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RESEARCH ARTICLE

From the ground up: Patterns and perceptions of herbaceous diversity in organic coffee agroecosystems

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Abstract

1. Smallholder farms that transition to organic and biodiverse production are increasingly recognized as strongholds of agrobiodiversity, with emerging work identifying important outcomes such as enhancing crop portfolios, mitigating extreme climate events and contributing to farmer well-being. Yet the emergent herbaceous communities in these organic systems remain understudied, with the functional diversity and management of this stratum relatively unknown.
2. This study identifies the taxonomic and functional diversity of the herbaceous community in organic coffee agroforestry systems, and describes the extent of this diversity with farm, and farmer, attributes. We measured leaf-level functional traits (e.g. specific leaf area) of the herbaceous community to derive functional diversity indices and collected localized environmental conditions on 15 organic coffee farms in Central Valley, Costa Rica. We also conducted semi-structured interviews with nine farmers to construct mental models on herbaceous community management using a cognitive mapping approach.
3. In total, 38 species from 20 taxonomic families were present in these organic coffee systems. The herbaceous communities were functionally diverse; however, functional evenness increased with canopy openness, suggesting that farms adopting agroforestry tend to have a more functionally diverse herbaceous stratum.
4. Farmer perception of plant traits in the herbaceous community was differentiated into competitive (weeds) or neutral/positive effects. These perceptions aligned with well-established functional trait trade-offs. The mental models representing farmer decision-making processes were highly variable, with a nearly 30% increase in cognitive map density from the simplest map to the most complex; this complexity in mental models was a key explanatory variable in the level of functional diversity of the herbaceous community.
5. Organic management practices that support agroforestry practices also, in turn, promote a functionally diverse herbaceous stratum. We show that functional trait syndromes in these herbaceous communities in agroforestry systems are linked with farmer perceptions of traits, and that highly interconnected farm

decision-making is related to greater functional diversity in the herbaceous community. Understanding pathways of farmer decision-making on managing this herbaceous community can appropriately situate on-farm practice and policy for the transition to organic production, and inform emerging agri-environmental programs.

KEYWORDS
agrobiodiversity, agroforestry, cognitive mapping, functional diversity, herbaceous community, organic coffee, social–ecological systems, weed management

1 | INTRODUCTION

Sustainable agriculture practices, including diversified organic farming, foster an increase in ecosystem functioning (Kremen et al., 2012; Tamburini et al., 2020), and mitigate the detrimental role of industrial agriculture as the largest driver of biodiversity loss globally (Dudley & Alexander, 2017). In particular, low-input smallholder farms play a critical role in conserving agrobiodiversity within their own fields (Isakson, 2014; Ricciardi et al., 2018). Coffee (*Coffea arabica*), a pantropical tree crop of high economic importance, is predominately grown on smallholder farms covering 11 million ha of land globally (Bertrand et al., 2016). In Costa Rica in particular, in the late 1990s and early 2000s the market for certification grew substantially (Giovannucci et al., 2008; Le coq et al., 2010) and today an estimated 32% of Costa Rican production is grown with an ecological or social certification with 70% estimated to be grown under shade (Somarriba et al., 2012), while only a small portion of farms are certified organic (GMD, 2021). Organic coffee production ensures the elimination of synthetic herbicides on the emergence of an herbaceous community, including weeds but also cover crops, flowers and various ground covers. While negative impacts of this herbaceous community have been shown in coffee systems, including competition for soil nutrients and suppressing coffee yield (Ronchi & Silva, 2006), and creating increased labour demands for farm workers (Labrada, 1997), positive impacts are also documented, such as increasing associated biodiversity (Soto-Pinto et al., 2002) and reducing soil erosion (Meylan et al., 2013).

The structure of this herbaceous community is shaped by current practices as well as legacy effects on soil conditions (Colbach et al., 2014; Ryan et al., 2010) resulting in dominant plant traits (Bàrberi et al., 2018). While studies have shown that the degree of competition between weeds in the herbaceous community and coffee is highly variable (Ronchi & Silva, 2006), the functional traits and diversity within these communities can be key indicators of plant strategies and function (Martin & Isaac, 2018). Taxonomic diversity metrics account for species composition and abundance (Kazakou et al., 2016), and functional traits provide insight into the resource acquisition strategies of these plant communities (Martin & Isaac, 2015; Violle et al., 2007). These traits, such as leaf dry matter content (LDMC), specific leaf area (SLA), and leaf nitrogen and carbon content (LNC and LCC), can be analysed to determine plant strategies, for instance resource acquisition, and effects on ecosystems, such as rates of nutrient cycling (Garnier & Navas, 2012). Such functional traits are characterized by various multi-trait diversity indices—functional richness (FR_{ic}: the number of species present indicating how much trait space is filled), functional evenness (FE_{ve}: the distribution of mean values of species traits within occupied trait space), functional divergence (FD_{iv}: the specialization of functional traits), and quadratic entropy of Rao (FD_Q: the pairwise functional differences between species in trait space) (Mason et al., 2005; Schleuter et al., 2010). These indices can offer insight into herbaceous plant strategies and are suggested as indicators of function, including nutrient acquisition, in agroforestry systems (Isaac & Borden, 2019).

Unlike in a natural system, these herbaceous communities can emerge from decisive selection or planting by farmers through processes such as consultation, design and decision-making. Indeed, the integrated social–ecological framework proposed by Lescourret et al. (2015) highlights the interconnectedness between social systems, agroecosystem management and agroecosystem structure. This framing shows the critical role of management practices in driving agroecosystems characteristics. Within diversified agricultural systems, there are multiple interfaces between farmers and plant diversity. As outlined in Figure 1, coffee farmers interact with the plant community at multiple strata, or vertical *spaces* of diversity, including shade tree diversity, crop intraspecific trait variation and herbaceous plant diversity. In the shade tree stratum, shade tree diversity is related to many environmental benefits including microclimate modifications (Cerda et al., 2017; Gagliardi et al., 2021), while the influence of farmer perception of shade trees on shade tree selection is established (Cerdán et al., 2012). In the coffee stratum, intraspecific variation of coffee leaf traits has been documented (Martin & Isaac, 2021; Martin et al., 2017), as has the farmer use of coffee leaf trait variation as an indicator for decision-making, such as the use of coffee leaf area in shade tree management (Isaac et al., 2018). Yet, herbaceous plant diversity in organic systems remains understudied and the services provided by, and the management of, the diversity in this stratum are relatively unknown.

Effectively analysing these links between decision-making and on-farm diversity, especially in the understory, remains a challenge. The cognitive mapping approach, however, has been successfully used to study farmer perception of management practices, such as shade

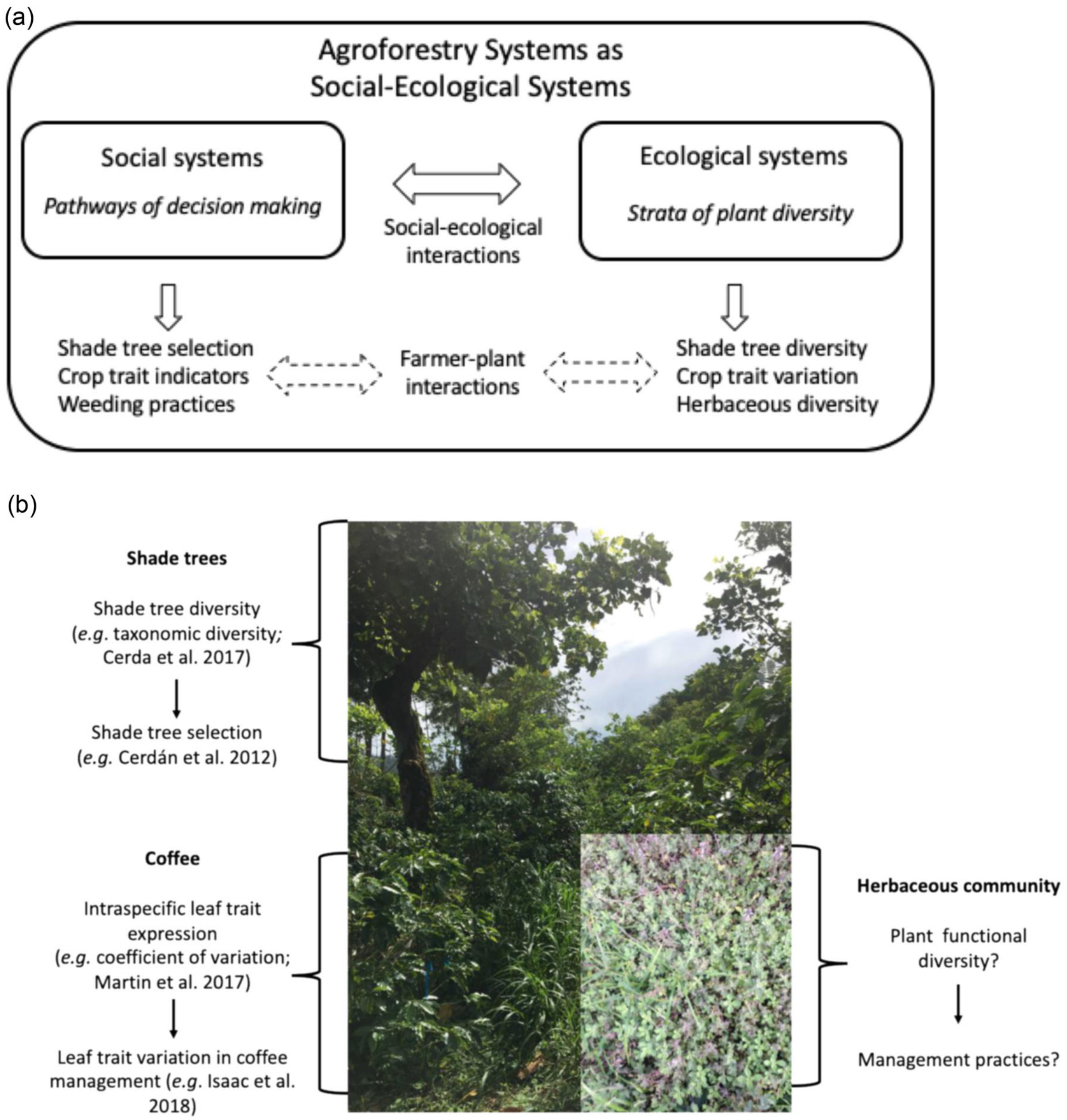

FIGURE 1 (a) Agroforestry systems as social–ecological systems as plant diversity interacts with farmer decision-making processes in various strata. (b) In the shade stratum, shade tree taxonomic diversity interacts with local selection drivers. In the coffee stratum, coffee leaf functional trait variation interacts with farmer use of trait expression in coffee management. In the herbaceous community, diversity and management are understudied, yet critical to on-farm diversity and function. The ecological and social interactions of this stratum are relatively unknown

tree management in cocoa agroforestry systems (Isaac et al., 2009) and risk management within various farmer types (van Winsen et al., 2013). This approach to describing decision-making steps in farm management provides important mental models in order to assess relationships between farmer identified variables that are not known with certainty and are evolving. Cognitive maps provide a demonstrative representation of an individual's conceptualization of a management issue (Jones et al., 2011) and are useful for analysing social–ecological systems (Gray et al., 2014). By linking actions and processes within a specific context (Jetter & Kok, 2014; Özesmi, & Özesmi, 2004), cognitive mapping describes an aggregated version of an individual's knowledge on a decision-making process.

Merging these multiple lines of inquiry, this study consolidates measures of herbaceous community diversity with farmer perception and decision-making in organic coffee agroforestry systems. In this paper, we (i) identify the taxonomic and functional diversity of herbaceous plants in converted organic coffee agroforestry systems, (ii) document the process of managing the herbaceous community, (iii) describe the extent of herbaceous community functional diversity in relation to farm environmental conditions and (iv) link functional diversity to farmer decision-making. To do this, we identified the taxonomy and measured leaf- and plant-level functional traits of the herbaceous community in organic coffee farms throughout Turrialba Valley, Costa Rica. We also conducted in-depth semi-structured interviews with farmers in order to construct mental models on herbaceous plant management using cognitive mapping techniques. Our study contributes new findings to support the management of agrobiodiversity and to the growing literature on agroecological transitions.

2 | MATERIALS AND METHODS

2.1 | Site description

Research was conducted on farms throughout Turrialba, a coffee-growing region, located within the Central Valley of Costa Rica. In Costa Rica, coffee was traditionally grown using agroecological principles which mimic coffee's natural growing conditions by fostering shade tree diversity, ground cover and closed nutrient cycling (Meylan et al., 2013; Munroe et al., 2015; Perfecto et al., 2014; Tully & Ryals, 2017). However, in the 1970s, more than 50% of farms in Costa Rica converted to high-yielding simplified systems with few trees and high inputs of agrochemicals largely due to the introduction of neoliberal economic policies and the Coffee Improvement Project to industrialize coffee production in coordination with USAID (Bellamy, 2011; Rice, 1999). In the Turrialba region, the Asociación de Productores Orgánicos y Agrosostenibles (APOYA) was formed in 2013 to promote organic coffee production in the region and transition farms into organic production.

Through the APOYA network and the Tropical Agricultural Research and Higher Education Center (CATIE), we sub-selected 15 participating farmers and their farms. Participants were chosen based on the criteria that farms (i) are owned and managed by smallholder (<3 ha) farmers, (ii) implement organic practices and excluding synthetic pesticides and fertilizers and (iii) have an herbaceous plant community present providing more than 30% ground cover within the coffee parcels. This selection criteria was applied to all organic coffee farmers in the region, and the selected farms represent ~50% of organic coffee farms regionally, but also are reflective of transitioned farms to organic production in the region and in Costa Rica broadly. The selected farms were all agroforestry systems with shade trees interspersed throughout the farm. And all farms were certified organic, only using inputs permitted under USDA Organic and Organic agriculture Europe certifications, and therefore no synthetic inputs.

2.2 | Taxonomic diversity and functional trait measurements

At each farm, three sampling quadrats of 1 × 1 m were selected with a stratified randomization to avoid a coffee plant within our quadrats (Nkoa et al., 2015). This resulted in a total of 45 quadrats for herbaceous community sampling. Each species in each quadrat was identified (with 36 of the 38 total species identified). The vegetative height of each species identified in the quadrat was determined by measuring the distance between the upper boundary of the main photosynthetic tissues of the tallest plant (top leaf) of that species and the soil (Pérez-Harguindeguy et al., 2013). We measured two morphological functional traits (SLA and LDMC]) and two chemical traits (leaf nitrogen concentration [LNC] and leaf carbon concentration [LCC]) related to resource use economy. These traits were selected a priori given their established role in litter decay rates and nutrient cycling (Bakker et al., 2011). For SLA, three representative leaves for each individual were chosen at ~60% of the height, and showing no signs of disease. Leaves were then transported to the laboratory for morphological and chemical trait analyses. Pictures of the leaves were taken immediately after returning from the field and then analysed with ImageJ software to obtain the leaf area (cm^2). Leaves were then dried at 60°C to constant mass and weighted to attain leaf dry mass (mg). SLA ($cm^2\ g^{-1}$) was calculated from these variables as the ratio between leaf area/dry mass. LDMC ($mg\ g^{-1}$) was calculated as the ratio of leaf dry mass to fresh mass. To determine LNC and LCC, leaf material was analysed with an elemental analyser to determine leaf C concentration ($mg\ g^{-1}$) and leaf N concentration ($mg\ g^{-1}$) (LECO Corporation, Minnesota, USA).

2.3 | Measurements of shade canopy

Dominant shade tree species included *Erythrina poeppigiana*, *Terminalia amazonia* and *Laurus nobilis* at a density of 100–300 shade trees per hectare. We characterized light environments below shade trees using hemispherical photographs at the height of 60 cm at the centre of each quadrat taken with a Nikon Coolpix 950 digital camera equipped with an FC-E8 fisheye converter (Nikon, Tokyo, Japan). All photos were taken directly above each plant under overcast conditions to minimize light scatter. Colour photographs were then converted to binary images and analysed for total light transmission expressed as percentage of open sky, using Gap Light Analyzer v2.0 (Frazer et al., 1999).

2.4 | Farmer cognitive maps

Semi-structured interviews conducted on farm lasted between 20 and 100 min depending on farmers' availability and elaboration on interview questions. All interviews were conducted in Spanish, recorded and saved in a password-protected encrypted folder. Interviews were transcribed directly into English and anonymized. This research received ethics approval from the Social Sciences, Humanities and Education Research Ethics Board, University of Toronto, for research involving human participants. Informed consent was secured in advance of every interview.

All questions were asked to farmers, though many participants answered multiple questions in one response. The word 'monte', meaning greenery/cover crop, was used in place of 'hierba/maleza' ('weed') at the start of the interview to avoid influencing interviewees towards a negative association with the word 'weed' and to discuss the herbaceous community in general. The interview covered three main areas: (i) general information on participant demographics and general farm characteristics, (ii) descriptions of the herbaceous community in their

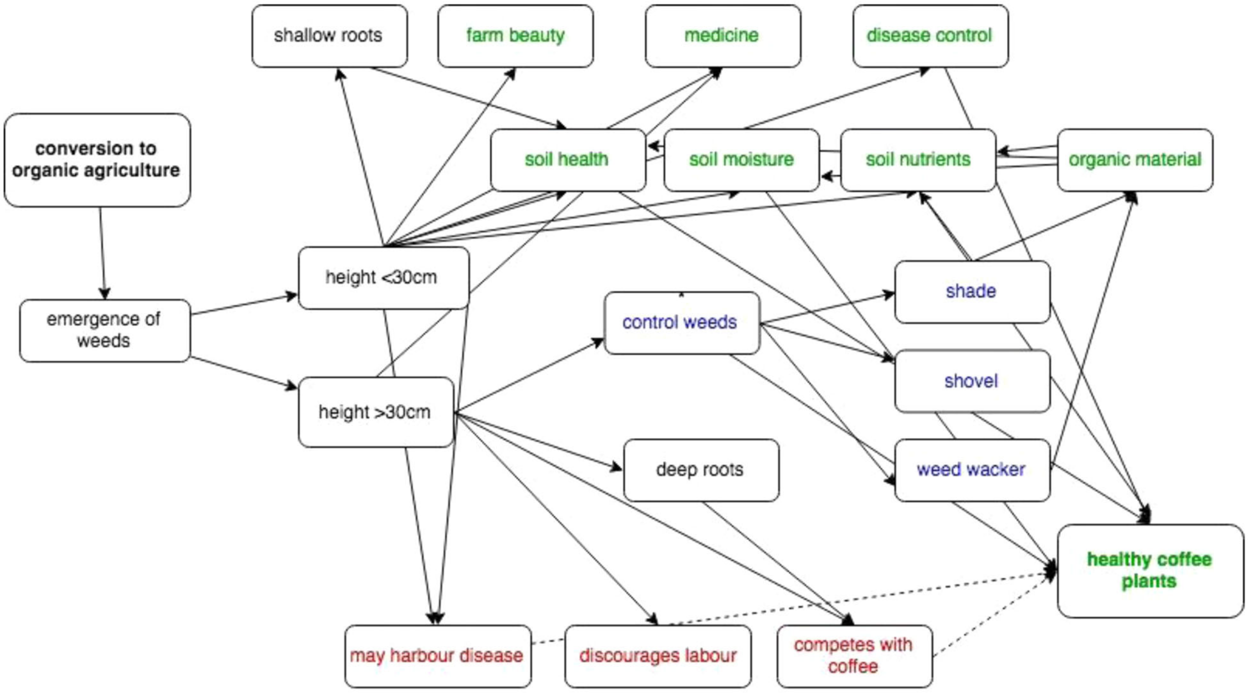

FIGURE 2 A sample cognitive map representing one farm and one farmer's perspective on their herbaceous community. The boxes indicate which includes farmer-identified concepts that were common across all interview, demonstrating a farmer's perception of ecosystem services (in green text), disservices (in red text) and key factors that affect decision-making and control of weeds (in blue text). Solid lines represent positive relationships, whereas dashed lines represent negative relationships

coffee farms and (iii) a suite of questions targeting decision-making practices in order to construct mental models on herbaceous community management. For the latter, our interview questions for each participant started with an initial point of herbaceous plants emerging, with subsequent questions targeting processes taken to identify plants and make decisions on the management of this plant community. The questions continued until we reached a pre-determined end point of healthy coffee plants. We then used a cognitive mapping software, Decision Explorer (Banxia Software Ltd., 2014), to develop a mental model for each participant. In these maps, the initial and end points were set, with subsequent complexity in managing the herbaceous community captured as key concepts coded by giving common labels to recurring themes (Bryman, 2004; Özesmi, & Özesmi, 2004) for a total of 45 common concepts across the interviews. Through an iterative process, these coded labels reflected farmer-identified concepts, termed 'variables', in the decision-making process on herbaceous community management. Directional arrows, termed 'connections', to one or more proceeding variables were established based on participant-identified processes between variables, thus making a continuity map.

Cognitive maps were analysed for connection-to-variable ratio, cognitive map density as well as domain and centrality variables (see Özesmi, & Özesmi, 2004). The connection-to-variable ratio is the number of links compared to the amount of farmer listed variables in each map. This ratio helps to determine the complexity of participant thinking (Dodouras & James, 2007) on the interconnectedness of their farm (Isaac et al., 2009). Map density was calculated by dividing the number of connections in the map by the maximum number of connections possible. Domain variables were identified by calculating the total number of in and out links (arrows) to each variable, thus indicating the complexity level of each individual variable. Centrality variables were identified by calculating both direct and indirect in and out links (arrows) beyond each variable, thus considering the interconnectedness of a variable, which may not be immediately connected but may be central to the overall map.

In order to capture and rank participants' perception of ecosystem services provided by the herbaceous community in organic coffee production, the percentage of time discussing services, or topics related to services, in the interview was operationalized as a metric of ecosystem service valuation, which we called 'value of ecosystem services'. Time allocated to discussing ecosystem services showed a nearly fourfold increase among participants, ranging from 1.9% to 7.6% of the interview.

2.5 | Statistical analysis

Statistical analysis was performed in R software version 3.3.3. All trait and environmental data were checked for normality using fitting distributions approach (Delignette-Muller & Dutang, 2015). Where data were not normally distributed, log-transformed values were used in analysis. Taxonomic diversity (H_0) was calculated using the Shannon diversity index; $H_0 = -P_i(\ln P_i)$, where $P_i = N_i/N_{total}$, where N_i is the abundance of species per plot (plants m^{-2}) and N_{total} is

TABLE 1 Mean, standard error (*SE*) and range of taxonomic diversity (Shannon index), and Functional Diversity indices (functional richness [FR_{ic}], functional evenness [FE_{ve}], functional diversity [FD_{iv}], quadratic entropy of Rao value [FD_Q])

			Linear regression with canopy openness	
Indices	**Mean (*SE*)**	**Range**	**Model R^2**	***p*-value**
Taxonomic diversity				
Shannon	0.75 (0.45)	0.06–1.58	0.114	0.013
Functional trait diversity				
FR_{ic}*	1.59 (1.36)	0.00–4.32	0.059	0.060
FE_{ve}	0.48 (0.26)	0.01–0.98	0.176	0.002
FD_{iv}*	0.78 (0.7)	0.37–1.00	−0.013	0.511
FD_Q	1.59 (1.07)	0.07–3.90	0.059	0.059

Note: Also presented are adjusted model R^2 and *p*-value associated with linear regression between canopy openness (as a proxy for shade tree coverage) and the corresponding herbaceous community indices ($n = 45$ plots). Indices that have been log-transformed are marked with an asterisk (*).

the total abundance of species per plot (plants m^{-2}). The Functional Diversity package (Laliberté et al., 2015) was employed to determine FR_{ic}, FE_{ve}, FD_{iv}, and FD_Q using the four leaf traits (SLA, LDMC, LNC and LCC) of the herbaceous community per plot. To determine the relationship between canopy openness and functional trait indices, we used linear regressions with farm as a random effect.

Principal component analysis (PCA) was employed using the 'vegan' r package (Oksanen et al., 2016) to determine the relationship between species' functional traits. Four leaf traits (SLA, LDMC, LNC and LCC) and one whole-plant trait (height) of the herbaceous species were used in the PCA. Based on these analyses, PCA axes 1 and 2 for each species were calculated and the broad perception of these species, based on interviews, overlaid.

To determine which farmer attributes best predict functional diversity indices, Akaike's information criteria (AIC) was employed. The full model was of the form: *Functional Diversity indices ~ farmer attributes [years organic + value of ecosystem services + cognitive map connection-to-variable ratio + cognitive map density]*. Using the full model, AIC analysis provided the most parsimonious model fit for each response variable. Significance of predictor variables in each AIC selected model was then assessed using multiple regression.

3 | RESULTS

3.1 | Taxonomic and functional trait diversity

In total, 38 species from 20 taxonomic families were present across the 45 plots (Table S1), with a mean Shannon index of 0.75 (±0.45; Table 1). Of the species present, 36% were native to Central America and 55% native to the Americas. Nearly 55% of herbaceous species found in this study were considered beneficial plants ('buena hierba' or 'buena cobertura'). These beneficial plants, such as *Hydrocotyle mexicana*, were not planted but likely from spontaneous growth. *Hydrocotyle mexicana* is a native species that was identified by farmers as contributing to ground cover, as well as soil nutrient and medicinal benefits. Of the 38 species, 21% were considered weeds ('mala hierba' or 'hierbas competidoras') and 24% were considered neutral ('hierba regular') by farmers in this study.

The herbaceous community under high-light environments (high canopy openness) exhibited significantly higher taxonomic diversity ($R^2 = 0.114$; $p = 0.0131$; Table 1) while also exhibiting significantly higher levels of functional evenness ($R^2 = 0.176$; $p = 0.002$) than the herbaceous community under a lower level of canopy openness.

3.2 | Farmer cognitive maps

The cognitive maps derived from interviews with farmers had a mean of 17.2 ± 2.1 variables and 26.8 ± 4.4 connections between variables (Table 2). The mean density of the maps was 0.78 ± 0.05 and the connection to variable ratio ranging from 1.35 to 1.76. The highest domain value was 'organic matter' (73%) followed by 'control weeds' (13%) (Table 3). This indicates that organic matter is the concept most connected in these mental models, and that management of weeds (herbaceous plants over 30 cm) has a variety of different connections indicating the many approaches to manage weeds, including 'shade', 'weed-wacker' and 'shovel' (Figure 3). The highest centrality variable was 'organic material' (33%), followed by 'soil nutrients' (27%), 'soil moisture' (27%) and 'erosion control' (13%). This indicates that these variables had the highest number of direct and indirect connections to other variables. Connections between variables were classified based on farmer-reported positive or negative effects on the health of coffee plants (see Figure 2 for an example map).

3.3 | Linking plant diversity to farmer perception

PCA was used to assess the multivariate relationship across morphological traits, where PCA axis 1 explained 30.8% of the total variation (Figure 3). Farmers identified herbaceous community plants

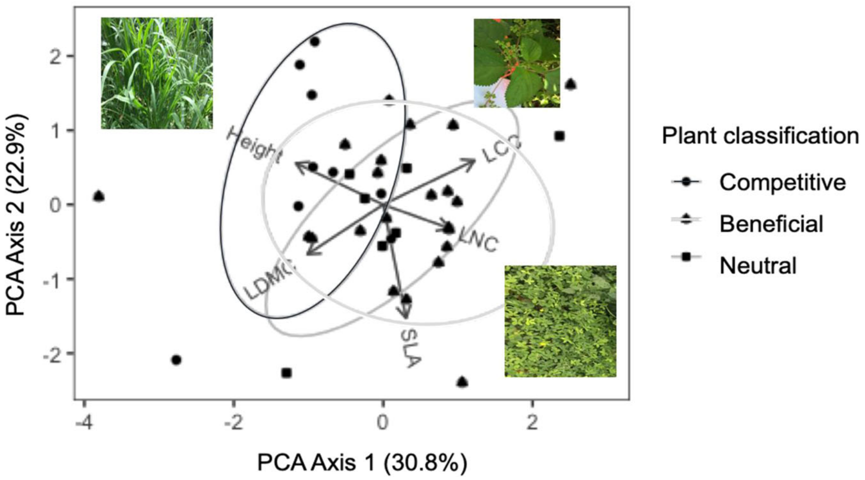

FIGURE 3 Principal components analysis (PCA) assessing relationships among respondent-identified classification (competitive, beneficial and neutral) of species in the herbaceous community and measured plant and leaf functional traits (plant height [height], specific leaf area [SLA], leaf nitrogen concentration [LNC], leaf carbon concentration [LCC] and leaf dry matter content [LDMC]) of the same species in the herbaceous community. Circles represent 95% confidence ellipses surrounding the plant classification groups

TABLE 2 Number of connections, variables, connection-to-variable (C:V) ratio, map density and the mean (± *SD*) derived from cognitive maps per farmer

Farmer	Connections (C)	Variables (V)	C:V	Map density
1	24	15	1.60	0.80
2	24	16	1.50	0.75
3	30	17	1.76	0.88
4	21	14	1.50	0.75
5	30	20	1.50	0.75
6	29	18	1.61	0.81
7	29	18	1.61	0.81
8	23	17	1.35	0.68
9	30	18	1.67	0.83
10	34	21	1.62	0.81
11	21	15	1.40	0.70
Mean	26.8	17.2	1.56	0.78
S.D.	± 4.4	± 2.1	± 0.12	± 0.05

Note: This table is developed from Farmer Cognitive Maps. Variables include farmer perspectives on management practices and ecosystem (dis)services of herbaceous communities on their farm. Farmers with higher connection to variable ratios indicate that they have a high complexity of thinking, seeing many connections between the variables on their farms. Density was determined with the equation density = connections/number of variables × (number of variables − 1). Higher map density signifies that a farmer will see many relationships between the variables and will have more options for implementing change (Isaac et al., 2009; Özesmi, & Özesmi, 2004).

TABLE 3 Highest domain and centrality variable derived from cognitive map analysis

Domain variable	Percentage of farmers with corresponding domain variable as highest
Organic material	73%
Control weeds	13%
Medicine	7%
Soil moisture	7%
Centrality variable	**Percentage of farmers with corresponding centrality variable as highest**
Organic material	33%
Soil nutrients	27%
Soil moisture	27%
Erosion control	13%

Note: Highest domain variables are concepts with most in and out linkages to other concepts in the cognitive maps. Highest centrality variables are concepts with the highest number of direct and indirect links to other variables.

as ‘beneficial’, ‘neutral’ and ‘competitive’, and these identifications were integrated into the PCA. Based on this, herbaceous species with greater height and low LDMC were considered competitive by farmers, whereas herbaceous species with high SLA and LNC were considered beneficial, and species with high leaf carbon content were considered neutral by farmers (Figure 3).

Using stepwise regression, we determined the farmer attributes, including the number of years organic, the individual valuation of ecosystem services plus cognitive map metrics including, connection-to-variable ratio and map density, that best predicted functional diversity of the herbaceous community (Table 4). These analyses determined that cognitive map connection-to-variable ratio was the best predictor for functional richness (model $R^2 = 0.151$; $p = 0.012$) with connection-to-variable ratio positively associated with functional richness. Connection-to-variable ratio was also significant in predicting functional evenness of the herbaceous community (model $R^2 = 0.194$; $p = 0.004$) but was negatively associated. Farmer value of ecosystem services, cognitive map density and connection-to-variable ratio were all significant predictors of functional diversity (FD) of the herbaceous community (model $R^2 = 0.423$; $p < 0.001$). Stepwise regression found that FD_Q declined with increased farmer value of ecosystem services and connection-to-variable ratio; however, FD_Q increased with increased cognitive map density.

TABLE 4 Stepwise and multiple regression model analysis to determine the farmer attributes that best predict indices of herbaceous community functional diversity (functional richness [FR_{ic}], functional evenness [FE_{ve}], functional diversity [FD_{iv}], quadratic entropy of Rao value [FD_Q])

Indices	AIC-retained parameters	Coefficient (*p*-value)	FullAIC	AIC	ΔAIC	Model R^2 (*p*-value)
FR_{ic}	(Intercept)	−2.77 (0.121)	−33.02	−40.51	3.93	0.151 (0.012)
	cv	30.51 (0.039)				
	density	−57.77 (0.057)				
FE_{ve}	(Intercept)	1.70 (<0.001)	−127.35	−129.34	1.99	0.194 (0.004)
	cv	−11.18 (0.042)				
	density	20.72 (0.067)				
FD_{iv}	(Intercept)	−0.12 (<0.001)	−180.44	−184.62	4.18	N/A
FD_Q	(Intercept)	3.00 (<0.001)	−14.42	−14.42	0.00	0.423 (<0.001)
	yorg	−0.075 (0.108)				
	ves	−0.188 (0.027)				
	cv	−88.27 (<0.001)				
	density	177.74 (<0.001)				

Note: Farmer attributes used as parameters are years organic (yorg), value of ecosystem services (ves), cognitive map connection-to-variable ratio (cv), and cognitive map density (density). Parameter estimates and *p*-values are shown for parameters retained in the AIC-selected model. Parameters in bold are significant ($p < 0.05$) in a multiple regression analysis. AIC values for full model and most parsimonious model are presented and ΔAIC values representing the difference between the two. Also shown is the explained variance for each AIC-model, where $n = 15$ for each model.

4 | DISCUSSION

High levels of plant diversity in coffee agroforestry systems have been well documented (Cerda et al., 2017; Haggar et al., 2011; Rigal et al., 2018; Toledo & Moguel, 1999), with particular drivers of diversity associated with organic production systems (Häger et al., 2015). This study provides insight into the previously undocumented source of associated diversity in these agroforestry systems, the herbaceous community under organic production. We report 38 herbaceous species from 20 taxonomic groups in the herbaceous community, contributing substantially to plant species richness within these agroforests. Importantly, this taxonomic diversity in the herbaceous community supports the growing body of research showing that smallholder organic agriculture provides key sources of biodiversity (Storkey & Neve, 2018).

While the taxonomic diversity was high relative to reported diversity in the shade tree stratum in similar coffee farms (Cerdán et al., 2012), the functional diversity was also high, and previously unreported. Broad-leaf species such as *Hydrocotyle bowlesioides* and *H. mexicana* expressed resource acquiring traits, namely relatively high SLA and leaf N values. These trait syndromes have an established role in litter decay rates and nutrient cycling (Bakker et al., 2011). During interviews, farmers identified these particular species as beneficial ground cover and sources of green manure, supporting previous work linking leaf traits and function in agroecosystems in Latin America (Rossi et al., 2011) and the Caribbean (Damour et al., 2014). In contrast, but as expected, grasses and sedges such as *Brachiaria platyphylla* and *Cyperus tenuis* expressed low leaf N and SLA and high LDMC values, all indicators of a resource conserving strategy and low rates of decomposition (Martin & Isaac, 2015), and thus contributing more slowly to nutrient inputs. While work has clearly shown that shade tree traits in agroforestry systems drive nutrient additions and cycling (Isaac & Borden, 2019; Nesper et al., 2018; Sauvadet et al., 2020a), the understorey stratum, with high leaf trait diversity shown in this study, paired with concentrated fine roots in the topsoil (Defrenet et al., 2016), arguably acts as a shorter term driver of nutrient cycling in agroforestry systems.

These patterns of taxonomic and functional diversity were not uniform among farms in this study. This is not unexpected as previous work has shown that weed communities are often structured by plot scale, and up to landscape scale, attributes (see review by Petit et al., 2011). In this study, we found that farms with lower canopy openness, or higher shade tree cover, were associated with herbaceous communities expressing lower functional evenness, while the taxonomic diversity increased with less shade tree cover. Clearly, the intensity of agroforestry adoption, reflected as more dense shade tree canopies and less light transmission to the understory, is significantly related to the herbaceous plant community taxonomic and functional diversity, with consequences for beneficial or competitive plant–soil interactions and nutrient dynamics (Nesper et al., 2018).

In this study, farmers perceived tall herbaceous species as competitive, as these species may compete with emerging coffee plants. On the other hand, farmers identified herbaceous species with high SLA and leaf N as beneficial. This dichotomy is captured by one farmer sharing their admiration for the herbaceous community saying that, '*every plant has a role*'. Farmers placed value on the soil health benefits from the herbaceous community, sharing that these plants '*refresh the soil and provide soil moisture*'. Farmers also consistently reported that the herbaceous community's overall role in supporting soil health and soil erosion control was key in their management decision-making. These two soil factors emerged as dominant centrality variables in the cognitive maps, with 'organic material' as the highest domain variable in 73% of farmer interviews. This variable as a central factor indicates that shade tree litter and pruning, as well as weeded material deposited as organic matter, is critical to organic farmers. The diversity in the herbaceous stratum contributes to sustained nutrient cycling as farmers cut this community for decomposition throughout the year. This supports previous findings in coffee agroforestry systems on the chemical role of mulch in soil nutrient status (Petit-Aldana et al., 2019) and physical and biological role of weeds in soil erosion control (Meylan et al., 2013).

While it is widely accepted that farmer management decisions influence biodiversity and ecosystem functions within coffee agroforestry systems (Cerdán et al., 2012; Isaac et al., 2018; Sauvadet et al., 2020b; Valencia et al., 2015), elucidating these links between decision-making and actual on-farm diversity, especially in the understorey, remains relatively unknown. Here, we model functional diversity indices from herbaceous community trait expression with measures of farmer management. These measures were inferred from farmer cognitive maps, for instance, a high connection-to-variable ratio in a cognitive map indicates complexity in management decision-making. This ratio signifies an intricacy in farmer thinking about the interconnectedness of their farm (Dodouras & James, 2007). In our study, these connection-to-variable ratios were higher than other reported connection-to-variable ratios in cognitive maps on farm management (agroforestry practices; Isaac et al., 2009). And importantly, these ratios were also a significant predictor of functional dissimilarity, functional evenness and functional richness of plant traits in the herbaceous community. We show that high connection-to-variable ratios were positively related to herbaceous community functional richness, and negatively related to functional evenness and functional dissimilarity. Arguably, farmers who use many herbaceous community management pathways cultivate farms with high functional diversity. As transitions to organic coffee farms occur, promoting a suite of interconnected options in on-farm management of the emerging herbaceous stratum can shape diverse and desirable plant communities.

Specifically, during farm establishment, maintaining herbaceous communities that express low stature (so as to not compete with emerge coffee plants) fits farmer prioritization of coffee health while also conserving this important community. With the life cycle of the farm, desirable characteristics of the herbaceous community change, selecting for species that express resource acquiring traits in order to stimulate fast nutrient cycles and contribute to nutrient availability. As shade trees grow, the interaction of shade with the herbaceous community becomes increasingly critical to herbaceous community dynamics. Trait syndromes change, as do the breadth and complexity of farmer management pathways. When working with farmers on strategies to minimize plant–crop competition and maximize services provided by this community, unlike shade trees which are longer term investments with slowly evolving biogeochemical dynamics, this herbaceous community–coffee–shade tree nexus should not be seen as static, rather rapidly evolving with farm development.

5 | CONCLUSIONS AND IMPLICATIONS

There are multiple interfaces between farmers and on-farm plant diversity (see Figure 1); farmers interact with plant communities and *spaces* of agrobiodiversity—shade trees, crop trait variation, and, as outlined in this study, the herbaceous community. We show that the expression of trait syndromes in these herbaceous communities is linked with perceptions of traits by farmers. This supports the literature on the nexus of farmer perception and plant functional traits as indicators of management, for instance in shade tree management (Cerdán et al., 2012; Isaac et al., 2018), and, in particular, supports the well-articulated but inconsistent role of the herbaceous community in providing ecosystems services in agricultural systems (Petit et al., 2011). Using both social and ecological factors in modelling functional diversity, we show that the complexity in herbaceous management underscores on-farm diversity. Indeed, the scope of perceived and realized options to modify herbaceous plants through on-farm management is incredibly important, and this is reflected in the emergence of highly diverse herbaceous community.

Many shade-grown coffee farms still use conventional practices including agrochemicals, with the estimate of certified organic coffee producers in Costa Rica below 2% (Soto & Le Coq, 2011). Evidently, there remain strong social, economic and environmental barriers for farmers to transition to organic production, including the emergence of weeds (Lyngbæk et al., 2001; Ronchi & Silva, 2006). Yet, the global demand for organic coffee is expected to increase by over 10% annually from 2020 to 2030 (GMD Research, 2021). Appropriately reflecting farmer decision-making and perception of the herbaceous community can properly situate on-farm practice and policy for the transition to organic production, and inform emerging agri-environmental programs.

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AUTHOR CONTRIBUTIONS

Sarah Archibald and Marney Isaac conceived of and designed the study. Sarah Archibald collected all data. Sarah Archibald and Marney Isaac analysed the data. Sarah Archibald, Clementine Allinne, Carlos R. Cerdán and Marney Isaac wrote the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Based on confidentiality protection outlined in our approved ethics protocols for research with human participants, data from this research will not be archived.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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