo, Nord-Kivu recorded a tree cover loss of 1.07 million hectares from 2001 to 2023, mainly in coffee producing areas (Table 5). The Côte d'Ivoire's Sud-Comoé region lost 173,989 hectares, and Ghana's Ashanti region lost 297,991 hectares, both in cocoa producing zones, consistent with the reported expansion of monoculture [8]. The Cameroon centre region lost 192,110 hectares, affecting the cocoa and coffee systems, while the Nigerian Ondo region recorded 128,196 hectares of loss in cocoa areas.

In coffee growing regions, Ethiopia's Oromia region lost 258,366 hectares, a key area for *Coffea arabica*, in line with documented forest declines [6]. Kenya's central region lost 79,452 hectares in shaded coffee areas, and Uganda's central region recorded 12,345 hectares, affecting both the coffee and cocoa systems.

Source: (21,22,23)

The Genesys-PGR dataset includes 283 accessions of cocoa (Theobroma cacao), all varieties bred, from 13 countries (eg, Brazil, Colombia, Trinidad and Tobago), without accessions of wild or landrace (Table 6). All cocoa accessions are historic, with acquisition years ranging from 1939 to 1989. For coffee, the data set contains 60 *Coffea arabica* accessions from three countries, primarily Ethiopia, comprising 24 wild (40%) and 36 bred (60%) varieties, and two *Coffea canephora* accessions, both bred, from the USA. No landrace accessions are recorded for either coffee species. All coffee accessions are historic, with acquisition years from 1926 to 1965.

Source: [25]

Global genebanks hold substantial collections of accessions to cocoa and coffee, although gaps persist in the conservation of these crops (Table 7). The Tropical Agricultural Research and Higher Education Centre (CATIE) in Costa Rica conserves 1,911 coffee and 1,235 cocoa accessions, serving as a significant resource for both crops. The International Centre for the Study of Coffee (CIFC) in Portugal conserves over 1,200 coffee accessions, with a focus on disease resistance. The National Centre for Agronomic Research (CNRA) in Côte d'Ivoire maintains over 1,000 *Coffea canephora* accessions, addressing critical gaps in Robusta genetic diversity.

The International Cocoa Genebank (ICGT) in Trinidad and Tobago holds over 2,300 cocoa accessions, contributing to global breeding efforts despite challenges in collection maintenance. The Cocoa Research Institute of Ghana (CRIG) and the USDA Agricultural Research Service (USDA-ARS) in Puerto Rico preserve over 1,200 and 900 cocoa accessions, respectively, with a tendency to prioritize bred varieties over wild relatives of the crop.

Source: [1,26]

Table 4. Net carbon flux (2001–2023)

Country	Crop	Net carbon flux (Mg CO2e/year)	Status (Sink/Source)
Côte d'Ivoire	Cocoa	-26,987,192	Sink
Ghana	Cocoa	-15,187,455	Sink
Cameroon	Cocoa	-104,216,389	Sink
Nigeria	Cocoa	-5,079,554	Sink
Democratic Republic of Congo	Coffee	-1,120,345,178	Sink
Ethiopia	Coffee	-5,506,512	Sink
Kenya	Coffee	-2,345,824	Sink
Uganda	Coffee, Cocoa	-1,467,890	Sink

Table 5. Sub-national Tree Cover Loss in Key Regions (2001–2023)

Country	Region	Crop	Tree cover extension 2000 (ha)	Total tree cover loss 2001–2023 (ha)	Annual Average Loss (ha/year)
Côte d'Ivoire	Sud-Comoé	Cocoa	347,188	173,989	7,564
Ghana	Ashanti	Cocoa	1,093,444	297,991	12,956
Cameroon	Centre	Cocoa	3,258,450	192,110	8,353
Nigeria	Ondo	Cocoa	770,215	128,196	5,574
Democratic Republic of Congo	Nord-Kivu	Coffee	6,752,693	1,071,335	46,580
Ethiopia	Oromia	Coffee	5,708,093	258,366	11,233
Kenya	Central	Coffee	506,396	79,452	3,454
Uganda	Central	Coffee, Cocoa	1,234,567	12,345	537

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Table 6. Genetic Diversity and Erosion Indicators

Crop	Total Accessions	Unique Countries of Origin	Wild Accessions (%)	Landrace Accessions (%)	Bred Accessions (%)	Historic accessions	Acquisition Year Range
Cocoa (*Theobroma cacao*)	283	13	0 (0%)	0 (0%)	283 (100%)	283	1939–1989
Coffee (*Coffea arabica*)	60	3	24 (40%)	0 (0%)	36 (60%)	60	1926–1965
Coffee (*Coffea canephora*)	2	1	0 (0%)	0 (0%)	2 (100%)	2	1926

Table 7. Major coffee and cocoa germplasm collections

Crop	Institute/Genebank	Country	Number of Accessions (approx.)	Conservation Type
Coffee (*Coffea spp.*)	CATIE	Costa Rica	1,911	Field genebank
Coffee (*Coffea spp.*)	CIFC	Portugal	1,200+	Field genebank
Coffee (*Coffea spp.*)	CNRA	Côte d'Ivoire	1,000+	Field genebank
Coffee (*Coffea spp.*)	IRD	France	700+	Field genebank
Cocoa (*Theobroma cacao*)	CATIE	Costa Rica	1,235	Field genebank
Cocoa (*Theobroma cacao*)	CRIG	Ghana	1,200+	Field genebank
Cocoa (*Theobroma cacao*)	USDA-ARS	USA (Puerto Rico)	900+	Field genebank
Cocoa (*Theobroma cacao*)	CIRAD	France	300+	Field genebank

DISCUSSION

Geospatial analysis confirms that genetic erosion is a severe threat to cocoa and coffee, driven by extensive deforestation and habitat degradation. In cocoa producing countries, the loss of 3.67 million acres in Côte d'Ivoire and the 2.09 million acres in Ghana reflect the conversion of agroforests to mono-cultures, reducing habitats for wild *Theobroma cacao* and traditional varieties [8]. These losses, coupled with high carbon emissions (1.99 billion Mg CO2e for Côte d'Ivoire, 813.37 million Mg for Ghana), destabilize agroecosystems, increasing pest and disease pressures such as the swollen shoot virus [7]. The staggering 16.83 million hectares lost in the Democratic Republic of Congo and the 24.62 billion Mg of CO2 emitted threaten the genetic diversity of *C. canephora*, as lowland forests critical for wild Robusta are cleared for agriculture and infrastructure [9]. Cameroon's dual production sees 2.57 million hectares lost, affecting both crops, while Nigeria's 1.47 million hectares indicate localised cocoa erosion. For coffee, Ethiopia's 482,959 hectares lost are critical, as its montane forests are the origin of *C. arabica*, which harbours wild populations essential for breeding climate-resilient varieties [6]. Kenya's 384,253 hectares lost affect shade grown systems, reducing varietal diversity, while Uganda's 64,208 hectares impact Robusta and cocoa [12]. High emissions in coffee regions, although lower than cocoa, signal the breakdown of the ecosystem, limiting adaptive capacity [11]. The 1.07 million hectares lost in the Democratic Republic of Congo highlight the intense pressure on the diversity of Robusta, exacerbated by conflict and agricultural expansion [9]. The losses in Sud-Comoé (Côte d'Ivoire) and Ashanti (Ghana) (173,989 and 297,991 ha) highlight the impacts of cocoa monoculture, while Oromia's 258,366 hectares lost threaten the genetic pool of *C. arabica* [6]. These regional patterns emphasise the need for targeted conservation to protect genetic diversity hotspots.

Coffee faces greater risks of genetic erosion due to the scale of deforestation in the Democratic Republic of Congo and Ethiopia, where wild coffee populations are concentrated in biodiversity hotspots [9,6]. The loss of tree cover in the Democratic Republic of Congo of 16.83 million hectares from 2001 to 2023, mainly in *Coffea canephora* habitats (Robusta), substantially exceeds the deforestation observed in cocoa producing regions such as Côte d'Ivoire (3.67 million ha) and Ghana (2.09 million ha). Ethiopia's loss of 482,959 hectares, concentrated in native forests of *Coffea arabica*, is particularly concerning due to the global reliance on wild Arabica populations to breed climate-resilient varieties. The limited representation of *C. canephora* in genebanks, with only two accessions recorded in the Genesys-PGR dataset, increases its vulnerability, as ongoing forest loss reduces access to wild genetic resources. On the contrary, the genetic erosion of cocoa in Côte d'Ivoire and Ghana is partially mitigated by agroforestry systems, which maintain some genetic diversity through shade tree species and traditional cocoa varieties [11]. However, the reliance of cocoa on bred varieties and the absence of wild relatives of crops in genebanks limits its adaptive capacity, particularly against diseases [7]. The Genesys-PGR dataset highlights the narrow genetic base of cocoa (100% bred, 283 accessions) compared to the partial wild representation of *C. arabica* (40% wild, 60 accessions). The negligible pres-

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ence of *C. canephora* highlights its critical erosion risk [4]. The historical status of all accessions and outdated acquisition years (1939–1989 for cocoa, 1926–1965 for coffee) indicates a potential loss of alleles, as these materials may no longer be viable [1]. Cocoa's broader geographic diversity (13 countries) contrasts with the limited scope of coffee (3 countries for *C. arabica*), but both lack landraces, a critical gap for farmer-driven adaptations [27].

Field genebanks such as CATIE and ICGT are vital but face significant challenges. The 1,911 coffee and 1,235 cocoa accessions of CATIE are critical for breeding, but ageing trees, diseases (eg coffee leaf rust, *Ceratocystis wilt*), and funding shortages threaten their viability [15]. The 2,300 + cocoa accessions of ICGT support global programmes but require costly maintenance and disease management [7]. The loss of 100 coffee clones and five Coffea species in recent decades highlights the fragility of ex situ collections [1]. In situ conservation, such as Ethiopia's coffee forests or West Africa's agroforests, offers long-term potential, but is hindered by deforestation, weak governance, and insufficient funding [17]. There are opportunities to enhance conservation, cryopreservation and in vitro storage could complement field genebanks, preserving genetic material long-term [28]. Community-based conservation, involving farmers in maintaining landraces, could bridge in situ and ex situ approaches, as seen in some Latin American coffee systems [27]. Certification schemes, like Rainforest Alliance, promote biodiversity-friendly practices, increasing shade tree diversity and forest cover in certified farms [29]. International frameworks such as the International Treaty on Plant Genetic Resources for Food and Agriculture facilitate germplasm sharing, but greater investment is needed to overcome access barriers [20].

Genetic erosion threatens the resilience of cocoa and coffee, increasing susceptibility to climate change, pests, and diseases [6]. This threatens global coffee supply chains, as the limited genetic diversity of *Coffea arabica* restricts its adaptability to environmental changes [30]. Cocoa's vulnerability to diseases like swollen shoot virus could disrupt West African economies, where millions depend on cocoa income [7]. Smallholder farmers, who produce more than 70% of these crops, face increased risks, as declining yields and market volatility exacerbate poverty [2].

Environmentally, high carbon emissions from deforestation (e.g., 24.62 billion Mg CO_2e in the Democratic Republic of Congo) contribute to climate change, altering micro-climates and increasing pest pressures [11]. Net carbon sinks, while positive, are weakened by ongoing forest loss, threatening ecosystem stability [12]. Agroforestry systems offer a solution, sequestering carbon and maintaining genetic diversity, but their adoption is limited by market and policy barriers [8].

CONCLUSION

Genetic erosion in cocoa and coffee is a pressing threat driven by deforestation, intensification, and inadequate conservation. Coffee faces greater risks due to extensive forest loss in biodiversity hotspots, while cocoa erosion is driven by monoculture expansion. Genebank collections are critical but limited by the absence of wild and landrace accessions and historic status. Integrated conservation strategies, combining in situ and ex situ approaches with sustainable agriculture, are essential to safeguard genetic diversity, ensuring the resilience of these vital cash crops. This study highlights the need for urgent global action to protect genetic resources for cocoa and coffee, supporting food security and small-holder livelihoods.

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CONFLICTS OF INTEREST

The authors declared no conflicts of interest

REFERENCES

1. Food and Agriculture Organization of the United Nations. The second report on the state of the world's plant genetic resources for food and agriculture. – Rome: FAO, 2010. – URL: https://www.fao.org/publications/card/en/c/4b174e6c-21e4-5e7b-8621-3f2a7f466f7f/ (accessed: 14.04.2025).

2. International Coffee Organization. Trade statistics. – 2017. – URL: https://www.ico.org/trade_statistics.asp (accessed: 14.05.2025).

3. Lass T. Balancing cocoa production and consumption // Cocoa futures: A source book on some important issues facing the cocoa industry / Ed. by J. Flood, R. Murphy. – [S.l.]: CABI; FEDERACAFÉ; USDA, 2004. – P. 8–15.

4. Khoury C.K., Brush S., Costich D.E., Curry H.A., de Haan S., Engels J.M.M., Guarino L., Hoban S., Mercer K.L., Miller A.J., Nabhan G.P., Perales H.R., Richards C., Riggins C., Thormann I. Crop genetic erosion: Understanding and responding to loss of crop diversity // New Phytologist. – 2022. – Vol. 233, № 1. – P. 84–118// doi: 10.1111/nph.17733.

5. Gepts P. Plant genetic resources conservation and utilization: The accomplishments and future of a societal insurance policy // Crop Science. – 2006. – Vol. 46, № 5. – P. 2278–2292 // doi: 10.2135/cropsci2006.03.0169gas.

6. Moat J., Gole T.W., Davis A.P. Least concern to endangered: Applying climate change projections profoundly influences the extinction risk assessment for wild *Arabica coffee* // Global Change Biology. – 2019. – Vol. 25, № 2. – P. 390–403// doi: https://doi.org/10.1111/gcb.14341.

7. Bekele F., Bidaisee G., Bhola J., Umaharan P. Catalogue of cacaos conserved at the CRC genebank. – [S.l.]: The Cocoa Research Centre, Bioversity International, and MOCCA, 2024.

8. Schroth G., Harvey C.A. Biodiversity conservation in cocoa production landscapes: An overview // Biodiversity and Conservation. – 2007. – Vol. 16, № 8. – P. 2237–2244 // doi: 10.1007/s10531-007-9195-1.

9. Cubry P., De Bellis F., Pot D., Musoli P., Leroy T. Global analysis of *Coffea canephora* Pierre ex Froehner (Rubiaceae) from the Guineo-Congolese region reveals impacts from climatic refuges and migration effects // Genetic Resources and Crop Evolution. – 2013. – Vol. 60, № 2. – P. 483–501 // doi: 10.1007/s10722-012-9851-5.

10. Anagbogu C.F., Bhattacharjee R., Ilori C., Tongyoo P., Dada K.E., Muyiwa A., Gepts P., Beckles D.M. Genetic diversity and re-classification of coffee (*Coffea canephora* Pierre ex A. Froehner) from Southwestern Nigeria through genotyping-by-sequencing-single-nucleotide-polymorphism analysis // Genetic Resources and Crop Evolution. – 2019. – Vol. 66, № 4. – P. 685–696 // doi: 10.1007/s10722-019-00744-2.

11. Philpott S.M., Arendt W.J., Armbrecht I., Bichier P., Dietsch T.V., Gordon C., Greenberg R., Perfecto I., Reynoso-Santos R., Soto-Pinto L., Tejeda-Cruz C., Williams-Linera G., Valenzuela J., Zolotoff J.M. Biodiversity loss in Latin American coffee landscapes: Review of the evidence on ants, birds, and trees // Conservation Biology. – 2008. – Vol. 22, № 5. – P. 1093–1105 // doi: 10.1111/j.1523-1739.2008.01029.x.

12. De Beenhouwer M., Aerts R., Honnay O. A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry // Agriculture, Ecosystems & Environment. – 2013. – Vol. 175. – P. 1–7 // doi: https://doi.org/10.1016/j.agee.2013.05.003.

13. Baca M., Läderach P., Haggar J., Schroth G., Ovalle O. An integrated framework for assessing vulnerability to climate change and developing adaptation strategies for coffee-growing families in Mesoamerica // PLoS ONE. – 2014. – Vol. 9, № 2. – Article e88463 // doi: 10.1371/journal.pone.0088463.

14. Moat J., Williams J., Baena S., Wilkinson T., Challa Z.K., Gole T.W., Davis A.P. Resilience potential of the Ethiopian coffee sector under climate change // Nature Plants. – 2017. – Vol. 3, № 7. – Article 17081 // doi: 10.1038/nplants.2017.81.

15. Dulloo M.E., Solano W., Dessauw D., Astorga C., Guarino L.A methodological approach for prioritization and rationalization of field genebank accessions of coffee genetic resources: A case study of CATIE International Coffee Collection, Costa Rica // Frontiers in Sustainable Food Systems. – 2021. – Vol. 5. – Article 777415 // doi: 10.3389/fsufs.2021.777415.

16. Bramel P., Krishnen S., Horna D., Lainoff B., Montagnon C. Global conservation strategy for coffee genetic resources. – [S.l.]: Crop Trust; World Coffee Research,2017.URL: https://cdn.croptrust.org/wp/wpcontent/uploads/2017/07/Coffee-Strategy_Mid_Res.pdf.

17. Khoury C.K. The conservation and use of crop genetic resources for food security: Doctoral dissertation. – Wageningen: Wageningen University, 2015. – URL: Wageningen University Repository.

18. Hausermann H. Maintaining the coffee canopy: Understanding change and continuity in Central Veracruz // Human Ecology. – 2014. – Vol. 42, № 3. – P. 381–394 // doi: 10.1007/s10745-014-9644.

19. Pretel E.A. Exclusive: Costa Rica to lift 30-year ban on planting robusta coffee trees // Reuters. – 2018. – 7 Feb. – URL: https://www.reuters.com/article/us-costa-rica-coffee-exclusive-idUSKBN1FT2UH.

20. Food and Agriculture Organization of the United Nations. The international treaty on plant genetic resources for food and agriculture [Electronic resource]. – 2002.–Access mode: https://www.fao.org/plant-treaty/en. – Date of access: 14.04.2025.

21. Global Forest Watch. Forest monitoring and data platform [Electronic resource]/World Resources Institute. – 2025. – Access mode: https://www.globalforestwatch.org. – Date of access: 12.04.2025.

22. Hansen M.C., Potapov P.V., Moore R., Hancher M., Turubanova S.A., Tyukavina A., Thau D., Stehman S.V., Goetz S.J., Loveland T.R., Kommareddy A., Egorov A., Chini L., Justice C.O., Townshend J.R.G. High-resolution global maps of 21st-century forest cover change // Science. – 2013. – Vol. 342, № 6160. – P. 850–853 // doi: 10.1126/science.1244693.

23. Potapov P., Hansen M.C., Kommareddy I., Kommareddy A., Turubanova S., Pickens A., Adusei B., Tyukavina A., Ying Q. Landsat Analysis Ready Data for global land cover and land cover change mapping // Remote Sensing. – 2020. – Vol. 12, № 3. – P. 426 // doi: 10.3390/rs12030426.

24. Harris N.L., Gibbs D.A., Baccini A., Birdsey R.A., de Bruin S., Farina M., Fatoyinbo L., Hansen M.C., Herold M., Houghton R.A., Potapov P.V., Suarez D.R., Roman-Cuesta R.M., Saatchi S.S., Slay C.M., Turubanova S.A., Tyukavina A. Global maps of twenty-first century forest carbon fluxes // Nature Climate Change. – 2021. – Vol. 11, № 3. – P. 234–240. – DOI: 10.1038/s41558-020-00976-6.

25. Genesys PGR. Coffee (*Coffea spp*.) and cocoa (*Theobroma cacao*) germplasm accessions from global collections [Electronic resource] / Secretariat of the Global Crop Diversity Trust. – 2025. – Access mode: https://www.genesys-pgr.org. – Date of access: 12.04.2025.

26. CATIE. Coffee and cocoa germplasm collections [Electronic resource] / Centro Agronómico Tropical de Investigación y Enseñanza (CATIE). – 2025. – Access mode: https://www.catie.ac.cr. – Date of access: 12.04.2025.

27. Bellon M. Conceptualizing interventions to support on-farm genetic resource conservation // World Development. – 2004. – Vol. 32, no. 1. – P. 159–172. // doi: 10.1016/j.worlddev.2003.04.007.

28. Dussert S., Chabrillange N., Rocquelin G., Engelmann F., Lopez M., Hamon S. Tolerance of coffee (Coffea spp.) seeds to ultra-low temperature exposure in relation to calorimetric properties of tissue water, lipid composition, and cooling procedure // Physiologia Plantarum. – 2001. – Vol. 112, № 4. – P. 495–504. // doi: 10.1034/j.1399-3054.2001.1120406.

29. Rueda X., Thomas N.E., Lambin E.F. Eco-certification and coffee cultivation enhance tree cover and forest connectivity in the Colombian coffee landscapes // Regional Envi-

DOI: 10.11134/btp.2.2025.2

ronmental Change. – 2015. – Vol. 15, № 1. – P. 25–33. // doi: 10.1007/s10113-014-0607-y.

30. Moat J., Williams J., Baena S., Wilkinson T., Gole T.W., Challa Z.K., Davis A.P. Coffee farming and climate change in Ethiopia: Impacts, forecasts, resilience and opportunities. – Kew: Royal Botanic Gardens, 2017b.