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Ecosystem service bundles associated with agrobiodiversity in agroforestry systems: A case study of two coffee-growing regions of Haiti

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ABSTRACT

Smallholder Coffee agroforestry systems (CAFS) deliver ecosystem services bundles crucial to farmer livelihoods, resilience of rural communities, maintenance of natural processes, and biodiversity conservation. Their importance is likely greatest in countries with vulnerable populations such as Haiti. Nevertheless, little is known about service delivery by Haitian CAFS. Therefore, we characterized the agrobiodiversity of 39 representative CAFS in two coffee-growing regions of Haiti (North and Southwest), and the multiple services they support. We investigated associations between the composition and structure of agrobiodiversity and service delivery. To that end, CAFS typologies were established from variables pertaining to coffee genetic diversity, stand structure and injury profiles, shade tree and associated crop diversity, and bioclimate. Associations between typologies were investigated. We also established a typology based on delivered services related to coffee performance, species and nutritional diversity, tree uses, carbon storage, and nitrogen availability. Surveyed coffee plots were generally varietally diverse, aging, and subject to pest and diseases. Most CAFS occurred on a spectrum of farm regeneration (old to renewed coffee plots) tied to the adoption of "modern" coffee varieties, with implications for ecosystem service delivery. Furthermore, we described 3 distinct ecosystem service bundles delivered by CAFS: subsistence-, coffee performance-, and tree utility-maximizing bundles, respectively. Finally, our results highlight the importance of the tree strata for ES, including conservation of native species. Overall, our study contributes to the still-limited knowledge of Haitian CAFS agrobiodiversity. Trade-offs between certain services, and absence of trade-offs between others, signal possible CAFS improvement pathways.

1. Introduction

Biodiversity underlies or enhances the delivery of several key ecosystem services upon which human and non-human communities rely (Daily, 1997). This is true of both natural and agricultural systems (Altieri, 1999). The former rely largely on agrobiodiversity, which can be defined as the diversity of organisms that contribute in a broad sense to food production and agriculture, and are associated with cropping and livestock raising within ecological complexes (Jackson et al., 2013). Agrobiodiversity can be promoted by several diversification practices, from crop-specific ones such as variety mixtures (Wuest et al., 2021; Reiss and Drinkwater, 2018) to system-wide approaches such as

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intercropping (Li et al., 2021; Machado, 2009). Agrobiodiversity can support crop yields, but also pest and disease regulation, nutrient cycling and erosion control, and can buffer against shocks to production systems (Jose, 2009; Renard and Tilman, 2021). Diversification is often at the core of agroforestry systems (Fig. 1A). In fact, some (e.g. traditional homegardens) rank among the most diversified cropping systems, combining dozens or hundreds of useful perennial and annual plants (Fernandes and Nair, 1986; Sharma et al., 2022). As such, they are central to the livelihood and resilience of many rural communities, and to the conservation of natural biodiversity in the face of ecological degradation, particularly in impoverished countries.

The Republic of Haiti exemplifies this important role: the country is faced with several economic and socio-political challenges that have left its mostly-rural population vulnerable. Furthermore, it has experienced a history of severe deforestation and natural habitat loss stretching from the time of European colonization, putting the delivery of ecosystem services at risk (Mompremier et al., 2022; Louis et al., 2024; Tarter et al., 2016). Agroforestry systems have helped mitigate this by providing farmers' needs for food, fuel, cash, and ability to manage risks (Steckley and Weis, 2016; Tarter et al., 2016; Sabin et al., 2022). This role has become more crucial in recent years, as widespread insecurity and instability has led to food shortages throughout the country (IPC, 2024). Furthermore, as a major part of Haiti's forest cover, agroforests provide important habitat for wild species and help protect soils and watersheds (Feller et al., 2006). The ecosystem service framework is particularly useful in cases like Haiti's, with much of its land subject to anthropic management and use, and scant political, social or economic resources for addressing ecological concerns.

As the ecosystem service studies have become well-established in recent decades, increasing attention has been paid to the fact that services are seldom delivered independently of one another, but rather often coincide spatially and/or temporally (Bennett et al., 2009; Meacham et al., 2022; Saidi and Spray, 2018; Finney et al., 2017). These so-called "ecosystem service bundles" occur because (dis)services can stem from interconnected elements of ecosystem structure and function, as well as human management and use. As such, they incorporate synergies and tradeoffs between multiple services, and are thus often more useful to researchers and decisionmakers than considering services separately. Here we apply this concept on Haitian coffee-based agroforests.

Coffee (*Coffea arabica* L.) has been a central component of Haitian smallholder agroforestry systems, also called Creole Gardens. From its introduction in 1726, coffee was central to the Haitian economy, and remained the main agricultural export well into the 1970s (Marquese and Rafael, 2022; Trouillot, 1982; Moral, 1955). However, faced with pest and disease (particularly the coffee leaf rust, *Hemileia vastatrix,* hereafter "Rust") outbreaks, government neglect, soil degradation, natural disasters and stand aging, Haitian coffee-based agroforestry systems (CAFS) have seen their yields severely reduced (Amaya et al., 1999; Vital, 2014; Arias et al., 2006). Despite this, Haitian coffee remains potentially attractive to specialty markets as an ethical, environmentally-friendly shade coffee provided proper post-harvest processing, especially as the historically significant, high-cup quality Typica variety is still prevalent (Millet et al., 2024a; Millet et al., 2024b).

Haitian CAFS typically have low management intensity and negligible (if any) agrochemical use. While Typica is the main cultivated variety, several farms feature multiple Arabica variety mixtures, considerable genetic mixing, and dynamic generation of diversity enabled by plant material exchange networks and regeneration of coffee plots by germination from the seed bank (Millet et al., 2024a). Therefore, these systems display diversity at several levels, from CAFS-wide species diversity to intraspecific coffee genetic and varietal diversity. However, agrobiodiversity (at any level) in Haitian CAFS has been little studied (but see Jean-Denis et al., 2014; Millet et al., 2024a,b), and its implication in the delivery of ecosystem services merits scientific attention.

Indeed, CAFS can vary greatly in the structure and complexity of their plant communities, influenced by farmer choices and management and in turn influencing them, with implications on service delivery. They range from rows of coffee grown under one or two carefully selected shade tree species to forest-like systems with hundreds of species (Toledo and Moguel, 2012). This leads to a diversity of ecological interactions that can generate synergies as well as trade-offs between coffee yields, pest and disease regulation, and other services (Allinne et al., 2016; Power, 2010). There exists a complex interplay of different components of CAFS structure such as coffee plot characteristics, shade extent and shade tree identity, and pest and disease assemblages (Durand-Bessart et al., 2020). For example, shade provided by the tree strata can have both direct and indirect, positive and negative effects on coffee disease incidence (Durand-Bessart et al., 2020; Motisi et al., 2022). Furthermore, this diversity of coffee-cropping systems exists on a spectrum of socio-economic and ecological sustainability, and so trajectories towards greater system resilience are highly context-specific (Poncet et al., 2024). However, there exists methodological frameworks to adequately characterize the different CAFS components and the ecosystem (dis)services they underly (Allinne et al., 2016; Bianconi et al., 2013; Teixeira et al., 2022).

Such frameworks fall under the umbrella of systemic agroecology, which aims to take a general view of agroecosystems and interactions between their various components (Rapidel et al, 2015), such as trees, crops, groundcover, pest and disease assemblages, etc. One major use of systemic agroforestry is diagnostic: pathways for CAFS improvement can be proposed through identification of "model" systems in which tradeoffs between services are minimized (Cerda et al., 2020). The identification of appropriate diversification trajectories to maximize resilience and ecosystem service delivery necessitates multi-dimensional approaches that incorporate the system's complexity. One simple strategy, proven effective, is to itemize their components, and reducing complex data into more manageable ones through multifactorial statistical analyses. Variable clusters representing the components of the system can then be described, and associations between them investigated (e.g. see Savary et al., 1997; Allinne, Savary, and Avelino, 2016; Bhattarai et al., 2017). Intra-specific genetic diversity, however, is seldom included in such studies despite likely impacts on system function and ecosystem services (Hajjar et al., 2008). Such methods are also useful to describing service bundles (Wu et al., 2022; Raudsepp-Hearne et al., 2010).

Here we use this methodology, on a set of Haitian agroforestry systems, in two historically important coffee growing regions which have since seen their yields significantly decline. Our objectives were to i) characterize coffee (genetic), crop, and shade tree diversity and structure within Haitian CAFS, ii) identify links between the composition and structure of this diversity and the delivery of major ecosystem services, iii) identify associations between services and iv) propose ways to increase service delivery through insight from the better-performing systems.

2. Materials and methods

2.1. Selection of study sites

A preliminary survey of 122 Non-intensive, diversified smallholder CAFS took place in 2021 in two administrative departments, Nord and Grande-Anse (northern and southern Haiti, respectively). These were conducted by the multilaterally-funded Agricultural and Agroforestry Technological Innovation Program (PITAG). Of these, 39 were subsequently surveyed in-depth (Feb-Mar. 2021), selected to represent a broad geographic spread and farm owner demographics (age, gender…). Data on variable categories relating to coffee management and injury profiles (pests and disease), tree cover and associated crops were measured in the field, and farmer-reported information about the farms, such as their surface area and their productivity, were recorded. KoboToolbox software (https://www.kobotoolbox.org/) was used for all field surveys. Twenty-eight of these farms (14 per department) were also sampled for genotyping studies aimed at characterizing their genetic diversity (Millet et al., 2024a). In many cases, the CAFS were part of a broader farm system which included other plots without coffee (and with or without tree cover). In this study, unless specified, we only refer to the parts of the farming system that constitute coffee-based agroforestry, even when the term "farm" is used over "CAFS" for legibility (see Fig. S1 for illustration). CAFS ranged from 0.04 to 5.5 ha (0.9 ha on average). In total, five municipalities (communes) were included: Bahon, Dondon and Grande Rivière du Nord in the Nord; and Beaumont and Pestel in Grande-Anse.

2.2. Data Acquisition

2.2.1. Coffee tree phenotyping and injury profiles

In each farm, 1000 m^2 coffee tree survey quadrats were established. Coffee trees were counted, and 14 to 16 individuals were phenotyped in the following manner: starting from the center, four trees were randomly selected in each of the cardinal directions. For each tree, the number of vertical axes and number of primary branches on the three main vertical axes were counted. On three primary branches per tree (located in the upper, middle and lower third of the coffee tree crown, respectively), the number of nodes and standing leaves per branch were counted. These were used to calculate percent defoliation rates in coffee trees (hereafter "% leaf loss"). This indicator is taken to represent leaf losses due to pests, diseases, senescence, and nutritional deficiencies, and therefore to indicate the overall healthiness of the tree. On all coffee trees, visible diseases and evidence of pest activity were recorded (as presence/absence). System-wide incidence of recorded pests and diseases (as proportion of affected trees) and percent pest and disease-free trees were then calculated.

2.2.2. Non-coffee trees and crops

To survey cover trees, a 1000 m^2 representative square quadrat was established in each CAFS, and the tree identity and diameter at breast height (dbh) of all major axes (trunks) were recorded. Associated crops were also surveyed by establishing representative 100 m^2 square quadrats, and recording the identity and number of each species therein.

2.2.3. Coffee genetic diversity variables

In the 28 genotyped CAFS, twenty coffee plants were sampled for genotyping, for a total of 607. As this took place during a different phase of the PITAG project, these were not necessarily the same trees on which the previously described measurements were taken. The genetic diversity data used in the present study was generated in Millet et al., (2024b). Sampled plants were assigned to five varietal groups using targeted genotyping of 87 biallelic Single Nucleotide Polymorphism markers via comparison to reference accessions. For the present study, we used varietal group presence/absence data, total number of varietal groups represented per farm, and gene diversity (expected heterozygosity, H_e). We also calculated the proportion of admixed individuals per farm, defined as individuals having $<$ 80 % contribution from any one varietal group, thereby likely resulting from inter-varietal genetic mixing.

2.2.4. Bioclimatic variables

Worldwide data for the 19 standard Bioclimatic variables (1970–2000 average) and elevation were downloaded at 30 s resolution from Worldclim (version 2.1). Data at sampled coordinates was then extracted with R package Raster (v 3.6–20, Hijmans, 2010). The five most relevant bioclimatic variables for coffee cultivation (Bio01-Annual temperature, Bio02-Diurnal range, Bio04-Temperature seasonality, Bio12-Annual precipitation and Bio15-Precipitaiton seasonality) were retained for analyses and checked for non-redundancy.

2.3. Ecosystem service indicators

In studies of ecosystem service delivery, consideration must be given to the appropriate choice of indicators (Van Oudenhoven et al., 2018). We chose to focus on indicators which were relevant to the Haitian context, in which agroforests play a crucial role in the material well-being of the communities that manage them. As such, we prioritized proxies for services that are directly beneficial to farmers, though some are also relevant for biodiversity conservation and other environmental concerns (Table S1). These all fall under the CICES ver 5.2 Provisioning, Regulation and Maintenance, and Cultural (Biotic/Biophysical; https://cices.eu/).

2.3.1. Coffee farm productivity

Farmers were asked how they would describe the average coffee productivity of their coffee plots over the past three years, in the commonly-used local unit of *marmite* which corresponds to approximately 2.7 kg of Coffee (a *marmite* is a standard n^o 10, ~110 oz tin can, universally used as a measuring cup for retail in local markets). This was used along with reported CAFS surface area to calculate an indicator of Coffee production, defined here as the actual yield accessed by farmers (coffee harvest).

2.3.2. Carbon sequestration and nitrogen cycling services

A conservative estimate of Above-Ground Biomass was calculated from the tree cover quadrat data and wood density estimates (at lowest taxonomic level) via allometric equations (Chave et al., 2014) using the R package BIOMASS v. 2.1.11 (Réjou-Méchain et al., 2016). In addition, we calculated AGB using the allometric equation for fruit trees proposed by Andrade et al (2022) and verified that both estimates were strongly correlated. We also calculated the proportion of nitrogen fixing species in the cover tree strata (total dbh—diameter at breast height—of Fabaceae/total dbh of all trees, per CAFS, hereafter $\varnothing_{legumes}/\varnothing_{total}$). While nitrogen fixation by legumes does not always translate to high availability for crops (Sauvadet et al., 2021; Palm, 1995), this can be considered an indicator of potential contribution by trees to nitrogen entry in the agrosystem (Herridge et al., 2008).

2.3.3. Tree and crop diversity

Mean abundance of associated crops per 1000 m^2 was calculated and combined with tree cover data to calculate species richness and Shannon and Simpson diversity indices per CAFS (excluding coffee) using the R package 'vegan' v. 2.6-4chili r (Oksanen et al., 2001). These indices were also calculated exclusively on tree data and on associated crop data, respectively.

2.3.4. Tree usefulness

In order to assess the usefulness to farmers of non-coffee trees in the CAFS, we described potential uses for each tree using categories from the Kew World useful plant species checklist (Diazgranados et al., 2020). We retained six categories of direct material importance to farmers ("Human food", "Invertebrate food", "Animal food", "Materials", "Medicine" and "Fuel") and omitted the other four either because of redundancy with our other indicators ("Environmental use", "Gene source"), or because their context-specific uses may not apply to our systems ("Poisons", "Social use"). In some cases, the Kew checklist did not list uses which were included in other sources specific to Haiti (Timyan, 1996; Koohafkan and Lilin, 1989). In others, it reported uses as "Human food" for species for which we could find no mention of this use by Haitians in the literature. In such cases, modifications were made to the species' usage lists. We then calculated a utility score per CAFS (as number of individuals of a species per CAFS × number of uses for its species, summed across all species).

2.3.5. Percent native species

As an indicator of biodiversity conservation, we calculated for each

CAFS the percentage of species which are native to Haiti in relation to the total species richness. Native status was determined according to the Kew Plants of the World Online database (https://powo.science.kew.org/).

2.3.6. CAFS contribution to household dietary diversity

As CAFS in Haiti were seldom restricted to coffee production, we sought to identify their contribution to household dietary diversity (hereafter Dietary contribution), as a food provisioning service. A score was calculated for each CAFS by tallying the number of food groups represented in the crop and tree data; only trees with reported "Human food" use were considered. We followed the Household Dietary Diversity Score (HDDS, Swindale and Bilinsky, 2006; Kennedy et al., 2011) methodology. Among the food groups listed in the score calculator, the following were applicable: "Roots, tubers and starches", "vegetables", "Fruits", "Pulses, legumes, nuts", and "Sugar/honey". Some species belonged to two food groups: e.g. *Anacardium occidentale* being both a fruit and a nut, and were counted twice.

2.4. Statistical analyses

When unspecified, the analyses were performed using R Stats base package.

2.4.1. CAF typologies

We sought to describe CAFS and classify them according to associations between their components using multivariate analyses. To that end, we established a typology of CAFS according to variable categories describing different components (after Savary et al., 1997; Allinne et al., 2016), including three components of CAF diversity: Coffee genetic and varietal diversity ("Gen"), Tree cover ("Tree"), and Associated Crops ("Crop"); as well as three additional system descriptors: Coffee plot structure ("Plotstructure"), Bioclimatic environment ("Clim"), and Injury profiles ("Injury"; see Tables S2–S7 for the list of variables used to establish typologies). For Plot Structure, Bioclimate and Injury profiles, we reduced the variables using PCA (excluding farms with missing data), then performed cluster analyses on resulting coordinates using the HCPC function in the R package FactomineR v 2.8 (Husson et al., 2006). The same methodology was done for the Coffee genetic diversity variables, using a factor analysis for mixed data (FAMD) instead of PCA. The number of clusters retained for each variable category were determined after preliminary data exploration by aiming to define a small number of contrasting clusters while considering inertia gain at each K value. For the Tree and Associated Crop data, Bray-Curtis distance matrices were calculated using the R package ecodist v 2.1.3 (Goslee and Urban, 2006) and used to cluster farms using the hclust (using Ward method) and cutree functions of the ade4 package (Dray and Dufour, 2007). We then investigated associations between variable clusters: we built contingency tables between clusters for each pair of variable categories, and applied Fisher's exact tests. We also tested for associations between the presence or absence of each varietal group (Typica-, CR95/Catimor-, Bourbon/Caturra-, Kent/I-60-like and Unlabeled) and the "Plotstructure" and "Injury" categories, and for associations between the farm typologies and the Department (Nord or Grande-Anse) the farms are in. We finally constructed a contingency table summarizing significant associations between the six typologies and performed a correspondence analysis in FactomineR.

2.4.2. Ecosystem services proxies: Patterns of associations and interactions

We sought to describe patterns of ecosystem service delivery in Haitian CAFS. Firstly, we compared service delivery among the CAFS typologies for each variable category in the following manner: for each ecosystem service indicator, a Levene test of equality of variables was performed, followed by an Analysis of Variance (ANOVA) and subsequent Shapiro-Wilk test of normality of the ANOVA residuals and, when appropriate, a Tukey post-hoc test. When conditions for ANOVAs were not met, Kruskal-Wallis and Dunn-Bonferroni post-hoc tests were used.

In order to test for associations and trade-offs between services, a pairwise correlation matrix was also calculated on service variables using Pearson's product-moment correlation tests. This was done using all available service indicators. Tree density ($trees.ha^{-1}$) was not considered as a service indicator, but we tested for correlations between it and the service variables as well. To evaluate potential competition between CAFS vegetation components, we also tested for pairwise correlation between the density of Coffee trees, Shade trees, and associated Crops.

We sought to describe ecosystem service bundles, as patterns of associations between multiple service indicators. For this, we chose the most relevant indicator variables following the pairwise correlation tests, reduced them using PCA, and performed hierarchical clustering (k = 3) of farms based on service delivery with FactomineR. For this analysis exclusively, farms with missing data were not excluded, but values were inputed for missing variables by FactoMiner's default method (considering group averages). Thus, another CAFS typology, "ES", was established. We avoided redundant variables (e.g. Species richness and Shannon Index). Dietary contribution was strongly correlated to Crop diversity (as trees contributed fewer points to the score), and was considered to incorporate it. Coffee diversity (H_e) was not included to build the typology as it was used to construct the Gen typology. Associations between the Service typology and the CAFS typologies were investigated using Fisher's exact tests, and another correspondence analysis was performed.

We also aimed to identify the farms that were able to provide multiple services, and could provide insights on pathways to improving CAFS. We applied k-means clustering (with k = 3) on each Service indicator variable independently in order to categorize farms with lower, intermediate or higher levels of delivery of a particular service. We then calculated an overall ecosystem service delivery score according to the Eq. (1):

$$\frac{\text{nb.higher} \times 3 + \text{nb. intermediate} \times 2 + \text{nb.lower} \times 1}{\text{nb.higher} + \text{nb.intermediate} + \text{nb.lower}} \quad (1)$$

where "nb.higher", "nb.intermediate" and "nb.lower" referring to the number of times a farm was categorized in the corresponding ES delivery tier. We then tested for differences in ecosystem service scores between ES typology clusters (Kruskal-Wallis).

Finally, we investigated how CAFS have impacted Haitian tree diversity by testing the relationships between the native status of the different taxa represented in the tree strata (this time using a native or pre-Columbian versus colonial or postcolonial introduction dichotomy) and their commonness (percent and number of farms present), abundance (mean number per farm) and number of reported uses using Kruskal-Wallis and Dunn-Bonferroni tests. Pre-Columbian trees were the neotropical species listed as introduced to Haiti (https://powo.science.kew.org/), but which are attested by literature as being possibly native or present since pre-colonial times (Pinto and Williams, 2005; Koohafkan and Lilin, 1989; Leal and Paull, 2023; Pontikis, 1996; Petersen et al., 2014).

3. Results

3.1. Common patterns of CAFS diversity

Overall, surveyed CAFS were quite diverse, with an average of 7.9 ± 2.3 SD recorded species (a range of 4–13), corresponding to a mean system-wide Shannon diversity index of H'= 0.97 ± 0.36 SD (range: 0.12 to 1.60). Coffee farms had on average 2.6 ± 1.1 Arabica varietal groups (range: 1–5), 30.4 % admixed individuals (range: 0.0–65.2 %), and a mean gene diversity (H_e) value of 0.23 ± 0.11 (range: 0.017–0.343). The most commonly encountered coffee variety across sampled farms was the rust-susceptible, historical Typica (Figs. 1B and

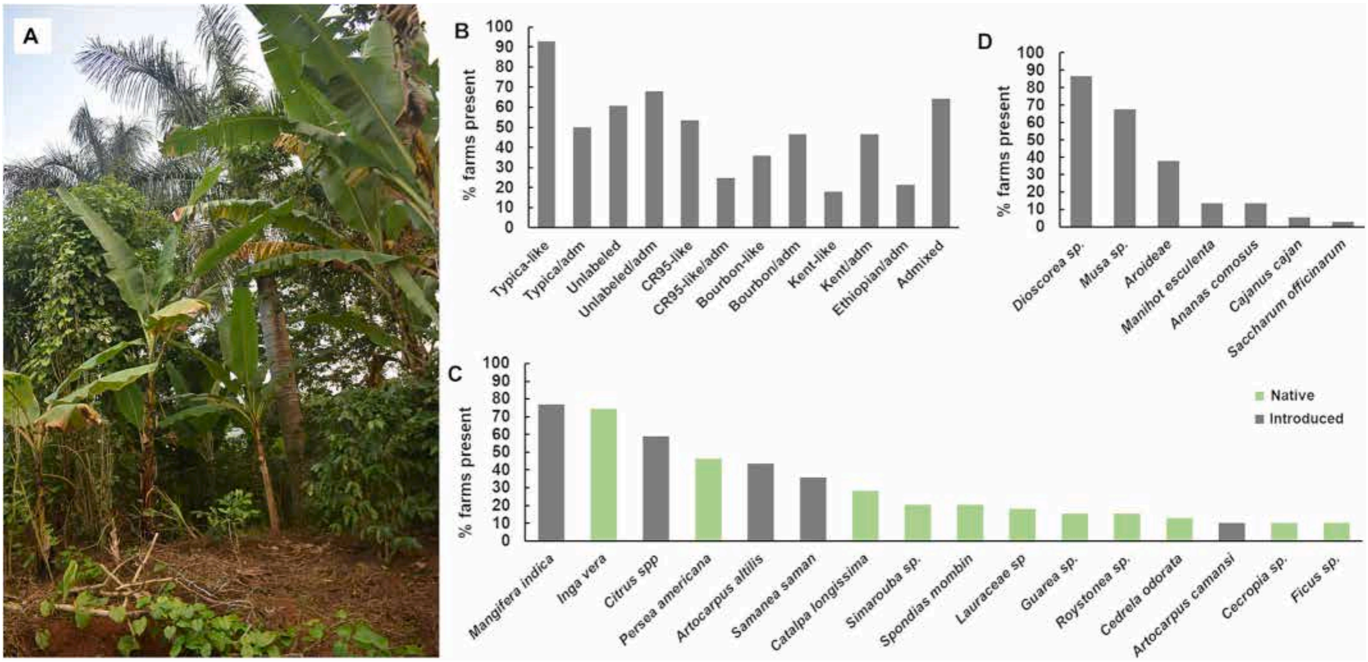

Fig. 1. Patterns of diversity in Haitian coffee agroforestry systems: A. Photograph of a typical Haitian agroforestry systems featuring coffee trees, associated trees and crops. Histograms show commonness (as % of farms in which a taxon is represented) of B. Coffee varietal categories, C. main tree species (present in > 10 % of farms), and D. associated crops.

S2).

Thirty-three shade tree taxa in at least 28 genera were recorded (Figs. 1B and S3), most of them native to Haiti, or introduced in pre-Columbian times. While non-native trees were present in more farms and in greater numbers per farm than native species, these differences were not significant (Kruskal-Wallis $p = 0.07$–0.08 in all cases, Fig. S4). However, they had significantly more reported uses ($p = 0.01$). Seven taxa of associated crops were recorded in surveyed CAFS (Figs. 1D and S5). Farms had on average 2.3 associated crop species ± 1.0 SD.

3.2. CAFS typologies

The CAF typologies established using hierarchical components had 3 clusters each for the "Gen", "Tree" and "Crop" variable classes. The Coffee genetic typology (Table_S2, fig. s6A) clustered together farms with low genetic and varietal diversity (Gen1), higher diversity including Catimors (Gen2), and higher-diversity excluding Catimors (Gen3), respectively. Overall, Gen2 was mostly present in the Nord Department, while Gen3 was mostly in Grande-Anse (Fishers' test $p = 0.032$). The Tree typology (Table_S3, Fig. S6b, S7a) was constructed along both the density (Tree1 being higher-density) and composition (with *Inga vera* and *Samanea saman* as the main legume species of Tree2 and Tree3, respectively) of the tree strata. The Tree1 and Tree3 clusters predominated in the North, and Tree2 in Grande-Anse (Fishers' test $p < 0.001$). Crop clusters (Table_S4, Fig. S6c, S7b) varied in both density and dominant crop identity. There was no significant association between Crop typologies and Departments.

The bioclimate and altitude (Clim, Table_S5) and coffee plot structure variables (Plotstructure, Table_S6) each had two classes representing contrasting environments and plot organization. Likewise, from the pest and disease incidence variables we identified two injury profiles (Injury, Table_S7), characterized by higher incidences of American Leaf Spot (*Mycena citricolor*) and Coffee berry borer (with more pests but fewer diseases overall; Injury1), or by higher Rust, Anthracnose and Leaf Miner incidence (and more diseases but fewer pests overall; Injury2), respectively. The Clim, Plotstructure and Injury typologies were all strongly associated with the departments and thus farm location (Fishers' test $p < 0.001$ for all).

Fisher's tests revealed significant association between typologies (Table S8) in patterns that are also apparent in the correspondance analysis (Fig. 2). In particular, the highly explanatory first axis of the latter opposed farms with higher tree densities, younger, less dense coffee plots containing CR95-like Catimors, affected by the *M. citricolor* and Berry borer-dominated injury profile (Tree1, Plotstructure1, Gen2, Injury1; hereafter "Renewed farms") to those with lower tree densities and older, denser but genetically diverse coffee plots particularly affected by Rust, and generally found at higher altitudes (Tree2, Plotstructure2, Gen3, Injury2, Clim2; hereafter "Aging farms"). Farms with presence of Catimors were more likely to belong to the Plotstructure1 ($p < 0.001$) and Injury1 clusters. No significant association was detected between either the Plotstructure or Injury typologies and any of the other varietal groups.

3.3. Interactions between ecosystem services

Pairwise correlation tests between ecosystem service proxies revealed significant correlations that were indicative of synergies or trade-offs (or lack thereof) between services delivered by CAFS (Table 1). For instance, Coffee production was positively correlated to the relative abundance of leguminous trees ($\varnothing_{legumes}/\varnothing_{total}$), negatively correlated with several diversity variables, and, notably, not correlated to Coffee % leaf loss.

On the PCA performed on ecosystem service indicator (Fig. 3A), The first dimension was most determined by %leaf loss (contribution: 25.78 %) and tree utility score (28.75 %). The second (24.24 % of variance) was most shaped by Coffee production (25.15 %), Tree Species Richness (19.33 %) and $\varnothing_{legumes}/\varnothing_{total}$ (18.60 %), the third (12.71 % of variance) by Aboveground Biomass (57.02 %), and the fourth (11.50 % of variance) by % native species (57.45 %). Variable distribution on the different axes was consistent with correlation test results. The ES typology resulted in 3 clusters (Table 2, Fig. 3), representing different service bundles. ES1, which included all Grande-Anse farms) had lower coffee health and productivity, lower tree-related services, and higher-than-average dietary contribution. ES2 had higher-than-average

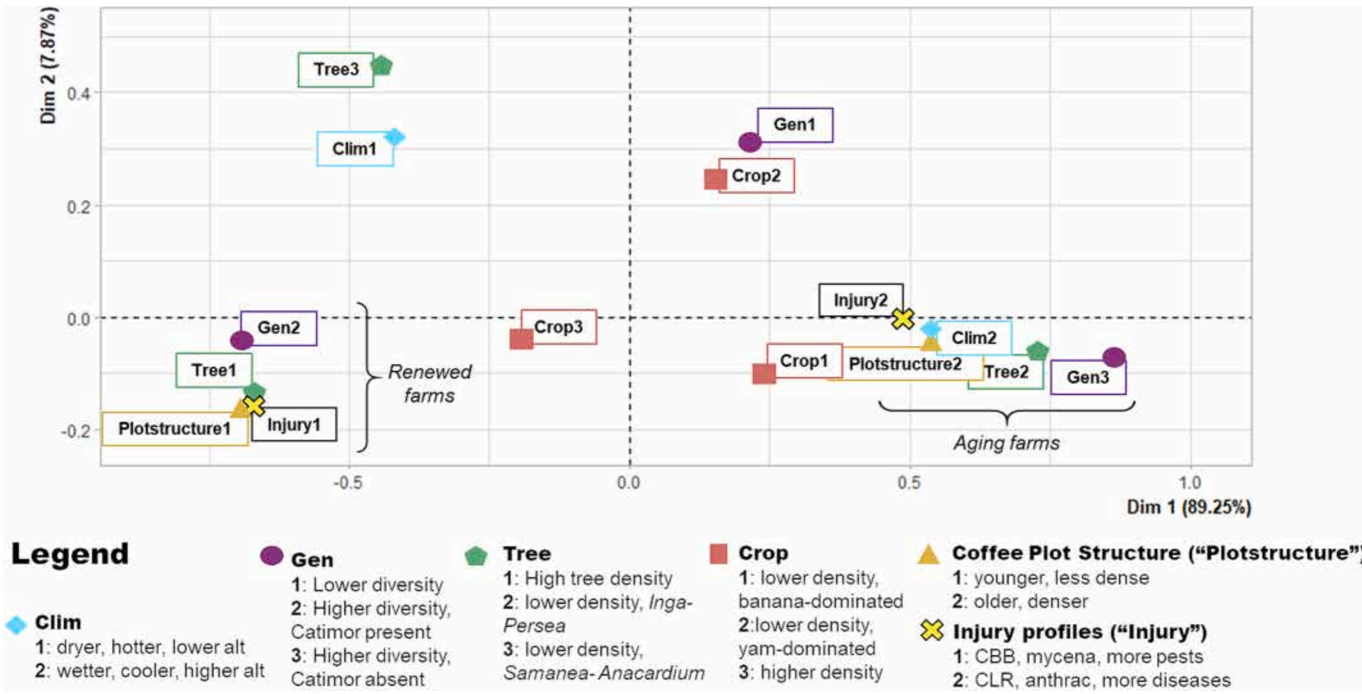

Fig. 2. Correspondence Analysis plot showing associations between clusters from typologies based upon components of agroforestry system diversity (Gen: coffee genetic and varietal diversity; Tree: tree composition; Crop: Associated crop composition, in red) and other system characteristics (Clim: Bioclimatic and elevation data; Plotstructure: coffee plot structure; Injury: pest and disease injury profiles, in blue). Abbreviations used are as follows: catimor: CR95-like catimor coffee variety, CBB: Coffee Berry Borer (*Hypothenemus hampei*), mycena: *Mycena citricolor*, CLR: Coffee Leaf Rust (*Hemileia vastatrix*), anthrac: Anthracnose (*Colletotrichum sp*). Tree2, Tree3 are labelled according to their dominant legume tree, Crop1 and 2 to their dominant crop species. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

productivity and $\varnothing_{legumes}/\varnothing_{total}$, but lower tree species richness and proportion of native species, and lower dietary contribution. ES3 has higher-than-average tree species richness and utility scores, as well as lower % leaf loss.

The ES clusters had significant differences in their overall service delivery scores (ANOVA $p < 0.001$). Tukey post-hoc test revealed the ES3 cluster has the highest scores (1.91 ± 0.19 SD), while the other two had lower scores that did not differ significantly from each other (ES1: 1.52 ± 0.23, ES2: 1.57 ± 0.25).

3.4. Ecosystem service delivery along CAFS typologies

We investigated ecosystem service delivery across the various CAFS typologies (Table S9). Notably, no significant differences in coffee productivity nor % leaf loss were detected between clusters in the coffee genetic (Gen) typology. Tree typology clusters differed significantly in some tree-related indicators, but not in others. Crop typology clusters did not differ in any of the crop-related indicators, nor indeed any indicator except coffee productivity.

Fishers's tests revealed significant association of the ES typology to the Tree, Clim, Plotstructure and Injury ($p < 0.001$ for all), but not Gen nor Crop typologies (Table S10). In the correspondence analysis combining ES delivery clusters with the CAFS typologies, ES1 was associated with "Aging farm" clusters, and ES3 with "Renewed farm" clusters, albeit more loosely, on the first dimension (88.95 % inertia) (Fig. 4). The second dimension (11.05 % inertia) further separated ES2 (coffee production-focused services) from the other clusters. Despite ES2 and ES3 clusters being overwhelmingly comprised of diverse coffee plots with CR95-like Catimors (Gen2), Fisher tests revealed no significant association to the Coffee genetic typology.

4. Discussion

To our knowledge, the present study is the first to describe ecosystem service bundles and (some of) their determinants in Haitian agroforestry systems. We established a typology of service delivery and tied it to several descriptive variables for agroforests. Three major bundles were identified, focusing on different aspects of CAFS composition and structure. Because studies describing Haitian agroforestry systems are exceedingly rare, it is worth discussing these descriptive variables in detail before focusing on ecosystem services and bundles thereof.

4.1. Haitian agroforestry systems display high agrobiodiversity at many levels, from coffee genetics to associated plant species

We found considerable agrobiodiversity in the CAFS surveyed in our study. Five coffee varietal groups were identified in Haiti. Admixed individuals (with significant contribution from more than one genetic group) were also widespread, indicative of genetic mixing and seedling recruitment from soil seedbanks (see also Millet et al., 2024a,b). This level of diversity is rather atypical of Arabica coffee farms. While there are relatively few reports on the varietal composition of coffee farms in Arabica-growing regions (Pruvot-Woehl et al., 2020 for Central America and East Africa; Koutouleas et al., 2022 for Hawai'i and Neotropics), many (at least in the Neotropics) appear to have little to no varietal diversity (Notaro et al., 2022; Läderach et al., 2011; Harvey et al., 2021, but see Ward et al., 2017; Ehrenbergerová et al., 2018). The rich and dynamic diversity of coffee observed in Haitian farms in therefore more similar to Ethiopian systems (the crop's area of origin and diversification), which combine local landraces and improved coffee diversity. Their levels of gene diversity (H_e) are in fact similar (Zewdie et al., 2022), despite Haiti's coffee trees all descending from the main traditional lines (Millet et al., 2024b). The most common coffee variety by far was the historically significant Typica, present in Haiti since 1726

Table 1
Pairwise Pearson's product-moment correlation matrix between ecosystem service delivery indicators measured in up to 39 Haitian coffee agroforestry systems in Nord and Grande-Anse departments. Abbreviations used are as follows: spRich: Species richness. H': Shannon diversity index, DietCont: Dietary contribution score, AGB: Above-ground biomass, $Ø_{legumes}/Ø_{total}$: ratio of the sum of diameter at breast height of all legume trees on the farm to that of all trees. p: *<0.05, **<0.01, ***<0.001, ·= not significant (<0.1), NS = not significant (>0.1). When significant, correlation coefficients are in parentheses.

Peason's product-moment correlation matrix	Coffee-related			Tree-related				Crop-related			System-wide diversity			AGB (Mg. ha^{-1})
	Diversity (H_e)	Productivity (kg. ha-1)	% Leaf Loss	$SpRich_{tree}$	H'_{tree}	% Native species	Tree utility score	$SpRich_{crop}$	H'_{crop}	Crop density	DietCont	$SpRich_{system}$	H'_{system}	
Productivity (kg. ha^{-1})	NS													
% Leaf Loss	NS	NS												
$SpRich_{tree}$	NS	.	* (−0.43)											
H'_{tree}	NS	*(−0.42)	NS	*** (0.86)										
% Native species	NS	NS	NS	NS	NS									
Tree utility score	NS	NS	*** (−0.64)	*** (0.65)	NS	NS								
$SpRich_{crop}$	.	* (−0.36)	NS	NS	NS	NS	NS							
H'_{crop}	.	* (−0.36)	NS	NS	NS	NS	NS	*** (0.94)						
Crop density	.	NS	NS	NS	NS	NS	NS	* (0.36)	* (0.38)					
DietCont	** (−0.51)	.	NS	NS	** (0.45)	NS	NS	*** (0.53)	** (0.50)	NS				
$SpRich_{system}$	NS	** (−0.49)	NS	*** (0.91)	*** (0.85)	NS	** (0.51)	* (0.36)	* (0.36)	NS	* (0.39)			
H'_{system}	NS	** (−0.49)	NS	* (0.40)	** (0.43)	NS	NS	*** (0.68)	*** (0.77)	NS	** (0.51)	*** (0.65)		
AGB (Mg.ha^{-1})	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	
$Ø_{legumes}/Ø_{total}$	** (0.56)	*** (0.59)	* (−0.35)	NS	NS	NS	NS	*** (−0.55)	*** (−0.57)	NS	*** (−0.55)	* (−0.38)	*** (−0.59)	NS

g.

(Ukers, 1922). Catimor-like plants, widely adopted in the last decades throughout Latin America following the arrival of Rust on the continent (Avelino et al., 2015; Harvey et al., 2021; Queneherve et al., 2015; McCook, 2006), were present in 53.6 % of surveyed farms.

Shade tree strata in Haitian CAFS were generally diversified, with Tree species richness comparable to that of organic coffee farms in Guatemala and Nicaragua, and greater than both conventional and organic farms in Costa-Rica (Haggar et al., 2015). Most taxa were native (though many had a broad neotropical distribution). Anecdotally, we observed other species outside of the established quadrats, both native (*Clusia* sp, *Ceiba pentandra*) and introduced (*Theobroma cacao, Cocos nucifera, Morinda citrifolia*). The present species list greatly overlaps a previous survey in another region of Haiti (Jean-Denis et al., 2014), in which other native species were also recorded. Agroforestry systems, including CAFS, are therefore important reservoirs of native tree species, and likely contribute to conserving their genetic diversity, particularly for species of conservation concern (e.g. *Cedrela odorata*, IUCN category "Vulnerable", Mark and Rivers, 2017). Even in the case of species which are native to Haiti but widespread in the Neotropics (e.g. *Inga vera*), CAFS may help conserve locally adapted genotypes by serving as living, evolving in-situ germplasm repositories (Brush, 2000). However, non-native species are more common overall, both within and across farms. Seven associated non-perennial crop taxa were identified in CAFS. The most common were yams (*Dioscorea* sp), a major crop in Haiti of which several species, native (*D. trifida*) or introduced, are cultivated (Shannon, 2001). It is important to note that the overall agroforestry system crop diversity may have been underestimated due to the focus on crops associated with coffee plots.

Many of the common species found in Haitian CAFS are also mainstays of diversified agroforestry systems and homegardens in tropical Africa (Sebuliba et al., 2022; Seid and Kebebew, 2022; Whitney et al., 2018), Asia (Chandrashekara, 2009; Mohri et al., 2013), the Pacific islands (Thaman et al., 2006), the Americas (Villa and García, 2017; Miller et al., 2006), and the Caribbean (e.g. Agnoletti et al., 2022; Wezel and Bender, 2003). Diversified agroforestry systems can indeed be very similar across regions, due to a process historians have dubbed the Neo-Columbian exchange (McCook, 2011) of taxa between the Paleo- and Neotropics. In particular, very useful trees were broadly disseminated across CAFS, hence the greater number of reported uses for introduced species on average. As we did not record herbaceous and shrubby species beyond food crops, total plant biodiversity in these systems is certainly greater than what is reported here. Nevertheless, Species richness in Haitian CAFS (7.9 on average, range 4–13, excluding coffee), is comparable to values reported from Ethiopian coffee forests (9 on average, range of 6–15,) and diversified homegardens (16 on average, range of 8–22), though their Shannon diversity is lower (Seid and Kebebew, 2022).

Importantly, CAFS were often part of a broader farming system that may also include more open areas that are solely focused on annual crops such as beans (*Phaseolus vulgaris*) and maize (*Zea mays*). This integration of agroforestry and open cropland is a common feature of Haitian agriculture (Jean-Denis et al., 2014) and likely affects farmers' decision to incorporate crops into CAFS (Sinclair, 1999).

4.2. CAFS mostly fall along a regeneration spectrum tied to Catimor variety adoption

The CAFS typologies highlighted a wide variety of structure, composition and management (Fig. 5). Haitian CAFS were typically diversified traditional polyculture "coffee gardens", with some more akin to commercial polycultures (*sensu* Toledo and Moguel, 2012). Bioclimatic variables reflected geographic differences in environmental conditions between the departments, which may explain the North-South divide in CAF composition, structure and injury profiles. Indeed, topoclimatic conditions are known drivers of injury profiles (Allinne et al., 2016), and plant diversity in agroforestry systems

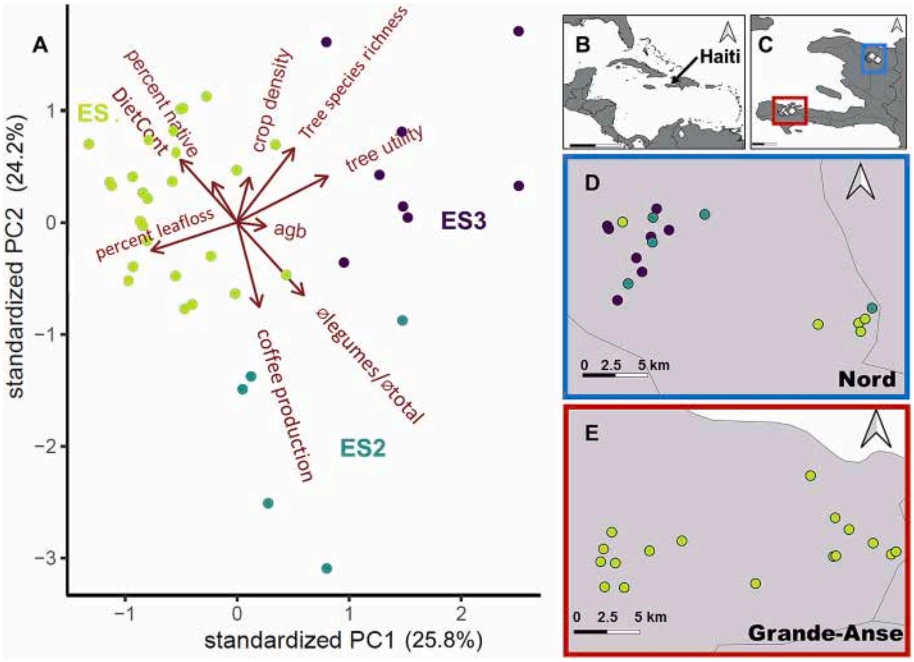

Fig. 3. Ecosystem service delivery patterns across Haitian Coffee Agroforestry Systems. A. Plot of farms and variable correlation circle along the first 2 axes of a Principal Component Analysis based on ecosystem service indicators. B. location of Haiti in the Caribbean (scale bar ticks = 250 km). C. Study locations in the Nord (North, blue) and Grande-Anse (South, red) departments (scale bar ticks = 25 km). In A., D. and E., farms a. D. Surveyed farms in the Nord and E. Grande-Anse departments colored according to the ecosystem service typology (ES) cluster to which they were assigned by hierarchical clustering. Maps created in QGIS v. 3.30.1 using Natural Earth (Free vector and raster map data @ naturalearthdata.com) and shapefiles from Hijmans and UC Berkeley (2015a,b) and Patterson and Kelso (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Birhane et al., 2020; Muche et al., 2022).

Most coffee plots were composed of multiple overlapping generations of coffee trees, from seedlings and saplings originating from the seedbank to very old, architecturally-complex trees (Fig. S8). Mean stand age was 34 years, and most farms contained old, architecturally complex coffee trees, in densities were often above or below the optimal range (Allinne et al., 2016; Teodoro et al., 2008; DaMatta, 2004). This is indicative of a lack of frequent pruning to rejuvenate vegetative tissue, which negatively impacts potential yield (Somarriba and Quesada, 2022). Only about two thirds of coffee trees within plots were productive. Most showed signs of pest and disease, especially Rust, with incidence in the upper range of what has been reported for Central America (Allinne et al., 2016). Our results are consistent with previous reports of major causes of coffee production decline in Haiti (Amaya et al., 1999; Vital, 2014).

Coffee plots with Catimors (Gen2) were generally part of the younger and less dense “Renewed farms”, which may be due to their relatively recent introduction on Haitian farms by development projects as part of technical packages that included coffee replanting (Queneherve et al., 2015). They were also with higher *Mycena citricolor* and less rust (Injury1), likely due to Catimors’ greater rust resistance, but higher *M. citricolor* susceptibility (Ribeyre and Avelino, 2012). This injury profile was also associated with more densely-forested Tree1 cluster. Closed canopies are shown to favor *M. citricolor* development (Avelino et al., 2007) and berry borer infestation (Bagny Beilhe et al., 2020) through their effect on microclimate.

The Injury2 profile, with more rust and fewer disease-free plants, was associated with older and denser “Aging farms” which, despite contrasting diversity levels, consisted mostly of rust-susceptible varieties like Typica (Gen 1 and Gen 3). Many varietal introductions (Bourbon, Caturra…) took place in the 1970s (Ester, 1978), before the rust epidemic reached Haiti, explaining why Aging farms may have diversity, but no Catimors. This injury profile is also associated with the low-density Tree2 cluster, echoing previous works linking canopy openness with greater rust incidence (Gagliardi et al., 2021).

4.3. ES typologies focus on specific components of system diversity, only some of which are constrained by trade-off

Using clustering analysis on ecosystem service indicator variables, we classified CAFS in 3 clusters representing distinct service bundles. The ES1 farms had lower coffee performance, and less predominant tree strata (lower Aboveground biomass and tree utility scores), but higher Dietary contribution. As the most numerous, and the only type found in Grande-Anse, these farms are seemingly representative of common management practices and difficulties encountered. These are seemingly subsistence systems. The ES2 farms appeared to be Coffee-related service maximizers with greater-than-average production and tree strata that are more geared towards supporting the Coffee crop, with lower diversity but greater importance of legumes. Finally, ES3 farms were tree-related service maximizers, with a greater number of species and thus uses. Interestingly, Coffee plants in these farms had lower leaf loss and therefore better health, possibly through various ecological processes supported by biodiversity; including pest and disease regulation (Venzon, 2021; Altieri, 1999; Ratnadass et al., 2012).

This typology partially results from trade-offs between ecosystem services. Farmers who focused on maximizing their coffee harvests may favor service trees that enrich soils in Nitrogen to support coffee growth at the cost of tree diversity. By contrast, farmers who seek to maximize the utility of their non-coffee trees may be sacrificing some coffee productivity. Beyond the Coffee-Legume association, there were relatively few synergies between services. Indeed, many positively correlated variables reflected overlap in the CAFS component they represent (for instance, between Tree and Crop richness on one hand, and overall system richness—Tree + Crop—on the other).

Some service variables had few or no correlations to others. Density of associated crops was only correlated to Crop diversity variables, and was not even associated to Coffee or Tree density. This suggests that

Table 2
Variation in ecosystem service delivery indicators (rows) across clusters of the ES typology. Underlined variables were used in the Principal Component Analysis and subsequent Hierarchical Clustering on Principal Components used to define the clusters. Presented as means (M) and standard deviation (SD), along with the significance level of the parametric (ANOVA "aov") or nonparametric (Kruskal-Wallis, "kw") test (as appropriate). Letters above the p values correspond to significant differences among clusters as identified by post-hoc tests (Tukey for aov, Dunn-Bonferroni for kw). Abbreviations used are as follows: spRich: Species richness. H': Shannon diversity index, AGB: Above-ground biomass, $\varnothing_{legumes}/\varnothing_{total}$: ratio of the sum of diameter at breast height of all legume trees on the farm to that of all trees.

Service clusters			ES1: Subsistence	ES2: Coffee productivity-favoring	ES3: Tree service-favoring
Coffee	Productivity (kg. ha-1)	Mean	105.71	1148.07	137.19
		SD	105.26	551.76	81.86
			a	b	ab
		p	** (kw)		
	% Leaf Loss	Mean	64.73	62.17	40.31
		SD	9.80	3.57	7.69
			a	a	b
		p	*** (aov)		
Tree diversity	$spRich_{trees}$	Mean	5.27	3.60	8.38
		SD	1.71	1.52	1.85
			a	a	b
		p	*** (aov)		
	H'_{trees}	Mean	1.58	1.11	1.79
		SD	0.33	0.26	0.30
			a	b	a
		p	** (aov)		
	% Native species	Mean	0.56	0.25	0.49
		SD	0.23	0.28	0.13
			a	b	ab
		p	* (aov)		
	Tree utility score	Mean	32.23	37.00	107.25
		SD	16.51	42.99	55.86
			a	a	b
		p	*** (kw)		
Crop diversity	$spRich_{crops}$	Mean	2.56	1.60	1.71
		SD	0.92	0.89	0.76
		p	* (kw)		
	H'_{crops}	Mean	0.71	0.29	0.43
		SD	0.42	0.41	0.43
		p	. (aov)		
Dietary contribution		Mean	3.84	3.00	3.29
		SD	0.62	0.00	0.49
			a	b	ab
		p	** (kw)		
System-wide diversity	$spRich_{system}$	Mean	7.92	5.20	10.00
		SD	1.96	1.64	2.16
			a	b	c
		p	*** (aov)		
	H'_{system}	Mean	1.04	0.55	1.04
		SD	0.31	0.35	0.37
			a	b	a
		p	* (aov)		
Carbon sequestration and Nitrogen cycling	AGB ($Mg.ha^{-1}$)	Mean	84.56	179.05	212.79
		SD	14.65	14.28	16.14
			a	ab	b
		p	** (kw)		
	$\varnothing_{legumes}/\varnothing_{total}$	Mean	0.18	0.62	0.43
		SD	0.15	0.25	0.20
			a	b	b
		p	*** (aov)		

there is not much competition for space or environmental resources between associated Crops and other CAFS components. This may explain why Coffee (ES2) and Tree (ES3)-related service maximizers do not have significantly lower crop diversities than Subsistence systems ES1): farmers need not sacrifice associated crop production to maintain or increase their coffee harvest, or the various services provided by shade Trees.

Likewise, Aboveground biomass, which is both an indicator of Carbon sequestration and timber provision, was not correlated to other ecosystem service variables. Farmers may therefore be able to increase the on-farm biomass without compromise. However, it is important to note that the present study does not include data related to tree canopy openness or extent of shade in the system. While shade is determined by Tree density, it is also dependent on the architecture, spatial arrangement, and (lack of) trimming of trees, which all influence the coexistence between trees and annual crops. For instance, Timyan (1996)

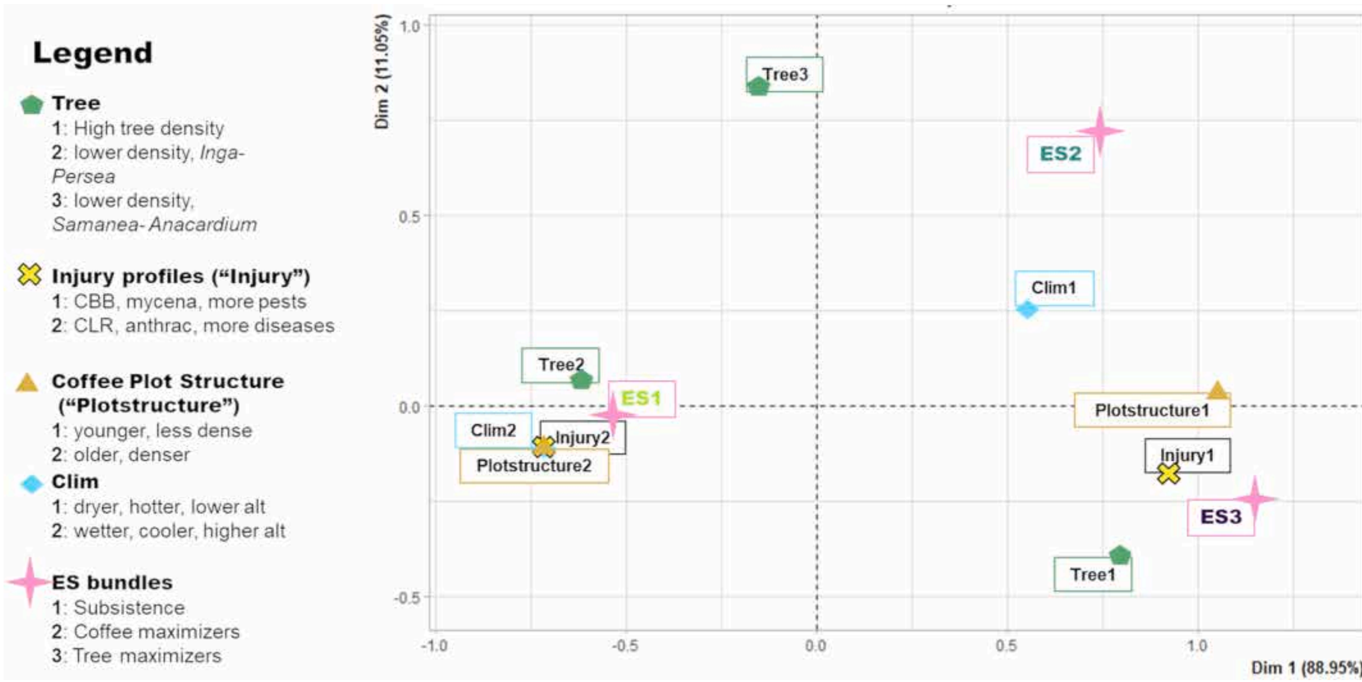

Fig. 4. Correspondence Analysis plot showing associations between clusters from typologies based upon agroforestry system characteristics (Tree: tree composition; Clim: Bioclimatic and elevation data; Plotstructure: coffee plot structure; Injury: pest and disease injury profiles, in red) and upon ecosystem service indicators (ES, in blue). Abbreviations used are as follows: CBB: Coffee Berry Borer (*Hypothenemus hampei*), mycena: *Mycena citricolor*, CLR: Coffee Leaf Rust (*Hemileia vastatrix*), anthrac: Anthracnose (*Colletotrichum sp*). Tree2, Tree3 are labelled according to their dominant legume tree. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

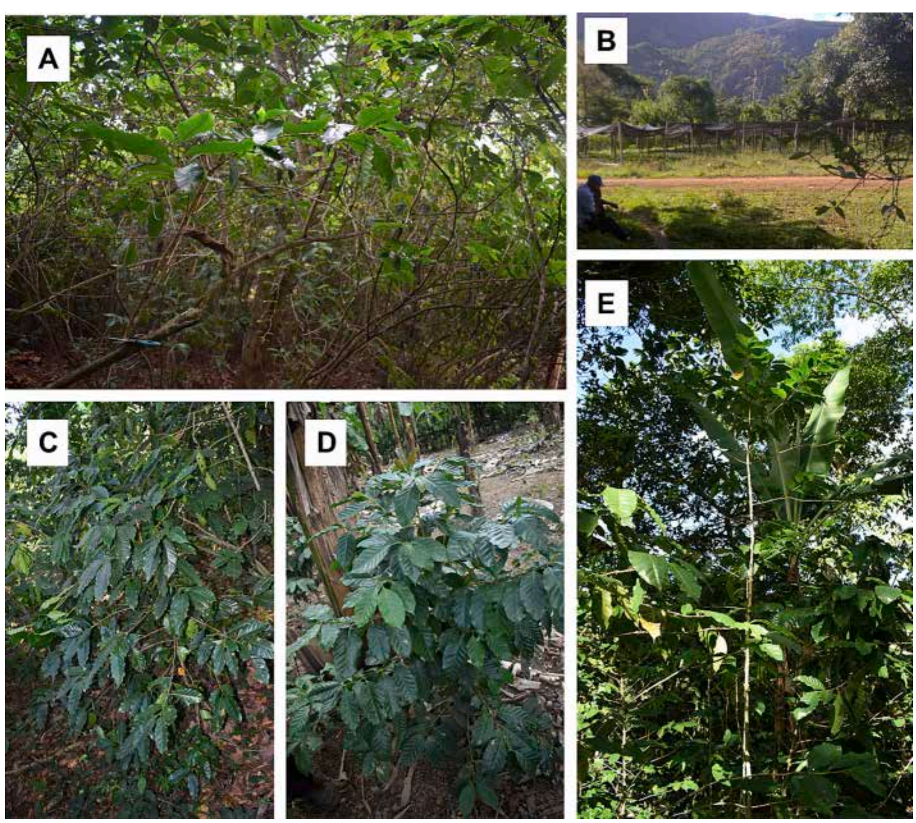

Fig. 5. Photographs of Haitian Coffee agroforestry systems from contrasting typologies. A. Farm from the Subsistence ES1 cluster with old, dense, architecturally complex, low-diversity coffee plots (Gen1, Plotstructure2). B. Nursery belonging to the owner of a Coffee-maximizing ES2 cluster, illustrating the focus on Coffee, including propagation for regeneration. C. Rust-susceptible traditional Typica. D. Rust-resistant, ALS-susceptible, compact CR95-like Catimor in a farm from the Coffee maximizing ES2 cluster (Gen2, Plotstructure1). E. Farm from the Tree-maximizing ES3 cluster (ES3, Tree1, Gen2, Plotstructure1). Photo credit: Claude Patrick Millet.

observed that herbaceous crops such as banana and sweet potato (*Ipomea batatas*) are often grown under the shade of *Catalpa longissima*'s sparse crown, with frequent trimming (additionally improving its lumber value and providing fuelwood). Shade extent also determines tree impacts on coffee yield components through competition for nutrients and light, and modification of coffee growth and phenology (Charbonnier et al., 2017; Bote et al., 2018). It also plays an important but complex and context-dependent role in dispersal, incidence and regulation of pests and diseases (Gagliardi et al., 2021; Durand-Bessart et al., 2020; Avelino et al., 2023). In yield-maximizing, relatively more intensive Latin-American coffee-growing systems, farmers are advised to keep shade extent below 35 % (Cerda et al., 2017a; Koutouleas et al., 2022). However, in Nicaragua, where tree-based provisioning services are also important to farmers, farms were found to be 73 % shaded on average (Durand-Bessart et al., 2020).

The proportion of native Tree species was also independent from other ES, suggesting that the contribution of CAFS to biodiversity conservation can be improved through greater incorporation of native, multi-use species. For instance, other Legumes trees (such as native *Erythrina* spp) could potentially be incorporated as service trees alongside *Inga*. However, despite the existence of a few valuable information sources (Timyan, 1996; Bossa et al., 2005), there is still a need to better characterize native tree functional traits and their relationship to service delivery (Willmott et al., 2023; Isaac et al., 2024).

Across the ES clusters (Figs. 3 and 5), ES3 (tree service-maximizing farms) had higher overall delivery scores. This is explained by the fact that many of the ecosystem service indicators considered in this study are tied to the tree strata (such as aboveground biomass or number of tree uses). Trees are also the CAFS component most likely to be the most important overall, as they provide many more services such as habitat for wildlife and epiphytic flora (De Leijster et al., 2021; Jezeer et al., 2017). ES1 and ES2 clusters had lower scores. In the case of ES2, this seems tied to a choice to focus on Coffee, and therefore service trees (legumes) to the detriment of more diverse, useful tree strata. ES1 appears less constrained by such choices, and their lower ES delivery scores may be associated (as cause, effect, or both) with socioeconomic and environmental hardships experienced by rural Haitian communities. In particular, many farms in Grande-Anse were impacted by natural disasters such as the 2016 Hurricane Matthew in 2016 (ACAPS, 2016, pers. obs) and the 2023 magnitude 7.2 earthquake (ACAPS, 2021), which may have contributed to lower Coffee production and health, direct loss or increased cutting of trees for cash, and overall lower ability to deliver ecosystem services. Still, the higher Dietary contribution scores in these farms suggest that they contribute to farmers' and their families' immediate nutritional needs. These ES1 farms could be improved through trajectories towards greater coffee production (ES2) or strengthening the tree strata (ES3).

4.4. ES typology linked to the regeneration spectrum and geographic location

We tested for associations between the descriptive variable CAFS typologies and the ES indicator typology, and for significant differences between service indicator values within typologies, in order to determine how the composition of systems impacted their ecosystem service delivery. We found significant overlap between the ES1 cluster and the "Aging farms", which likely explains ES1 farms' lower Coffee harvests, greater leaf loss, and lower AGB (as for Tree2). The CAFS in the ES2 and ES3 clusters are "Renewed farms", which are predominantly in the Nord department. This geographic divide may be due to farmers in the North having access to more support to regenerate their farms, namely through Catimor adoption. Northern farms are close to Cap-Haitien, the second largest Haitian city and a seat of both NGO and private sector activity, including in agriculture. In fact, most Northern ES1 cluster farms were also aging, monovarietal Typica farms located in the most remote and hard-to-access areas (pers. obs.). Grande-Anse farms are comparatively more isolated from major areas of commerce, particularly as gang violence in recent years has made road traffic between the area and Port-au-Prince (the capital) much more difficult.

Interestingly, and despite the Gen typology being a major feature of the CAFS regeneration spectrum, it was not associated with the ES typology. There were no significant differences in coffee production nor % leaf loss between Gen clusters. This is likely due to the fact that the relationship between yield and overall plant health and coffee varietal composition is mediated by agronomic factors such as variety-specific nutritional requirements. Overall, management-related factors (e.g. stand age) and biotic stresses (injury profiles) appear as stronger determinants of coffee plant performance in Haitian CAFS than genetics. Furthermore, and somewhat counter-intuitively, there was no correlation between Coffee production and % leaf loss. The likely explanation is that our production indicator, as a farmer-reported variable, is not a measure of potential or accessible yield (Nutter et al., 1993), but of the amount of coffee harvested by farmers from CAFS. Farmers may be limited by labor availability, insufficient market access or demand and personal circumstances, and may therefore not be harvesting their coffee to the fullest extent. This may also promote the incidence of Berry borer, with unpicked cherries serving as refuge for the pest (Aristizábal et al., 2023). Furthermore, studies modelling primary and secondary yield losses in coffee have shown a temporal decoupling between foliar pest and disease injuries and yield, due to staggered effects of the former on the latter (Cerda et al., 2017b). Overall, our study provides insights into possible improvement of ecosystem service delivery by acting upon CAFS structure and management.

4.5. Ecosystem service delivery by CAFS goes beyond identified bundles

The present study focused on several ecosystem services for which we had access to quantitative indicators, but others merit future attention. For instance, while our indicator of Coffee production is useful to describe the current state of affairs, there remains a need to quantify the accessible yields and actual yield losses in these systems in order to compare their efficiency and production potential, especially in relation of genetic and varietal identity (World Coffee Research, 2019). Furthermore, many others are also delivered by CAFS. While we looked at conservation of native trees, these systems provide habitats for a variety of organisms such as insects, birds and reptiles (including many endemic species), and herbaceous understory and epiphytic plants (pers. obs. consistent with reports from Colombia by De Leijster et al., 2021). While they typically hold fewer species than natural forests, CAFS still constitute valuable biodiversity reservoirs (Haggar et al., 2019; Bhagwat et al., 2008; Kessler et al., 2012), a role which is likely greater in the context of Haiti with > 99 % primary forest loss (Hedges et al., 2018). Indeed, local studies have shown that agroforestry systems can provide important habitats for native and migratory birds (Exantus et al., 2021), as well as insects (Beaujour and Cézilly, 2022), even when embedded in urban landscapes. As a major type of tree cover on the island, CAFS are also important for erosion control (Blanco Sepúlveda and Aguilar Carrillo, 2015). However, they may also constitute a threat, for instance through their expansion or via introduction of exotic species (Richardson et al., 2013). In fact, some of the surveyed farms were concerningly close to Macaya National Park, one of Haiti's main hotspots of endemism (pers. obs.). With so few data available on Haitian biodiversity in these fragmentary hotspots, most studies have focused on describing and cataloguing species (Ionta et al., 2012; Majure et al., 2013; Joly et al., 2023), or monitoring habitat loss via land use changes (Hedges et al., 2018; Pauleus and Mitchell Aide, 2020). However, understanding how these fragments are embedded in the larger Haitian landscape will provide insights on how to protect them.

In addition, these systems provide a variety of cultural services. Haitian Coffee agroforests are traditional systems that arose after the nation acquired its independence, partly as a repudiation of colonial plantation systems (Lundahl, 1984; Moral, 1955), and are still host to the historically significant heritage Typica variety. Finally, they arguably contribute aesthetically to the Haitian landscape, and many of the trees they hold, such as *Ficus* spp and *Cedrela odorata*, hold great importance in local belief systems (Tarter, 2015).

4.6. Identifying ES bundles may elucidate trajectories towards greater system sustainability

The ES bundles described in the present study correspond to different strategies of CAFS biodiversity planning and management. These strategies can be tweaked, updated or altogether modified to bring systems towards a state of ecosystem service delivery ever more aligned with farmers' needs and goals. By characterizing agrobiodiversity and associated ecosystem service delivery, and identifying trade-offs and synergies between them, it may be possible to improve or "optimize" agroforestry systems by striking the balance between the expectations of social, economic and ecological benefits placed upon them. Our study contributes to the still-limited knowledge of service delivery by agroforestry systems in general, and of Haitian CAFS in particular. The limits and constraints on CAFS optimization are unclear. This is in part due to the diversity, complexity, and context-specificity of trajectories that could lead to improving CAFS' ability to respond satisfactorily and sustainably to economic and ecological needs (Poncet et al., 2024; Cunningham et al., 2013). This is compounded by the uncertainties faced by farmers in light of the unstable, precarious social-political-economic conditions that prevail in Haiti. Farmers strive for more profitable systems, which cash crops such as coffee could theoretically provide under appropriate conditions, but they also strongly value farm resilience, agricultural portfolio diversification, and food sovereignty (Steckley and Weis, 2017, 2016). Much more research on the relative importance of these values is needed for the improvement or optimization of CAFS.

Previous studies have shown that CAFS need not conform to a single structure to provide multiple ecosystem services, but that there exist combinations of agroforestry structure and management practices that can provide these outcomes (Cerda et al., 2020). While management of these systems is quite different from Haitian CAFS, with annual to biannual pruning, and application of fungicides and (in most cases) fertilizer, our results suggest that pathways for improvement can be similarly varied. Improvement of CAFS performance may be achieved by re-thinking and re-organizing the composition, spatial arrangement and management of their agrobiodiversity. Possible steps may include 1) harmonizing coffee varieties' level of shade tolerance (Koutouleas et al., 2022) with the extent of tree shade in the system (possibly within a mosaic of canopy openness and coffee varieties); 2) Increasing the proportion of legume trees and implementing adequate management such as frequent pruning and use of trimmings to enhance soil fertility (Haggar et al., 2011; Sauvadet et al., 2019), 3) increasing the proportion of associated crops that are better aligned with farmers' priorities and farm bioclimatic conditions, 4) incorporating trees with greater timber value or nutritional benefits; 5) identifying more native trees that can fulfill many of the needs of farmers. Policies could also be implemented that incentivize greater incorporation of native species, such as payments for ecosystem services (though unlikely in the current sociopolitical climate). The local impact of climate change on coffee production, and agriculture in general (Eitzinger et al., 2013) must also be considered. Because intraspecific genetic groups may not all have the same vulnerability to climate change (de Aquino et al., 2022; Vi, 2023), integrating genetics and climate change will also help agrobiodiversity planning. On a basic level, the extent to which farmers may even consider coffee a priority (particularly those of the Subsistence and Tree Maximizing clusters) should be determined: some may prefer to transition their farms away from coffee, entirely or in part.

Our study highlights the need for service delivery evaluation methodologies that are holistic and consider the complex interactions both within and between the various components of agroforestry systems, and the trade-offs in service delivery that may result from them (Rapidel et al., 2015; Notaro et al., 2022).

5. Conclusion

In this study, a view emerges of Haitian CAFS as bet-hedging systems in which farmers value multifunctionality to increase resilience and access to ecosystem services, despite social, economic and political vulnerabilities. Through the organization of agrobiodiversity on their farms, coffee farmers are able to access different ecosystem service bundles. We argue, based on this and other works (Zimmermann, 1986; Feller et al., 2006; Steckley and Weis, 2016; Poncet et al., 2024), that diversified agroforestry systems are crucial to the fabric of rural communities and to the integrity of ecological processes of Haiti. We have shown that, within the considered range, certain systems perform better and can serve as promising examples. These can help identify realistic roadmaps for improving service delivery within the context and limitations of Haitian systems.

Farmers cannot undertake the process of farm improvement or optimization alone. Greater and more equal participation of various actors and stakeholders in agricultural production chains, including agronomists, researchers, and decisionmakers will enhance the co-conception of improved cropping systems (de Groot et al., 2012; Dumont et al., 2021). Smallholder farmer perceptions on land and food sovereignty, diversification for resilience, and individual preferences must be given appropriate consideration and embedded into program designs (Valencia et al., 2015; Singh et al., 2016; Dumont et al., 2019).

CRediT authorship contribution statement

Claude Patrick Millet: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Wesly Jeune:** Supervision, Project administration, Funding acquisition. **Jephthé Samuel Guervil:** Project administration. **Luc André St Armand:** Project administration. **Jean Fritzner Amazan:** Investigation. **Guerlande Duval:** Investigation. **Reuben Bersonly Jean Louis:** Investigation. **Brunet Robert:** Investigation. **Valérie Poncet:** Writing – review & editing, Supervision, Funding acquisition. **Clémentine Allinne:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoser.2025.101782.

Data availability

Data will be made available on request.

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