From the Ground Up: Herbaceous Community Diversity and Management in Coffee Agroforestry Systems

by

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A thesis submitted in conformity with the requirements for the degree of Master of Science
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Abstract

The herbaceous community (HC) is an understudied yet critical aspect of tropical agroecosystems. I measured the diversity and perceptions of the HC within organic coffee systems in the Central Valley of Costa Rica. The HC was taxonomically and functionally diverse; comprised of 39 species from 20 taxonomic groups. Farms below the regional mean size and those with canopy openness of 20-30% had higher HC functional diversity. Farmers perceived tall species with low SLA and LNC, but high height and LDMC to be undesirable, due to slow decomposition rates and management limitations. Farmers’ cognitive map complexity was positively related to HC functional richness, and negatively related to functional evenness and functional dissimilarity. All farmers placed higher emphasis on soil health and organic matter than coffee yield, which may be indicative of their role as land stewards. Workshops are needed to disseminate HC management information to optimize labour and ecosystem functioning.
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Chapter 1 - Introduction

1.1 Background

Industrial agriculture is responsible for detrimental environmental degradation such as decreasing biodiversity (Jones et al. 2018), fragmenting habitats (Newbold et al. 2015), and contributing to high levels of air and water pollution (Tilman et al. 2017). Increasing concerns about industrial agricultural have catalyzed the development of sustainable agricultural systems that promote conservation and biodiversity (Sandhu et al. 2010). Sustainable agriculture systems, including organic agriculture, foster an increase in ecosystem functioning and the provisioning of ecosystem services (Naeem et al. 1994; IFOAM 2009; Isbell et al. 2017). Organic agricultural practices can provide greater food security while fostering nutrient cycling, promoting soil health and reducing deforestation (Altieri 2009; Foley et al. 2011). Global organic production is growing at a rate of approximately 7% per year (Willer & Lernoud 2017). As of 2015, there were 2.4 million organic farmers worldwide who were managing 50.9 million hectares of land across 179 countries (Willer & Lernoud 2017).

Coffee has become a leading crop in organic agriculture and now represents over 25% of all permanent organic cropland (Willer & Lernoud 2017). Coffee is a crop of great importance from a conservation perspective as it is produced on 11 million hectares of land (Bertrand et al. 2016) located within tropical biodiversity hotspots (Myers et al. 2000). Since its introduction to the Americas in the early 19th century, coffee has been a force in shaping policies, economies, landscapes and livelihoods (Sick 1999; Perfecto et al. 2014). Recently, many smallholder farmers across Latin America have shifted to agroecological coffee production, including organic production (Toledo & Moguel 2012), which mimics coffee’s natural growing conditions by fostering shade-tree diversity, herbaceous communities and closed nutrient cycles (Tully & Ryals 2017). Research has found that the inclusion of shade-trees in coffee systems improves ecosystem function (Perfecto et al. 1996; Perfecto et al. 2014) and ecosystem services such as biodiversity conservation (Méndez et al. 2010; Tscharntke et al. 2011; De Beenhouwer et al. 2013), erosion control (Meylan et al. 2013) and carbon sequestration (Wardle et al. 2012).
Organic coffee production protocol ensures the elimination of the synthetic herbicides that cause water and soil contamination (Nestel 1995; Relyea 2005). Without the use of synthetic herbicides, the herbaceous communities which naturally occur in traditional coffee systems re-emerge. Herbaceous communities include cover crops, weeds, flowers and other ground covers. A few studies have found positive impacts of the emergence of the herbaceous community in coffee systems such as increasing biodiversity (Soto-Pinto et al. 2002) and reducing soil erosion (Meylan et al. 2013). Other studies indicate negative impacts of herbaceous communities including suppressing coffee yield (Ronchi & Silva 2006) and creating increased labour demands for farm workers (Labrada 1997). Overall, however, the role of herbaceous communities in coffee agroforestry systems is understudied (Ronchi & Silva 2006). New approaches to understanding the herbaceous community, such as through a functional ecology lens, and the ecosystem services it provides within coffee agroforestry systems will provide significant benefits to farmers, scientists and policymakers alike.

Functional ecology has been an essential approach to advancing the understanding of natural plant community dynamics yet has only recently been applied to agroecosystem research (Garnier & Navas 2012; Martin & Isaac 2015). The measure of ecologically relevant plant traits, for example leaf traits, through a functional ecology lens can provide insight into how plants respond to environmental variation and how plants, in turn, affect ecosystem functions (Lavorel & Garnier 2002; Garnier et al. 2004; Martin & Isaac 2015). A functional traits approach can provide evidence to answer questions around plant community assembly and ecosystem functioning in a way that can be more meaningful than species richness or composition (Cadotte et al. 2011; McGill et al. 2006). Researchers have used functional traits to provide important insights into coffee leaf expression among a range of management scenarios as well as response to and influence on ecosystem functions (DaMatta 2004; Matos et al. 2009; Gagliardi et al. 2015; Martin et al. 2017; Isaac et al. 2017) but the herbaceous community remains understudied from a functional traits approach.

1.2 Research questions and objectives

My research questions are: (1) How taxonomically and functionally diverse is the herbaceous community in organic coffee agroforestry systems? (2) What factors best explain the level of
diversity in organic coffee agroforestry systems’ herbaceous community? (3) What are farmer perceptions of the herbaceous community in their coffee systems and how do these perceptions affect management practices?

To answer these questions, I conducted a field study in the Turrialba Region of Costa Rica to record the taxonomic and functional diversity of the herbaceous community; to measure soil conditions including soil carbon, nutrients and moisture; and to determine the impact of herbaceous community diversity on coffee health indicators by measuring coffee yield and coffee leaf rust incidence. I paired this field study with semi-structured interviews with organic coffee farmers (n=11), all members of the local organic cooperative the Organic and Sustainable Producers Association (APOYA) and performed subsequent cognitive mapping analysis.

On these organic farms in the Central Valley of Costa Rica, I proposed the following objectives:

1. Measure the taxonomic and functional diversity of the herbaceous community within organic coffee agroforestry systems.
2. Determine how farm management practices (weeding intensity, shade tree management) and farm characteristics (farm size) affect organic coffee agroforestry systems’ herbaceous communities.
3. Present farmer perceptions of the herbaceous community through a cognitive mapping approach.

1.3 Research significance

My research aims to provide some of the first insights into herbaceous community functional diversity in tropical agroecosystems to the growing body of community ecology literature (Soto-Pinto et al. 2000; DaMattia 2004; Beer et al. 1998; Haggar et al. 2011; Gagliardi et al. 2015). There is currently a gap in knowledge about the role that herbaceous communities in coffee agroforestry systems play in ecosystem service provisioning such as enhancing soil carbon. Functional traits, such as leaf physiological, morphological and chemical characteristics (McGill et al. 2006; Westoby & Wright 2006; Violle et al. 2007) of the herbaceous community will contribute to an understanding of its ecological function. By measuring functional traits, soil conditions and coffee health indicators, this project explores how the herbaceous community contributes to ecosystem services.
From a social-agroecological perspective, weeds are the number one obstacle for farmers to shift from conventional to organic coffee production due to increased labour and potential yield decline (Lyngbæk et al. 2001; Ronchi & Silva 2006; personal correspondence, 5 July 2018). While coffee has been cultivated without chemicals since its arrival in Latin America in the 18th century (Perfecto et al. 2014), currently, most support for weed management comes from chemical companies, such as Bayer CropScience, which promote herbicide use (Bellamy 2011). My research aims to provide farmers with an agroecological alternative by presenting the ecological and cultural elements of farmers’ current management practices and their methods of evaluation in a way that allows for collective knowledge to guide interests of the local community (Stirling et al. 2017). To better understand the role that organic farmers play in the management of the herbaceous community and the provisioning of ecosystem services, this study employs a cognitive mapping approach to investigate farmer perspectives (Isaac et al. 2009).

Finally, my research aims to inform future iterations of payment for ecosystem services. Specifically, with payments for ecosystem services as a growing mechanism for conservation in Costa Rica, insight into the herbaceous community’s role in ecosystem service provisioning is essential. For example, the role of the herbaceous community in increasing soil carbon may be important information for Costa Rica to reach its goal to become the first carbon neutral country by 2021 (Defrenet et al. 2016). Including the herbaceous community in payments for ecosystem service programs may offer more comprehensive supports for smallholder farmers who currently do not benefit from these payments (Lansing 2017). My research will be disseminated in the Central Valley of Costa Rica through partnerships with the Organic and Sustainable Producers Association of Turrialba (APOYA), Nationally Appropriate Mitigation Action (NAMA) and the Tropical Agricultural Research and Higher Education Center (CATIE). Finally, since Costa Rica is known as a leader in environmental and conservation policy, such as its payment for ecosystem service program (Keenan 2017), it is my hope that this research will inspire other countries to consider the ecosystem services provided by their own herbaceous communities.
Chapter 2 - Literature Review

2.1 Agriculture and biodiversity

Agriculture is currently the largest contributor to biodiversity loss (Dudley & Alexander 2017) and is responsible for over 30% of greenhouse gas emissions worldwide (Balmford et al. 2009; Tillman et al. 2017). As the world’s single largest land use, agriculture must change to meet the needs of future generations (Dudley & Alexander 2017). Farmers, particularly small-holder farmers in the global South, foster a variety of crops and herbaceous species within in their fields and thereby sustain and conserve agricultural biodiversity (Isakson 2014). Practices such as conservation agriculture, agroforestry and organic agriculture foster biodiversity (Dudley & Alexander 2017). Organic coffee agroforestry systems, for example, promote ground covers and tree intercropping to support soil health, ecosystem services and local livelihoods (De Beenhouwer 2013; Atangana et al. 2014).

2.2 Transitions in coffee production

Coffee is one of the world’s most important agricultural commodities with an estimated annual retail value of 70 Billion USD (Talhinhas et al. 2017). Coffee also has significant ecological and social influence with more than 11 million hectares of land in coffee production (Bertrand et al. 2016) and more than 100 million people who depend on coffee as their main source of income (ICO 2016; Talhinhas et al. 2017). Coffee originates from the montane rainforest of Ethiopia, where it naturally grew as an understory crop beneath shade-trees and among shrubs and herbaceous communities (Toledo & Moguel 2012). When the crop was first introduced to the Americas, it was planted within forest ecosystems to mimic coffee’s natural habitat of a diverse shade tree and herbaceous species (Vandermeer & Perfecto 2015). Since its original introduction, coffee production has dramatically shaped the landscapes of countries across the Americas (Sick 1999; Perfecto et al. 2014).

2.2.1 Rise in coffee monoculture

In the 1980s, countries across Latin America, including Costa Rica, experienced economic stagnation and financial crisis (Conroy et al. 1996). In an attempt to boost the economy, USAID and local governments encouraged farmers to increase coffee production for export. The increase
in coffee production was achieved through agricultural intensification including increased chemical inputs and deforestation (Conroy et al. 1996; Perfecto et al. 2014). This monoculture system ensured that coffee plants would not have to compete with shade-trees and herbaceous communities for light, water or nutrients. While coffee monoculture yielded three to four times the harvest compared to traditional agroforestry systems, it disrupted natural ecological processes and lowered global coffee prices which resulted in economic vulnerability for many smallholder farmers (Haggar et al. 2011).

2.2.2 Herbicide use in coffee monoculture

Coffee intensification promotes the use of synthetic chemical herbicides to control herbaceous communities. Herbicides are applied to more hectares of land than any other category of chemical pesticide (National Research Council 1989; Bellamy 2011). The two most dominant herbicides used in coffee systems are paraquat and glyphosate (Bellamy 2011). Paraquat is a water-soluble herbicide which has been banned in the United States due to its high toxicity and long persistence in the soil (US EPA 1997; Bellamy 2011; Green 2014). Glyphosate is a broad-spectrum systemic herbicide that is used world-wide. Recently, glyphosate was found to be a probable carcinogen due to its long half-life in water and soil (Myers et al. 2016). As with many herbicides used in coffee production, both glyphosate and paraquat are non-selective and can cause damage to the coffee plant itself (Njoroge 1994).

The application rates of herbicides are not economically, ecologically, nor socially sustainable. During the Expert Consultation on Weed Ecology and Management Conference, Gerowitt (1997) presented findings that farmers were spraying up to 20-50% more herbicides than needed. Moreover, an estimated 85–90% of herbicides never reach target species and instead move into the air, soil and water (Moses et al. 1993; Bellamy 2011). Many farmers are aware of the dangers of herbicides. A recent study in the Turrialba region of Costa Rica found that 80% of conventional and organic farmers interviewed believed that the use of herbicides decreased the fertility or changed the structure of their soil (Cerdán et al. 2012). With agrochemical availability predicted to decline as a result of reduced access to fossil fuels and phosphorus in the coming years, herbicides will become even more costly (Cordell et al. 2009; Woods et al. 2010; Garnier & Navas 2012).
2.2.3 The transition towards organic coffee production

Due to the damaging economic, ecological and social impacts of monoculture coffee production, many smallholder farmers worldwide have transitioned back to diversified agroforestry coffee systems including certified organic coffee production (Toledo & Moguel 2012). The organic movement has been a prominent agroecological alternative for coffee producers over the past three decades with 8.9% of the world’s harvested coffee now being produced organically (Willer & Lernoud 2017). The area under organic coffee production has increased four-fold since 2004 to almost one million hectares which represents 25% of the organic permanent cropland globally (Willer & Lernoud 2017).

Organic systems prohibit the use of synthetic chemicals and rely solely on biological nutrient sources (Ayalew 2014). Therefore, organic producers integrate nutrients through practices such as planting and pruning shade-trees, mechanically or manually cutting their herbaceous community and integrating it as green manure (Bellamy 2011). Organic practices provide many ecological benefits but often require more labour and can result in lower coffee yields (Haggar et al. 2011; Cerda et al. 2017a). To compensate for increased labour and potential yield decline, organic coffee farmers receive a price premium (Mendéz et al. 2010). While these premiums may not be enough incentive for farmers to transition to organic farming yet, there are emerging opportunities. The rapid growth of the global organic market (Willer & Lernoud 2017), local network support (personal correspondence, July 5 2018), and the potential for payment for ecosystem service programs (Pagiola 2008), all provide farmers with opportunities to benefit from organic production. However, with weed management named as the number one barrier for conventional farmers to transition to organic agriculture in the Central Valley of Costa Rica (personal correspondence, July 5 2018), there is an urgent need to understand the role the herbaceous community plays in coffee agroforestry systems.

2.3 The emergence of the herbaceous community: ecosystem services and disservices

The elimination of herbicides in organic agriculture has led to the emergence of herbaceous communities in coffee agroforestry systems. Grasses and broad-leaf weeds are the most
prominent herbaceous species that emerge (Njoroge 1994), though tree seedlings and woody perennials also appear within coffee systems globally.

In coffee agroforestry systems, the herbaceous community provides provisioning services (MEA 2005) including coffee yield, forage for animals and medicine (Soto-Pinto et al. 2002). Herbaceous communities also provide supporting services including the enhancement of bird and small mammal diversity (Gordon et al. 2007) and cultural services including spiritual or aesthetic elements to farms (Toledo & Moguel 2012). Herbaceous communities provide many regulating services including promoting pollination (Gordon et al. 2007) and improving soil fertility (Sarno et al. 2004). Research from vineyards indicates that after being cut, the herbaceous community itself becomes a layer of organic matter which supports soil moisture (Morlat & Jacquet 2003) and nutrient cycling (Garcia et al. 2018) and can be a viable alternative to the application of chemical fertilizers (Hartwig & Ammon 2002). Herbaceous covers also play an important role in soil protection by physically covering topsoil and strengthening the belowground soil which protects soil from water and wind erosion (Novara et al. 2011). Within coffee-agroforestry systems, the roots of herbaceous species have been found to support belowground soil biota and macroporosity (Sarno et al. 2004; Meylan et al. 2013; Martins et al. 2015). Across agroecosystems, the herbaceous community has been found to support carbon sequestration by increasing soil organic matter (Kaye & Quemada 2017). There are many herbaceous species that do not have known services or disservices and therefore, are considered neutral by farmers (Filho et al. 2013).

The herbaceous community can also create ecosystem disservices, which are ecosystem generated functions or attributes that have negative impacts on human wellbeing (Shackleton et al. 2016). Herbaceous community ecosystem disservices including competition for limited resources and reduction of coffee yields, are accordingly referred to as weeds (Ronchi & Silva 2006). Coffee plants respond to water and nutrient competition by pushing their roots further into the soil, which transfers energy from fruit production to below-ground growth thereby reducing yields (Njoroge 1994). Moreover, herbaceous communities may decrease the amount of plant available nitrogen by immobilizing nitrogen, particularly in dry soil (Celette et al. 2009), though this depends greatly on the leaf nitrogen concentration of the plant substrate (Yadvinder-Singh et al. 2005). Nutrient and water competition can stress coffee plants and predispose the
crop to severe pathogen attacks (Zambolim et al. 1997). Moreover, herbaceous communities can interfere with management practices including fertilization and harvesting (Njoroge 1994). Controlling the herbaceous community can be the most labour-intensive aspect of coffee production (Lyngbæk et al. 2001), particularly for conventional farmers who employ both chemical and mechanical practices to weed (Bellamy 2011). In the Central Valley of Costa Rica, hiring labour for weeding is common and can be a significant expense (Bellamy 2011). For example, hiring labour to control the herbaceous community may cost farmers approximately $30 USD per day, which is the equivalent price farmers receive for approximately 15lbs of green organic coffee (personal correspondence, June 2018). Appropriate education and incentive programs could encourage shifts management practices to decrease labour demands while reducing ecosystems disservices and promoting ecosystem services of herbaceous communities (Power 2010).

Costa Rica is leading the movement to address and foster ecosystem services through a payment for ecosystem services (PES) program (Pagiola 2008). The PES program is organized through the country’s National Fund for Forest Financing (FONAFIFO), a semi-autonomous government agency with independent legal status (Pagiola 2008). The FONAFIFO organization supports farmers and other land stewards who provide ecosystem services such as water filtration, greenhouse gas mitigation, biodiversity conservation, the creation of natural beauty (FONAFIFO 2018). Costa Rica’s payment for ecosystem service program is seen as a conservation success story (Pagiola 2008). However, there are still challenges with the program including the payment for services provided only by trees and the skewed benefits towards large landowners (Lansing 2017). The role of the herbaceous community has been overlooked in ecosystem function and service provision in Costa Rica, though is starting to be explored in other countries (Woodbury et al. 2017). Further exploration of the role of the herbaceous community could support the development of a more equitable and comprehensive payment for ecosystem service program.

2.4 Herbaceous community functional diversity

Many studies have supported the positive relationship between herbaceous diversity and ecosystem function (Smith et al. 2009), but the drivers behind this relationship are not clearly understood (Cadotte 2017). Taxonomic diversity measures into herbaceous communities
provide useful information about species richness, native versus non-native species and impact of management practices (Kazakou et al. 2016). Assessing leaf functional traits and trait trade-offs in managed systems can inform a more mechanistic understanding of plant responses to environmental conditions and the influence of plants on ecosystem function, than taxonomic species diversity alone (Cadotte et al. 2011; Granier & Navas 2012; Martin & Isaac 2015). Three commonly measured leaf traits - specific leaf area (SLA), leaf dry-matter content (LDMC), and leaf nitrogen concentration (LNC) are considered functional markers as they can assess the impacts of community changes on ecosystem properties (Garnier et al. 2004). These traits provide an understanding of plant strategies for resource use and ecosystem functioning (Wright et al. 2004). Plants with high LNC and high SLA indicate fast-growing, short-lived plants with faster decomposition rates. Plants with low LNC and low SLA are often longer-living plants with lower decomposition rates (Wright et al. 2004; Garnier & Navas 2012). Leaf carbon concentration (LCC) provides important insight into community carbon accumulation (Derroire et al. 2018) and plant height provides intel into competitive capacity (Garnier & Navas 2012). Collectively, these traits inform both functional diversity indices and community weighted mean approaches to better understand herbaceous community diversity.

Functional diversity metrics – functional richness, functional evenness, functional divergence (Mason et al. 2005) and functional dissimilarity (Botta-Dukát 2005) – are central to describing the functional diversity of a plant community. Functional richness (FRric) is related to the number of species present in a plot and indicates how much niche or trait space is filled (Mason et al. 2005). Functional evenness (FEve) indicates the distribution of mean values of species traits within occupied niche space (Mason et al. 2005; Schleuter et al. 2010). Functional divergence (FDn) indicates the specialization of the functional traits, for instance, high functional divergence signals that there is a high amount of niche differentiation and low resource competition (Mason et al. 2003; Mason et al. 2005). The quadratic entropy of Rao (1982), also referred to FDQ (Schleuter et al. 2010), incorporates the relative abundance of species and measures pairwise functional differences between species to quantify the functional similarity of individuals in the trait space (Shimatani 2001; Botta-Dukát 2005). A high FDQ value signifies that individuals are less similar and therefore do not fill the same functional role (Karadimou 2016). Interestingly, FRric and FDQ may be negatively related as pairwise differences between species may decline as more species are introduced (Botta-Dukát 2005).
Another useful tool for understanding herbaceous community diversity is through community weighted single-trait indices. Community weighted means (CMW) are plot-level single-trait values weighted by the relative abundance of the species present. Given that the mass-ratio hypothesis suggests that the most abundant species are most important in driving ecosystem functioning (Grime 1998; Díaz et al. 2007), CMWs are a useful measure in complex landscapes (Butterfield & Suding 2013). Community weighted means are frequently used as an indicator of functional composition in order to understand trait variation of plant communities (Díaz et al. 2007).

2.5 Farmer perception and management of herbaceous communities

Farmer knowledge and management decisions influence biodiversity conservation and ecosystem functions within coffee agroforestry systems (Cerdán et al. 2012; Valencia et al. 2015). Local farming knowledge is often developed within the community (Raedeke & Rikoon 1997), with producer networks as important spaces for the transfer of knowledge and adoption of management practices (Isaac 2012; Cadger et al. 2016; Isaac & Matous 2017). The importance of producer networks supports the need to substantively include the perspectives of farmers in any and all agriculture related policy and practice (Halbrendt et al. 2014; Stirling et al. 2017). Current farmer knowledge intersects with the management of herbaceous communities in three ways: management of shade trees, mechanical and biological control of the herbaceous community, and the farm labour/farm engagement nexus.

Shade trees can affect the herbaceous community by reducing the amount of light that filters through the canopy and by forming a litter layer through a leaf fall and pruning residues (Beer et al. 1998; Staver et al. 2001). Nestel and Altieri (1992) found that the biomass of herbaceous community in coffee monoculture was two times the amount compared to a diverse agroforestry system due to light reduction and shade-tree pruning litter. Shade trees can also affect the types herbaceous species present, with shaded plots fostering more broad-leaf species, often considered good herbaceous species, whereas full sun plots foster the growth of more grasses, which are often considered bad weeds (Nestel & Aliteri 1992). A local guide encourages farmers to use shade-trees and prune them at least once a year (Montagnini et al. 2015), but no specific
level of canopy openness is suggested. Since herbicides are prohibited within organic systems, mechanical and biological controls are permitted in organic production.

The mechanical management of the herbaceous community includes the use of a machete, weed-wacker, and/or shovel (Bellamy 2011). A Costa Rican coffee weed management guide suggests that farmers should use a machete and weed-wacker to cut herbaceous species down to encourage decomposition and nutrient cycling of herbaceous biomass. The guide also suggests that farmers use a shovel, hoe or their hands to remove herbaceous species with rhizomes during the dry season to reduce their spreading (Filho et al. 2013). Other mechanical management options include burning herbaceous communities, letting animals graze, and planting cover crops (Filho et al. 2013). Research suggests that herbaceous species competition only occurs during the early stages of growth for young coffee plants (Ruthenberg 1971; Terry 1984) and throughout the months of crop flowering and fructification for adult coffee plants (Ronchi & Silva 2006).

As herbaceous community management can constitute over 50% of farm labour time (Labrada 1997), techniques that reduce labour while providing ecosystem services are essential to support coffee production and farmer livelihoods. It is of importance to note that organic coffee systems may be able to tolerate a higher level of herbaceous community biomass compared to conventional systems due to fertility management within organic systems (Ryan et al. 2009; Rossi et al. 2011). Moreover, conventional farmers often spend significantly more time on herbaceous species control than organic producers, as they utilize both chemical and mechanical management (Lyngbæk et al 2001; Bellamy 2011). Recent studies have determined that plant-based indices to diagnose the success of farm management practices is highly related to a farmer’s level of engagement with crops (Isaac et al. 2018), leading to decisions on fertilization, pruning, species selection (Isaacs et al. 2016; Dickinson 2017) and soil health (Valencia et al. 2015). These plant-based indices are at least partly derived from physical engagement with plants in the field (Isaac et al. 2018). Interestingly, research into hired labour has observed that there can be a negative effect on agricultural biodiversity (Isakson 2011), perhaps due to a greater variety of agricultural tasks (Van Dusen & Taylor 2005) or a reduction in regular engagement with plants on the land (Isaac et al. 2018).
2.6 Mental models

Integrative frameworks which bridge biophysical and social domains are needed to understand human-altered ecosystems, particularly agroecosystems (Collins et al. 2010). The integrated social-ecological framework for agroecosystem services proposed by Lescourret et al. (2015) highlights the interconnectedness between social systems, agroecosystem management, ecosystem structure and ecosystem services. Building off of socio-ecological theory and research into coffee agroforestry systems, farmers are seen as important agroecosystem managers (Bandeira et al. 2002; Cerdán et al. 2012; Lescourret et al. 2015). Understanding how farmers generate and apply knowledge to management practices has significant impacts for biodiversity conservation of agroforests (Valencia et al. 2015).

Research on knowledge, skills and attitude (Greiner 2015) gives a more complete understanding of intrinsic motivations for decision making (Ingram et al. 2013) and management practices (Hoffman et al. 2014). Furthermore, it is essential to consider farmers’ perspectives when introducing or supporting agricultural development programs (Pretty 1995; Halbrendt et al. 2014), including payment for ecosystem programs (Lansing 2017). Mental models, such as cognitive mapping, are a widely accepted approach to understanding individual and group decision-making processes (Jones et al. 2011; Gray et al. 2014; Halbrendt et al. 2014) and have recently provided important insights into sustainable agricultural (Isaac et al. 2009; van Winsen et al. 2013) and food systems management (Stier et al. 2017).

Cognitive mapping is a valuable tool to visually represent how local knowledge and human actions affect ecosystems (Özesmi & Özesmi 2004; Christen et al. 2015). Cognitive mapping, an approach first coined by Tolman (1948), supports the creation of participatory management plans in ecological systems and helps to represent individual’s understanding of the systems around them (Özesmi & Özesmi 2004; Gray et al. 2014). The cognitive mapping approach has been successfully used to include farmer perception of management practices (Isaac et al. 2009; van Winsen 2013) and provides important insights for planning needed to increase sustainability (Dodouras & James 2007). Since cognitive maps allow for the modelling of relationships between variables that are not known with certainty and are ever-evolving, they are useful in an agricultural context. Cognitive mapping approaches allow for the inclusion of complex ideas yet facilitate the ease of obtaining information which is useful in adapting to farmers’ busy schedules.
One disadvantage of cognitive mapping is that the approach requires the researcher to construct the map without a standardized methodology (Eden 2004; van Winsen et al. 2013). Therefore, the quality of the interviewer as listener and interpreter (Eden 2004) and investment in the time-consuming process of constructing cognitive maps is essential (Isaac et al. 2009).

### 2.7 Gaps in literature

While there is substantial research into ecological benefits of coffee agroforestry systems (Soto-Pinto et al. 2002; Cerdán et al. 2012; Gagliardi et al. 2015; Cerda et al. 2017a), the role of the herbaceous community is understudied (Ronchi & Silva 2006; Rossi et al. 2011). The majority of research on herbaceous species in coffee systems in Costa Rica has been conducted by chemical companies, which does not meet the needs of smallholder organic farmers (Bellamy 2011). Few studies have looked at the taxonomy of herbaceous communities within coffee agroforestry systems and none have taken a trait-based approach. Therefore, understanding the herbaceous community from a functional ecology lens will provide important insight into its role in ecosystem functioning and service provisioning.

Recent research indicates that leaf functional traits knowledge provides mutually beneficial insights for farmers and scientists alike (Martin & Isaac 2015; Dickinson 2017; Isaac et al. 2018). However, these studies have focused on crop leaf traits rather than the traits of the herbaceous community. This study will contribute information to the important field of functional diversity and farmer knowledge. Finally, recent research on payment for ecosystem programs have indicated that there is an urgent need to incorporate smallholder farmers into this payment scheme (Lansing 2017). This research aims to provide insight to inform payment for ecosystem programs to better support for smallholder farmers providing ecosystem services through the management of their herbaceous communities.
Chapter 3 - Description of Sites and Methodology

3.1 Description of sites

3.1.1 Turrialba region of Costa Rica

Research was conducted at sites throughout the Turrialba region, located within the Central Valley of Costa Rica. Turrialba is a prominent coffee-growing region with an annual temperature of 22.2°C and small variations across months. The region has a mean annual rainfall of 2800mm (Cerda et al. 2017a), though rainfall patterns have become increasingly unpredictable (Cerdán et al. 2012; Isaac et al. 2018) due to climate change (IPCC 2013). Coffee is grown from altitudes of 600 to 1400m, with farms at higher elevations having slightly more rain and cooler temperatures than farms at lower elevations (Cerda et al. 2017a). Soils in Turrialba region are generally acidic and have moderate fertility (CIA 2016; Cerda et al. 2017a) with risk of nutrient depletion due to monoculture (Isaac et al. 2018). Recently, coffee leaf rust (CLR), a fungal pathogen has destroyed 12-25% of coffee yield annually by hindering vegetative development and causing death of branches (Avelino et al. 2015; Allinne et al. 2016). The CLR crisis, known locally as “La Roya” affected all farm sites involved in this study. The 45 sites in this experiment took place within six organic plots at CATIE’s experimental farm (Figure 3.1) and on nine organic farms within from the Asociación de Productores Orgánicos y Agrosostenibles (APOYA) network all located in Turrialba region (Figure 3.2).

3.1.2 CATIE research plots

The CATIE experimental farm is located at 685m above sea level. Soils at the CATIE site are Typic Endoaquults (Ultisols) derived from volcanic alluvium. Soils are acidic (pH<5.5) and have clay content greater than 50% (Rossi et al. 2011). Until 2000, sugar cane (Saccharum officinarum) was the main crop grown on the site (Mora & Beer 2013). Both organic and conventional coffee production has been taking place at the CATIE site for 18 years. For this study, six organic treatments with different shade tree combinations were chosen (Table 3.1). These plots contained the Caturra variety of coffee which is very susceptible to CLR.
Figure 3.1 A map of the Central Valley region of Costa Rica from Satellite view with yellow dots representing research sites (Google Map Pro 2018). Research was conducted on 9 independent organic farm sites (F2, F4, F5, F8, F10, F11, F13, F14, F15) in the region and 6 sites at the Tropical Agriculture Research and Higher Education Centre (F1, F3, F6, F7, F9, F12) for a total of 15 farm sites.
Figure 3.2 Map of CATIE sites with plots involved in study highlighted. The six green boxes represent areas of study at the CATIE farm (F1, F3, F6, F7, F9, F12). Areas of study had different management practices and shade-tree species.
Table 3.1 Descriptions of farm sites involved in study including the years the farm had been organic in organic coffee production, the altitude and size of the farm. The size of coffee farm indicates the land in organic coffee production. The variety of coffee and shade tree species varied between farm and are included.

<table>
<thead>
<tr>
<th>Farm</th>
<th>Years Organic</th>
<th>Altitude (m)</th>
<th>Coffee Farm Size (ha)</th>
<th>Variety of Coffee</th>
<th>Shade Tree Species Scientific name (Common name to farmers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>18</td>
<td>685</td>
<td>3</td>
<td>Caturra</td>
<td><em>Erythrina poeppigiana</em> (Poró); <em>Chloroleucon eury cyclum</em> (Chloroleucon)</td>
</tr>
<tr>
<td>F2</td>
<td>14</td>
<td>700</td>
<td>1</td>
<td>Caturra</td>
<td><em>Citrus reticulata</em> (Mandarina) <em>Psidium guajava</em> (Guayaba); <em>Musaceae</em> (Banano)</td>
</tr>
<tr>
<td>F3</td>
<td>18</td>
<td>685</td>
<td>3</td>
<td>Caturra</td>
<td><em>Terminalia amazonia</em> (Terminalia); <em>Chloroleucon eury cyclum</em> (Chloroleucon) <em>Erythrina poeppigiana</em> (Poró); <em>Psidium guajava</em> (Guayaba); <em>Theobroma cacao</em> (Cacao)</td>
</tr>
<tr>
<td>F4</td>
<td>18</td>
<td>750</td>
<td>0.5</td>
<td>Caturra, Tipica</td>
<td><em>Erythrina poeppigiana</em> (Poró); <em>Citrus reticulata</em> (Mandarina); <em>Musaceae</em> (Banano)</td>
</tr>
<tr>
<td>F5</td>
<td>18</td>
<td>700</td>
<td>2</td>
<td>Caturra</td>
<td><em>Erythrina poeppigiana</em> (Poró)</td>
</tr>
<tr>
<td>F6</td>
<td>18</td>
<td>685</td>
<td>3</td>
<td>Caturra</td>
<td><em>Erythrina poeppigiana</em> (Poró); <em>Terminalia amazonia</em> (Terminalia)</td>
</tr>
<tr>
<td>F7</td>
<td>18</td>
<td>685</td>
<td>3</td>
<td>Caturra</td>
<td><em>Erythrina poeppigiana</em> (Poró); <em>Musaceae</em>; (Banano) <em>Carica papaya</em> (Papaya)</td>
</tr>
<tr>
<td>F8</td>
<td>22</td>
<td>800</td>
<td>2</td>
<td>Caturra</td>
<td><em>Terminalia amazonia</em> (Terminalia)</td>
</tr>
<tr>
<td>F9</td>
<td>18</td>
<td>685</td>
<td>3</td>
<td>Caturra</td>
<td><em>Laurus nobilis</em> (Laurel), <em>Erythrina poeppigiana</em> (Poró), <em>Bactris gasipaes</em> (Palma)</td>
</tr>
<tr>
<td>F10</td>
<td>18</td>
<td>720</td>
<td>1</td>
<td>Obota</td>
<td><em>Laurus nobilis</em> (Laurel), <em>Bactris gasipaes</em> (Palma); <em>Psidium guajava</em> (Guayaba); <em>Carica papaya</em> (Papaya); <em>Musaceae</em> (Banano)</td>
</tr>
<tr>
<td>F11</td>
<td>6</td>
<td>700</td>
<td>2.5</td>
<td>Caturra, Catimore, Costa Rica 95</td>
<td><em>Laurus nobilis</em> (Laurel), <em>Bactris gasipaes</em> (Palma); <em>Psidium guajava</em> (Guayaba); <em>Carica papaya</em> (Papaya); <em>Musaceae</em> (Banano)</td>
</tr>
<tr>
<td>F12</td>
<td>18</td>
<td>685</td>
<td>2</td>
<td>Caturra</td>
<td><em>Erythrina poeppigiana</em> (Poró)</td>
</tr>
<tr>
<td>F13</td>
<td>15</td>
<td>775</td>
<td>1</td>
<td>Catimore</td>
<td><em>Laurus nobilis</em> (Laurel); <em>Musaceae</em> (Banano); <em>Citrus reticulata</em> (Mandarina)</td>
</tr>
<tr>
<td>F14</td>
<td>20</td>
<td>750</td>
<td>0.75</td>
<td>Esperanza, Centroamericana</td>
<td><em>Erythrina poeppigiana</em> (Poró); <em>Musaceae</em> (Banano)</td>
</tr>
<tr>
<td>F15</td>
<td>15</td>
<td>1000</td>
<td>1</td>
<td>Esperanza, Milenio, Centroamericana</td>
<td><em>Erythrina poeppigiana</em> (Poró); <em>Musaceae</em> (Banano)</td>
</tr>
</tbody>
</table>
3.1.3 Organic farms in the Turrialba region

This study also included nine organic farms in the Turrialba region. Sites were chosen based on the criteria that farms i) are part of the APOYA network, ii) are owned by smallholder farmers, iii) implement organic practices, and iv) have an herbaceous community present. All farms in this study integrated shade-tree intercropping. The shade tree species and coffee varieties differed between farms and were documented (Table 3.1). Due to the coffee leaf rust crises, most producers replaced the susceptible Caturra variety of coffee with more resistant varieties including Esparanza, Costa Rica 95, Milenio, Centroamericano, and Obata between 2015-2018.

3.1.4 Land size and management practices in the region

In this study, the area of organic coffee production on each farm ranged from 0.5 to 3 ha, which falls within the global definition of “smallholder” farms (World Bank 2003; Conway 2011; Graeub et al. 2016; Lowder et al. 2016). This size range is representative of organic farms in the Turrialba region (eco-LOGICA 2017), however is much smaller than nearby countries including Nicaragua and El Salvador (Méndez et al. 2010). Using data from organic farms in the region (eco-LOGICA 2017), I determined the regional mean organic coffee farm size as 1.57 ha. In analysis, farms were divided into those above the regional mean and those below the regional mean.

The farms in this study all followed guidelines provided by the eco-LOGICA® certification (Naturalba 2018), however farmers had different approaches to their management practices. Particularly, the frequency of weeding and canopy openness varied between farms. Farmers controlled their herbaceous community by chopping it with a machete, weed-wacker or a shovel two times to six times per year. Farms that weeded two times per year or less were classified as having low weeding intensity (Soto-Pinto et al. 2002). Farms that were weeded between three and five per year were classified having medium weeding intensity, which is the recommended weeding schedule by the local weed management guide (Filho et al. 2013). Farms that weeded more than six times per year were considered as having high weeding intensity. Farms also had different levels of canopy management from varied shade tree planting (as seen in Table 3.1) and pruning practices. Canopy openness was measured using hemispherical canopy image analysis; n = 3 per plot. Overall, canopy openness ranged 10.6% to 40.47%. Canopy openness of less than
20% was considered low, canopy openness of 20-30% was classified as medium. Farms with over 30% canopy openness were classified as high canopy openness.

3.2 Study design

At each site, three sampling quadrats of 1m x 1m were randomly selected (Nkoa et al. 2015) within which all sampling of the herbaceous community and soil was conducted (Figure 3.3). This resulted in a total of 45 quadrats in the study design sampling (Table 3.2).

3.2.1 Aboveground herbaceous community identification and sampling

Photos of herbaceous species were taken in the field and identified using a local identification guide (Laurito et al. 2016), CATIE resources and on-site expertise. Herbaceous species cover was determined by the percentage of physical space each species covered in the plot, determined by visual inspection using a 1m x 1m grid system (Carmona et al. 2015). The vegetative height was based off of the tallest individual from each species to account for competitive capacity. The vegetative height of each species was determined by measuring the distance between the upper boundary of the main photosynthetic tissues of the tallest herbaceous species and the soil (Pérez-Harguindeguy et al. 2013).

To determine the herbaceous community biomass, water content and functional traits, all herbaceous plants within the quadrat were clipped with scissors and transported in coolers (Butterfield & Suding 2013) to the CATIE lab. Upon arrival at the lab, the wet mass was recorded for each herbaceous species. In cases where plant material could not be weighed immediately, samples were wrapped in moist paper towel and placed in sealed plastic bags. To reduce transpiration water loss, I breathed into the plastic bags to increase CO₂ concentration and air humidity before placing bags in a dark refrigerator (as suggested by Pérez-Harguindeguy et al. 2013). After wet weight was recorded, herbaceous species biomass was dried at 65°C for 72 hours and weighed to determine dry mass.
Figure 3.3 Example of 1m x 1m sampling quadrat. Plant cover and exposed soil was recorded, and each species was identified. All herbaceous community biomass within the quadrat was cut and taken to the lab for further analysis. Soil sampling was conducted in the middle of the quadrat (where meter sticks cross).
Table 3.2 Ecological variables measured in this study including leaf functional traits, whole-plant traits and environmental data.

<table>
<thead>
<tr>
<th>Name</th>
<th>Abbreviation</th>
<th>Ecological Function</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Leaf Traits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Leaf Area</td>
<td>SLA</td>
<td>Related to growth capacity and photosynthesis activity.</td>
<td>Mm(^2) mg(^{-1})</td>
</tr>
<tr>
<td>Leaf dry-matter content</td>
<td>LDMC</td>
<td>Related to resource acquisition</td>
<td>mg g(^{-1})</td>
</tr>
<tr>
<td>Leaf nitrogen concentration</td>
<td>LNC</td>
<td>Related to resource acquisition</td>
<td>mg g(^{-1})</td>
</tr>
<tr>
<td>Leaf carbon concentration</td>
<td>LCC</td>
<td>Related to rates of carbon accumulation</td>
<td>mg g(^{-1})</td>
</tr>
<tr>
<td>2. Whole-plant Traits</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vegetative height</td>
<td>H</td>
<td>Competitive capacity and species response to environmental conditions</td>
<td>cm</td>
</tr>
<tr>
<td>Basal diameter</td>
<td>BD</td>
<td>Used to determine age of plant</td>
<td>mm</td>
</tr>
<tr>
<td>Biomass</td>
<td>Biomass</td>
<td>Competitive capacity and species response to environmental conditions</td>
<td>g</td>
</tr>
<tr>
<td>Yield</td>
<td>Yield</td>
<td>Productivity of coffee plant</td>
<td>g plant(^{-1})</td>
</tr>
<tr>
<td>3. Environmental Data</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil moisture</td>
<td>sm</td>
<td>Indicates soil water availability</td>
<td>%</td>
</tr>
<tr>
<td>Total soil carbon</td>
<td>SoilC</td>
<td>Indicates soil carbon storage</td>
<td>mg g(^{-1})</td>
</tr>
<tr>
<td>Total soil nitrogen</td>
<td>SoilN</td>
<td>Pool of potentially mineralizable N</td>
<td>mg g(^{-1})</td>
</tr>
<tr>
<td>Soil phosphorous</td>
<td>SoilP</td>
<td>Mediates the availability of P to plants</td>
<td>mg g(^{-1})</td>
</tr>
<tr>
<td>Soil ammonia/nitrates</td>
<td>SoilAN</td>
<td>Potential for nitrogen-fixation and organic material addition, and related to canopy coverage</td>
<td>mg g(^{-1})</td>
</tr>
<tr>
<td>Distance to shade trees</td>
<td>Distance</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>Canopy Openness</td>
<td>CO</td>
<td>Indicator of light that reaches herbaceous community</td>
<td>%</td>
</tr>
</tbody>
</table>
3.2.2 Leaf functional trait analysis

The leaf functional trait sampling of all herbaceous species was performed following protocols in Pérez-Harguindeguy et al. 2013. To determine specific leaf area (SLA) and leaf dry-matter content (LDMC), I selected five fully expanded young leaves from the upper 20% of height from different plants of the same species within the quadrat to ensure consistency across sites. Whenever possible, leaves with pathogenic or pest attack symptoms were avoided (Pérez-Harguindeguy et al. 2013). The five fresh leaves from each species per plot were blotted with dry paper towel to remove surface water, flattened and photographed alongside a ruler. These images were later analyzed using ImageJ software to determine average leaf area (mm²) per each species per quadrat (Abramoff et al. 2004). These leaves were then dried at 65°C for 72 hours. The dry leaves’ mass was measured and recorded in mg. Specific leaf area was determined using by leaf area (mm²) /oven dry mass of leaf (mg). Using the same leaves in SLA analysis, LDMC was determined as the mass of dry leaves (mg)/wet mass of leaves (g). Overall, 1105 herbaceous leaves from the 45 plots were analyzed.

After measuring SLA and LDMC, dry leaves were placed in labelled envelopes and transferred to the Isaac Agroecology Lab for chemical analysis, following Canadian import permit regulations. Each replicate was ground separately with a mechanical grinder and dried at 65°C for 12 hours before chemical analysis (Pérez-Harguindeguy et al. 2013). The material was then analyzed with a LECO CN628 analyzer to determine leaf carbon concentration (mg g⁻¹) and leaf nitrogen concentration (mg g⁻¹) (LECO Corporation, Minnesota, USA). Throughout the analyses aspartic acid was tested to ensure accuracy.

3.2.3 Coffee plant measurements

Variety, plant height, yield, age and coffee leaf rust incidence were measured for all coffee plants within a 1m radius of the experiment quadrat. Coffee variety was determined through discussions with farmers and confirmation using the World Coffee Research Coffee Variety Guide (2016). Coffee plant height was measured from the highest photosynthetic leaf and the base of the coffee plant (Cornelissen et al. 2003). The age of coffee plants was measured using a digital caliper approximately 10cm above ground or stump-pruned growth. Based on allometric data, the equation:
\[ \text{coffee age} = \frac{(10.36 - \text{diameter in mm})}{4.64} \]  

(1)

This equation was used to determine plant age (Audebert 2011). The age of coffee plants determined through this equation matched farmer knowledge.

Coffee yield was determined by the equation:

\[ \text{coffee yield} = (8.58 + 3.88 \times \text{Number of Productive Stems per Plant}) + 1.95 \times \text{Number of Fruiting Nodes} + 0.03 \times \text{Number of Fruiting Nodes per Plant} - 0.18 \times \text{Number of Dead Branches}^2 \]  

(2)

developed by Cerda et al. (2017b). The equation provides grams of fresh coffee per plant, which is helpful in determining the impact of herbaceous communities on the yields of surrounding coffee plants. Coffee leaf rust was determined by choosing three random branches, one from upper, middle, and lower heights of coffee plant (Soto-Pinto et al. 2002). Number of leaves on branch with rust were measured and incidence was determined through equation:

\[ \text{coffee leaf rust incidence} = \frac{\text{number of leaves with infection}}{\text{(number of leaves with infection + number of leaves without infection)}} \times 100. \]  

(3)

3.2.4 Shade tree and canopy measurements

As shown in Table 3.1 a variety of shade trees were present on farm sites. The distance to shade trees within a 10m diameter of the centre of the quadrat was measured and significant characteristics (i.e. pruning, disease) were noted. To measure the light levels reaching the herbaceous community, digital fisheye photographs were taken at a height of 60cm at the centre of each quadrat. Photographs were taken with a Nikon Coolpix 950 digital camera was used with a Nikon Fisheye Converter FC-E8 0.21x lens. Gap Light Analyzer (GLA) software (Frazer et al. 1999) was used to determine total light transmission and canopy openness (%).

3.2.5 Soil sampling and analysis

Once the biomass of the herbaceous community was cleared for analysis, soil samples were taken. Using a soil corer (111cm\(^3\)), samples were taken from the centre of each quadrat at a depth of 10cm. Soil bulk density was determined by drying soil at 105°C for 72 hours and
dividing the dry soil weight (g), sieved to 2mm, by soil volume (cm$^3$). Soil moisture was determined by using the equation:

$$\text{soil moisture} = \left(\frac{\text{wet soil mass (g)} - \text{dry soil mass (g)}}{\text{dry soil mass (g)}}\right) \times 100\%.$$ \hspace{1cm} (4)

For soil phosphorous analysis, 4g of soil was airdried. For soil carbon and soil nitrogen analysis, 10g of soil was dried. Soil samples were brought to the Isaac Agroecology Lab following Canadian import permit regulations.

In the lab, soil available nitrates and phosphorous were determined with a flow injection analyzer (Lachat QuikChem, Colorado USA). For nitrate analysis, a soil subsample of 2 g was placed in Erlenmeyer flasks and 20 mL of potassium chloride (KCl) was added. This solution was shaken for 30 minutes and then filtered through #1 Whatman filter paper into glass vials. Subsamples from each vial were analyzed with a flow injection analyzer (Lachat QuikChem, Colorado USA) to determine ammonium (mg g$^{-1}$) and nitrates (mg g$^{-1}$) colourmetrically. For soil available phosphorus analysis, air dried and sieved soil was placed in in Erlenmeyer flasks and 20 mL of Brays 1 was added, shaken for 5 minutes and the mixture was filtered through #1 Whatman filter paper into glass vials. Subsamples from each vial were analyzed with a flow injection analyzer (Lachat QuikChem, Colorado USA) to determine soil phosphorus (mg g$^{-1}$) colourmetrically. Total soil carbon and total soil nitrogen were measured by weighing 100mg of dried soil and running through a CHN628 analyzer (LECO Corporation, Minnesota, USA).

### 3.3 Farmer perspectives of the herbaceous community

#### 3.3.1 Participant selection

The APOYA network of organic coffee farmers was contacted to determine the initial list of project participants. Using a snowball technique, all connections were made with farmers through consensual introductions. All farmers followed the criteria outlined in 3.1.4. Ethics approval from the University of Toronto Social Sciences, Humanities, and Education Research Ethics Board for research involving human participants was obtained. Participant selection and interview process followed protocols outlined in the approved Ethics application including ensuring informed consent and confidentiality of project participants.
This research project was assisted by a significant trust developed between me, an international research student, and organic coffee farmers who have long been implementing agroecological practices. Building trust was facilitated by the Isaac Agroecology Lab’s 10-year relationship with CATIE and local partners including the APOYA network. Moreover, my positionality as a farmer in Canada and a Spanish-speaker provided the skills to support farmers with their on-farm activities, allowing for relationships to build prior to interviews.

3.3.2 Interview format

Interviews were conducted at locations and times that were convenient for participant (Bryman 2012). Interviews took place in participants’ houses, offices, in car rides to farms, or on farm (Figure 3.4). These semi-structured interviews lasted between 20 and 100 minutes depending on farmers’ availability and elaboration on interview questions. All questions (Appendix B) were asked to farmers, though many participants answered multiple questions in one response. The words “monte” (greenery/cover crop) was used in place of “hierba” (“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. Throughout this paper the term “herbaceous community” includes all good, neutral and bad herbaceous species. All interviews were conducted in Spanish, recorded and saved in a password protected encrypted folder. Interviews were translated directly into English and anonymized.

3.3.3 Participant information

Information on participant demographics, history of the land, farm characteristics, management practices and participant perspectives on herbaceous communities was collected. All participants were asked questions about their management practices including their transition to organic agriculture, herbaceous community management strategy and overall perspective of the herbaceous community within their farm. Farmers were encouraged to discuss their perspective on the ecosystem services and disservices provided by herbaceous communities. In cases when participants’ response to one question answered later questions, these questions were not asked
Figure 3.4 A farmer demonstrates his knowledge of the herbaceous community within his organic coffee agroforestry system during an interview. This farmer specifically discussed his values of ecosystem services of pollinating herbaceous species such as the flowers he holds in hand, and the beneficial ground coverage and soil erosion protection of *Commelina diffusa*, which he calls “canutillo” or “oreja de ratón” (mouse ear), on his farm.
again. Interview format ensured that all participants had responded to all questions. Interviews ended in a discussion about current educational resources available to farmers to support their herbaceous community management and what resources would be useful in the future.

### 3.3.4 Interview processing: cognitive mapping and valuation of services

To best understand farmer decision-making practices within their complex agroecosystem, a cognitive mapping approach using Decision Explorer software was employed (Banxia Software Ltd. 2014). Key concepts on farmer values, perspectives on role of ecosystem (dis)services of the herbaceous community and management practices were identified from interview transcripts and coded by giving common labels to reoccurring themes (Özesmi & Özesmi 2004; Bryman 2012). Through an iterative process of re-listening to the interviews, these coded labels reflected farmer-identifed concepts as much as possible, resulting in a total 45 concepts. Based on interviews, I determined start and end points as the basis of each cognitive map (Isaac et al. 2009). The starting point for each map was “conversion to organic agriculture” and the ending point was “healthy coffee plants” which relates to economic viability including coffee yields and quality.

Cognitive maps were analyzed for connection-to-variable ratio, density and domain and centrality variables. 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) about the interconnectedness of their farm (Isaac et al. 2009). The density of cognitive map is determined by the number of connections that farmers see between concepts compared to the total possible number of connections (Hage & Harary 1983). The measure of cognitive map density is a useful tool to determine the comparable complexity of farmer’s cognitive map (van Winsen et al. 2013). If the density of a map is high, this signifies that farmers will see many relationships between the variables and will have more options for implementing change (Özesmi & Özesmi 2004; Isaac et al. 2009). To determine density, I used the equation:

\[
\text{density} = \frac{\text{connections}}{\text{number of variables}} \times (\text{number of variables} - 1) 
\]

\[(Hage & Harary 1983)\]
I determined domain and centrality variables for each of the cognitive maps using analysis within Decision Explorer software. The highest domain variables are the concepts with the most in-and-out linkages to variables, whereas the highest centrality variables are those with the highest number of direct and indirect links to other variables. These results help to determine prominent variables and trends across interviews (van Winsen et al. 2013).

Finally, values of ecosystem services were quantified by determining the time farmers spoke about each ecosystem service and disservice in relation to the total time of the interview (Goodwin & Hertiage 1990; Bryman 2012) and is therefore presented in a percentage. Since farmers spent a significant amount of time discussing the farm history and management practices, value of ecosystem services never accounted for more than 10% of the interview.

### 3.4 Statistical analysis

Statistical analysis was performed in RStudio statistical analysis 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 (i.e. Fric, FDiv, LDMC, LNC, soilC, soilN, soiP, herbaceous community biomass) log-transformed values were used in analysis.

The FD package (Laliberté et al. 2015) was employed to determine FRic, FEve, FDiv, FDQ and community weighted means for the herbaceous community traits per plot. The Functional Diversity package utilized data from the relative abundance of each species and trait-data per species per quadrat to determine functional diversity indices and community weighted mean values. These outputs were used in standardized major axis bivariate analysis, one-way analysis of variance and stepwise-regression analysis.

Principal component analysis (PCA) was employed using the “vegan” r package (Oksanen et al. 2016) to determine the relationship between farmer perception of the herbaceous species and the species’ functional traits. Four leaf traits (SLA, LDMC, LNC and LCC) and one whole-plant trait (height) of the herbaceous species were used. Based on these analyses, PCA axis 1 and 2 for each species were calculated.
To determine the relationship between herbaceous community functional diversity metrics and biomass, soil conditions and coffee health correlates, I employed standardized major axis bivariate analysis. To understand the effect of management approaches on the herbaceous community trait indices, I employed one-way analysis of variance (ANOVA) and Tukey post-hoc test to determine the significant differences within the herbaceous community’s traits across farm size, weeding intensity and canopy openness. To determine if and how farmer perceptions and attributes may predict functional diversity of the herbaceous community, Akaike’s Information Criteria (AIC) was employed. The full model was of the form:

*Functional Diversity response ~ farmer attributes [years organic + value of ecosystem services + cognitive map connection-to-variable ratio + cognitive map density]*

Using the full model, AIC analysis provided most parsimonious model fit to each response variable. Significance of predictor variables in each AIC selected model was then assessed using multiple regression.
Chapter 4 – Results

4.1 Taxonomic and functional composition of the herbaceous community

In total 39 herbaceous species were present across the 45 plots, with a mean of 4.82 (± 0.23) species per plot. Of the species present, 36% were native to Central America and 55% native to the Americas. The remaining 45% of species were native to Asia, Africa, Australia and Europe. The herbaceous species in the plots represented a total 20 taxonomic families. Nearly 55% of herbaceous species found in this study were considered beneficial plants (“buena hierba” or “buena cobertura”), 21% were considered bad weeds (“mala hierba” or “hierbas competidoras”) and 24% of species were perceived to neither have a beneficial role nor cause harm to their coffee plants and were considered neutral (“hierba regular”) by farmers in this study. All herbaceous communities present were naturally occurring and had not been planted by farmers (personal correspondence, May 2018).

Herbaceous community biomass ranged from 71.4-3524.1g per plot with a mean of 88.5 (± 15.7) percent cover per plot. The five most common species (Table 4.1) were found in over 33% of the sampled plots. All 39 species and their functional traits are presented in Appendix A. The mean herbaceous community species leaf dry-matter content (LDMC) ranged from 95-500mg g⁻¹ and the mean specific leaf area (SLA) ranged from 8.18 to 59.30mm² g⁻¹. The mean leaf nitrogen concentration (LNC) ranged from 22.32-83.10 mg g⁻¹ and the mean leaf carbon concentration (LCC) ranged from 316.35-526.20mg g⁻¹. The height of the tallest species in each plot ranged from 3cm to 138cm. Herbaceous community functional richness ranged from 0.003 to 4.32. The range of functional evenness was 0.01 to 0.98, and functional divergence was from 0.37 to 1. Across all plots, FDQ values ranged from 0.07 to 3.9.

4.2 Herbaceous community functional diversity, soil conditions and coffee health correlates

Standardized major axis regression analysis revealed many relationships between herbaceous community functional diversity, soil conditions and coffee health (Table 4.2). Total herbaceous community biomass and functional richness were significantly positively correlated (r²=0.163; p=0.003). Herbaceous community functional richness and soil moisture were significantly
Table 4.1 Most frequent herbaceous species found in plots are listed here in order of frequency. Taxonomic family and scientific name are given (Laurito et al. 2016), as well as place of origin. Farmer perception of species as well as notes from farmer interviews are presented.

<table>
<thead>
<tr>
<th>Scientific Name</th>
<th>Taxonomic Family</th>
<th>Place of origin</th>
<th>Frequency (n=45)</th>
<th>Farmer Perception of Species</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Commelina diffusa</strong></td>
<td>Commelinaceae</td>
<td>Asia</td>
<td>36</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Soft plant that is easy to work with. Good ground cover. Contains beneficial soil nutrients. Edible.</td>
</tr>
<tr>
<td><strong>Brachiaria platyphylla</strong></td>
<td>Poacea</td>
<td>North America</td>
<td>26</td>
<td>Bad</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Challenging grass to work with. Grows quickly and spreads easily.</td>
</tr>
<tr>
<td><strong>Hydrocotyle mexicana</strong></td>
<td>Araliaceae</td>
<td>North America</td>
<td>20</td>
<td>Good</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Soft plant that is easy to work with. Good ground cover. Contains beneficial soil nutrients. Medicinal.</td>
</tr>
<tr>
<td><strong>Pseudelephantopus spicatus</strong></td>
<td>Asteraceae</td>
<td>Central America</td>
<td>18</td>
<td>Bad</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Grows quickly and can be difficult to work in. However, can attract pollinators to coffee plants.</td>
</tr>
<tr>
<td><strong>Cyperus tenuis</strong></td>
<td>Cyperaceae</td>
<td>Central America</td>
<td>15</td>
<td>Bad</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Very competitive. Grows and spreads quickly.</td>
</tr>
</tbody>
</table>
Table 4.2 Bivariate relationships among functional diversity indices, herbaceous community, soil and coffee health metrics (where n=45 for all values except for \( FE_{ve} \) and \( FD_{iv}^{*} \) where n=42). Indices and metrics that have been log-transformed are marked with an asterisk (*). The upper section of this matrix displays the slopes and associated 95% confidence intervals for each relationship, based on standardized major axis regression analysis. The lower section of the matrix displays model \( r^2 \) and one-tailed p-values (in brackets) for each bivariate model. Significant relationships (p ≤ 0.05) are bolded.

<table>
<thead>
<tr>
<th>Functional diversity indices</th>
<th>H.C. metrics</th>
<th>Soil metrics</th>
<th>Coffee health metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>( FR_{ic}^{*} )</td>
<td>( FE_{ve} )</td>
<td>( FD_{iv}^{*} )</td>
<td>( FD_{Q} )</td>
</tr>
<tr>
<td>-</td>
<td>6.15</td>
<td>-1.59</td>
<td>1.51</td>
</tr>
<tr>
<td>( FE_{ve} )</td>
<td>0.018</td>
<td>-2.33</td>
<td>4.06</td>
</tr>
<tr>
<td>( FD_{iv}^{*} )</td>
<td>0.021</td>
<td>0.083</td>
<td>9.43</td>
</tr>
<tr>
<td>( FD_{Q} )</td>
<td>0.299</td>
<td>0.213</td>
<td>0.005</td>
</tr>
<tr>
<td>( Biomass^{*} )</td>
<td>0.163</td>
<td>0.264</td>
<td>0.004</td>
</tr>
<tr>
<td>( SoilC^{*} )</td>
<td>0.035</td>
<td>( &lt;0.001 )</td>
<td>0.089</td>
</tr>
<tr>
<td>( SoilN^{*} )</td>
<td>0.086</td>
<td>( &lt;0.001 )</td>
<td>0.108</td>
</tr>
<tr>
<td>( Soil Moisture )</td>
<td>0.116</td>
<td>0.077</td>
<td>0.028</td>
</tr>
<tr>
<td>( SoilP^{*} )</td>
<td>0.105</td>
<td>0.043</td>
<td>0.001</td>
</tr>
<tr>
<td>( Yield )</td>
<td>0.002</td>
<td>0.048</td>
<td>0.026</td>
</tr>
<tr>
<td>( CLR )</td>
<td>0.003</td>
<td>0.005</td>
<td>0.023</td>
</tr>
</tbody>
</table>
negatively correlated ($r^2=0.116; p=0.011$), as were functional richness and soil nitrogen ($r^2=0.086; p=0.025$). Herbaceous community functional richness and soil phosphorous were significantly positively correlated ($r^2=0.105; p=0.015$).

The herbaceous community biomass and functional evenness were significantly negatively correlated ($r^2=0.264; p<0.001$). There was a significantly positive relationship between functional evenness and soil moisture ($r^2=0.077; p=0.037$). Total herbaceous community functional evenness and functional divergence had a significantly negative correlation ($r^2=0.083; p=0.032$). Total herbaceous community functional divergence and soil nitrogen were significantly negatively correlated ($r^2=0.108; p=0.017$). Functional divergence and soil carbon were also significantly negatively correlated ($r^2=0.089; p=0.027$). The herbaceous community FDQ and functional richness was significantly negatively correlated ($r^2=0.299; p<0.001$). However, FDQ was significantly positively correlated with functional evenness ($r^2=0.213; p=0.001$). Herbaceous community FDQ and biomass were negatively correlated ($r^2=0.292; p<0.001$). Herbaceous community FDQ was significantly positively correlated with both soil nitrogen ($r^2=0.081; p=0.029$) and soil moisture ($r^2=0.187; p<0.001$) but was significantly negatively correlated with soil phosphorus ($r^2=0.138; p=0.006$). The FDQ of the herbaceous community was significantly positively correlated with coffee yield ($r^2=0.082; p=0.029$) and significantly negatively correlated with coffee leaf rust ($r^2=0.012; p=0.010$).

The herbaceous community biomass and soil moisture were negatively correlated ($r^2=0.184; p=0.002$). Total herbaceous community biomass and soil nitrogen were also negatively correlated ($r^2=0.085; p=0.026$). Total herbaceous community biomass and coffee leaf rust were significantly positively correlated ($r^2=0.069; p=0.041$). As expected, soil carbon and soil nitrogen were significantly positively correlated ($r^2=0.888; p<0.001$). Soil carbon was positively correlated with soil moisture ($r^2=0.208; p<0.001$) and coffee yield ($r^2=0.096; p=0.020$), whereas soil carbon and coffee leaf rust were significantly negatively correlated ($r^2=0.116; p=0.011$). Soil nitrogen and soil moisture were significantly positively correlated ($r^2=0.237; p<0.001$), whereas soil nitrogen was significantly negatively correlated with soil phosphorous ($r^2=0.067; p=0.042$). Soil nitrogen was positively correlated with yield ($r^2=0.063; p=0.049$) and negatively correlated with coffee leaf rust ($r^2=0.144; p=0.005$).
Soil moisture and soil phosphorous were significantly negatively correlated ($r^2=0.209; p<0.001$). Soil moisture was significantly positively correlated with coffee yield ($r^2=0.199; p=0.001$); and was significantly negatively correlated with coffee leaf rust ($r^2=0.135; p=0.006$). Soil phosphorous and coffee leaf rust were significantly positively correlated ($r^2=0.145; p=0.005$). As expected, coffee yield and coffee leaf rust were negatively correlated ($r^2=0.172; p<0.001$).

4.3 Functional diversity across farm sizes, weeding and canopy openness

Multi and single-trait indices of the herbaceous community varied across farm size (Table 4.3). The herbaceous community on farms less than the regional mean had significantly higher $FD_Q$ values ($2.23 \pm 0.90$) than farms greater than the regional mean ($1.16 \pm 0.97$). Farms less the regional mean size also had higher values of $CWM_{LNC}$ (log-value $1.58 \pm 0.42$ mg g$^{-1}$) as compared to farms greater than the regional mean farm size (log-value $1.51 \pm 0.13$ mg g$^{-1}$). There were no significant differences in herbaceous community functional richness, functional evenness, functional divergence, $CWM_{LDMC}$, $CWM_{SLA}$ or $CWM_{LCC}$ across farm size.

Analysis of variance showed significant (p<0.05) effect of weeding intensity for three multi-and single-trait functional traits of the herbaceous community (Table 4.4). Herbaceous community functional richness was lowest (-1.18 ± 0.83) on farms with high weeding intensity, compared to farms with low (-0.27 ± 0.54) and moderate (0.18 ± 0.39) weeding intensities. Farms with moderate weeding intensity had the lowest $FD_Q$ (1.20 ± 0.99) compared to low (2.24 ± 0.78) and high (2.56 ± 0.76) weeding intensities. The herbaceous community $CWM_{LDMC}$ was lowest on farms with low weeding intensity (log-value 2.17 ± 0.10 mg g$^{-1}$) as compared to moderate weeding intensity (log-value 2.31 ± 0.14 mg g$^{-1}$).

The level of canopy openness had an effect on three multi-and-single traits of the herbaceous community (Table 4.5). The herbaceous community under a high level of canopy openness exhibited significantly lower functional evenness (0.37 ± 0.30) than herbaceous community under a low level of canopy openness (0.69 ± 0.19). A high level of canopy openness also had an herbaceous community with low $FD_Q$ (1.03 ± 0.99) compared to plots with medium canopy openness (2.02 ± 1.01). As well, high canopy openness had an herbaceous community with
Table 4.3 One-way analysis of variance of herbaceous community multi-trait and community weighted mean (CWM) single-trait indices across farm size. Regional mean farm size determined from data on all organic farms in the Central Valley region (1.57 ha). Farms this study are thus describes as above regional mean and below regional mean. Mean and standard errors (where n=45 for all values except for FEve and FD\textsubscript{iv}* where n=42) are presented. Indices that have been log-transformed are marked with an asterisk (*). F and p-values are provided. A Tukey post-hoc test was used and is denoted by superscripts a and b, whereby letters indicate significant difference between levels (where p ≤ 0.05). Significant p values are bolded.

<table>
<thead>
<tr>
<th>Trait Indices</th>
<th>Farm Size</th>
<th>F-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Below regional mean</td>
<td>Above regional mean</td>
<td></td>
</tr>
<tr>
<td>Multi Trait</td>
<td>FR\textsubscript{ic}*</td>
<td>-0.27 ± 0.81\textsuperscript{a}</td>
<td>0.07 ± 0.49\textsuperscript{a}</td>
</tr>
<tr>
<td>Indices</td>
<td>FE\textsubscript{ve}</td>
<td>0.55 ± 0.22\textsuperscript{a}</td>
<td>0.41 ± 0.27\textsuperscript{a}</td>
</tr>
<tr>
<td></td>
<td>LogFD\textsubscript{iv}*</td>
<td>-0.10 ± 0.079\textsuperscript{a}</td>
<td>-0.13 ± 0.13\textsuperscript{a}</td>
</tr>
<tr>
<td></td>
<td>FD\textsubscript{Q}</td>
<td>2.23 ± 0.90\textsuperscript{a}</td>
<td>1.16 ± 0.97\textsuperscript{b}</td>
</tr>
<tr>
<td>Single Trait</td>
<td>CMW\textsubscript{LDMC}*</td>
<td>2.28 ± 0.13\textsuperscript{a}</td>
<td>2.29 ± 0.14\textsuperscript{a}</td>
</tr>
<tr>
<td>Indices</td>
<td>CMW\textsubscript{SLA}</td>
<td>30.61 ± 5.03\textsuperscript{a}</td>
<td>27.27 ± 10.31\textsuperscript{a}</td>
</tr>
<tr>
<td></td>
<td>CWM\textsubscript{LNC}*</td>
<td>1.58 ± 0.04\textsuperscript{a}</td>
<td>1.51 ± 0.13\textsuperscript{b}</td>
</tr>
<tr>
<td></td>
<td>CWM\textsubscript{LCC}</td>
<td>421.19 ± 11.01\textsuperscript{a}</td>
<td>400.44 ± 45.29\textsuperscript{a}</td>
</tr>
</tbody>
</table>
Table 4.4 One-way analysis of variance of herbaceous community multi-trait and community weighted mean (CWM) single-trait indices across weeding intensities. Mean and standard errors (where n=45 for all values except for FEve and FDQ* where n=42) are presented. Indices that have been log-transformed are marked with an asterisk (*). F and p-values are provided. A Tukey post-hoc test was used and is denoted by superscripts a and b whereby letters indicate significant difference between levels (where p ≤ 0.05). Significant p values are bolded.

<table>
<thead>
<tr>
<th>Trait Indices</th>
<th>Weeding Intensity</th>
<th>F-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-trait indices</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>FRic*</td>
<td>-0.27 ± 0.54&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.18 ± 0.39&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-1.18 ± 0.83&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>FEve</td>
<td>0.53 ± 0.21&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.45 ± 0.29&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.48 ± 0.10&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FDQ*</td>
<td>-0.13 ± 0.86&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-0.12 ± 0.12&lt;sup&gt;a&lt;/sup&gt;</td>
<td>-0.08 ± 0.04&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>FDQ</td>
<td>2.24 ± 0.78&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.20 ± 0.99&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2.56 ± 0.76&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Single-trait indices</td>
<td>CWM&lt;sub&gt;LDMC&lt;/sub&gt;*</td>
<td>2.17 ± 0.10&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.31 ± 0.14&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>CWM&lt;sub&gt;SLA&lt;/sub&gt;</td>
<td>29.65 ± 12.47&lt;sup&gt;a&lt;/sup&gt;</td>
<td>28.02 ± 7.00&lt;sup&gt;a&lt;/sup&gt;</td>
<td>30.92 ± 5.91&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>CWM&lt;sub&gt;LNC&lt;/sub&gt;*</td>
<td>1.55 ± 0.04&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.54 ± 0.12&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.58 ± 0.05&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>CWM&lt;sub&gt;LCC&lt;/sub&gt;</td>
<td>417.63 ± 11.74&lt;sup&gt;a&lt;/sup&gt;</td>
<td>407.29 ± 40.65&lt;sup&gt;a&lt;/sup&gt;</td>
<td>421.66 ± 6.86&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>
Table 4.5 One-way analysis of variance of herbaceous community multi-trait and community weighted mean (CWM) single-trait indices across levels of canopy openness. Mean and standard errors (where n=45 for all values except for FEve and FDv* where n=42) are presented. Indices that have been log-transformed are marked with an asterisk (*). F and p-values are provided. A Tukey post-hoc test was used and is denoted by superscripts a and b whereby letters indicate significant difference between levels (where p ≤ 0.05). Significant p values are bolded.

<table>
<thead>
<tr>
<th>Trait Indices</th>
<th>Canopy Openness</th>
<th></th>
<th></th>
<th>F-value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-trait</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>indices</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRic*</td>
<td>-0.15 ± 0.69</td>
<td>-0.25 ± 0.74</td>
<td>0.17 ± 0.50</td>
<td>1.849</td>
<td>0.170</td>
</tr>
<tr>
<td>FEve</td>
<td>0.69 ± 0.19</td>
<td>0.47 ± 0.20</td>
<td>0.37 ± 0.30</td>
<td>4.391</td>
<td><strong>0.019</strong></td>
</tr>
<tr>
<td>FDv*</td>
<td>-0.12 ± 0.061</td>
<td>-0.11 ± 0.10</td>
<td>-0.11 ± 0.14</td>
<td>0.0306</td>
<td>0.970</td>
</tr>
<tr>
<td>FDQ</td>
<td>1.53 ± 0.95</td>
<td>2.02 ± 1.01</td>
<td>1.03 ± 0.99</td>
<td>4.361</td>
<td><strong>0.019</strong></td>
</tr>
<tr>
<td>Single-trait</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>indices</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CWM_LDMC*</td>
<td>2.22 ± 0.20</td>
<td>2.30 ± 0.13</td>
<td>2.31 ± 0.09</td>
<td>1.0253</td>
<td>0.368</td>
</tr>
<tr>
<td>CWM_SLA</td>
<td>31.04 ± 12.32</td>
<td>29.43 ± 4.63</td>
<td>26.38 ± 8.88</td>
<td>1.0789</td>
<td>0.349</td>
</tr>
<tr>
<td>CWM_LNC*</td>
<td>1.59 ± 0.062</td>
<td>1.57 ± 0.11</td>
<td>1.49 ± 0.08</td>
<td>4.0911</td>
<td><strong>0.029</strong></td>
</tr>
<tr>
<td>CWM_LCC</td>
<td>420.11 ± 15.35</td>
<td>412.15 ± 37.37</td>
<td>404.73 ± 39.72</td>
<td>0.579</td>
<td>0.057</td>
</tr>
</tbody>
</table>
significantly lower $CWM_{LNC}$ ($1.49 \pm 0.08 \text{mg g}^{-1}$) than medium canopy openness ($1.57 \pm 0.11 \text{mg g}^{-1}$). The level of canopy openness did not have a significant effect on functional richness, functional divergence or on the $CWM_{LDMC}$, $CWM_{SLA}$ or $CWM_{LCC}$ of the herbaceous community.

### 4.4 Farmer perception of the herbaceous community

I interviewed 11 farmers and farm-workers who represent over 50% of organic coffee farmers in the region. Of the organic farmers interviewed 64% were farm owners and 36% were farm workers who did not own their land. Only 9% of farmers interviewed were female, however 27% of land was owned by females. Whereas 91% of farmers interviewed were male, however 73% of land was owned by males. The mean age of farmers interviewed was $57.8 \pm 5.4$ years. All participants had been farmers for their whole lives and had farmed both conventionally and organically. All farmers interviewed had participated in workshops on organic coffee production lead by regional institutions (iCafe, CATIE, and APOYA). The farms’ time since conversion to organic coffee production ranged from 6 to 22 years with a mean of $16.9 \pm 3.6$ years. During informational interviews, farmers responded to the question “what motivated you to transition to organic coffee production?” Overall, there were eight motivations named (Table 4.6). The most common motivation to switch to organic production, stated by 45% of participants, was that it was “better for the earth and/or soil”, followed by for “better health.”

The cognitive maps derived from interviews with farmers had a mean of $17 \pm 2.4$ variables and $26.8 \pm 4.5$ connections between them (Table 4.7; see Figure 4.1 for example). The highest domain value was organic matter followed by healthy coffee plants. The highest centrality variable was healthy coffee plants, followed by soil nutrients, soil moisture and organic matter, soil moisture and erosion control (Table 4.8). The mean density of the maps was $0.77 \pm 0.05$, which suggests that level of complexity in herbaceous community management was similar between participants and that there are many options to implement change.

During farm tours and interviews, as well as in a local guidebook (Filho et al. 2013), farmers referred to herbaceous species as bad when they were competitive “hierbas competidoras,” or when they were difficult to manage, “malas hierbas,” such as species within the Poaceae (grass) family. Herbaceous communities were considered good when they were seen as a good
Table 4.6 Guiding motivations that farmers indicated for switching to organic agriculture ranked from most frequent response to least frequent. Some farmers had multiple motivations for transitioning from conventional to organic agriculture.

<table>
<thead>
<tr>
<th>Value</th>
<th>Number of responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Better for earth and/or soil</td>
<td>5</td>
</tr>
<tr>
<td>Better health</td>
<td>3</td>
</tr>
<tr>
<td>To better provide for my family</td>
<td>2</td>
</tr>
<tr>
<td>To join a movement/good culture with organic agriculture</td>
<td>2</td>
</tr>
<tr>
<td>Out of conviction/religious reasons</td>
<td>2</td>
</tr>
<tr>
<td>Higher prices /better quality coffee</td>
<td>2</td>
</tr>
<tr>
<td>Educational purposes</td>
<td>2</td>
</tr>
<tr>
<td>To diversify farm</td>
<td>1</td>
</tr>
<tr>
<td>Farmer</td>
<td>Years Organic</td>
</tr>
<tr>
<td>--------</td>
<td>---------------</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>7</td>
<td>22</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
</tr>
<tr>
<td>11</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 4.7 Number of connections, variables, connection-to-variable ratio, and map density derived from cognitive maps. Value of ecosystem services determined through interview analysis is also provided.
Figure 4.1 A sample cognitive map demonstrating a farmer’s perception of ecosystem services (in green text), disservices (red text), and key factors that affect decision making and control of weeds (blue text). Solid lines represent positive relationships whereas dashed lines represent negative relationships.
Table 4.8 Highest domain and centrality variable derived from cognitive map analysis using Decision Explorer (Banxia Software Ltd. 2014). 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.

<table>
<thead>
<tr>
<th>Farmer</th>
<th>Highest domain variables</th>
<th>Highest centrality variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>healthy coffee plants, organic material</td>
<td>healthy coffee plants, soil nutrients</td>
</tr>
<tr>
<td>2</td>
<td>organic material</td>
<td>soil moisture</td>
</tr>
<tr>
<td>3</td>
<td>healthy coffee plants, organic material</td>
<td>healthy coffee plants, soil moisture</td>
</tr>
<tr>
<td>4</td>
<td>organic material</td>
<td>healthy coffee plants, organic material</td>
</tr>
<tr>
<td>5</td>
<td>healthy coffee plants, organic material</td>
<td>healthy coffee plants, erosion control</td>
</tr>
<tr>
<td>6</td>
<td>healthy coffee plants, organic material</td>
<td>healthy coffee plants, organic material</td>
</tr>
<tr>
<td>7</td>
<td>healthy coffee plants, organic material</td>
<td>soil moisture</td>
</tr>
<tr>
<td>8</td>
<td>healthy coffee plants, organic material</td>
<td>healthy coffee plants, soil nutrients</td>
</tr>
<tr>
<td>9</td>
<td>healthy coffee plants, organic material</td>
<td>healthy coffee plants, soil nutrients</td>
</tr>
<tr>
<td>10</td>
<td>organic material</td>
<td>erosion control</td>
</tr>
<tr>
<td>11</td>
<td>organic material</td>
<td>healthy coffee plants, organic material</td>
</tr>
</tbody>
</table>
groundcover, “buena cobertura,” or “buena hierba” when they played an important role such as soil coverage, or nutrient cycling for instance species within the Fabaceae, Commelinaceae or Convolvulaceae family. Farmers perceived herbaceous species that were neither good nor bad as “regular”, or neutral plants which did not harm their crop but did not provide a noticeable service, such as species within the Amaranthaceae family. Principal component analysis assessed the multivariate relationship across morphological traits, where PCA axis 1 explained 30.8% of the total variation (Fig 4.2). Qualitatively, herbaceous community categories of good, neutral, and bad broadly overlap with these data indicating traits along the axis 1 align with HC categories. Based on this, herbaceous species with high heights and high LDMC were considered bad by farmers, whereas herbaceous species with increased SLA and LNC were considered good, species with high LCC were considered neutral by farmers.

In order to capture and rank participants’ perception of ecosystem services in organic coffee production, the percentage of time discussing services in the interview was operationalized as a metric of ecosystem services. Time allocated to discussing ecosystem services showed a nearly four-fold increase among participants ranging from 1.9% to 7.6% of informational interviews (Table 4.7). Participants’ value of ecosystem services was varied across gender and was not significantly related to management practices (weeding intensity, farm size, number of years organic and shade tree management).

4.5 Social and ecological predictors of herbaceous community composition and farm health

Using stepwise regression, farmer attributes that predicted functional diversity of the herbaceous community were identified (Table 4.9). This analysis determined that cognitive map connection-to-variable ratio was the best predictor for functional richness (model $r^2=0.151; p=0.012$). With a positive coefficient, this indicates that an increase in connection-to-variable ratio was positively associated with functional richness. Connection-to-variable ratio was also the significant farmer attribute in predicting functional evenness of the herbaceous community (model $r^2=0.173$;
Figure 4.2 Principal component analysis of the community weighted mean values for four leaf-level traits (specific leaf area, leaf dry-matter content, leaf nitrogen concentration, leaf carbon concentration) and one whole-plant trait (plant height) of 39 herbaceous species found in 45 organic plots across the Turrialba region. Colours represent farmer perspective on herbaceous species as being good, neutral or bad within their organic coffee agroforestry farms. Ellipses correspond to 95% confidence ellipses for community weighted mean values for herbaceous species sampled in this study.
Table 4.9 Stepwise and multiple regression model analysis to determine the farmer attributes that best predict indices of herbaceous community functional diversity. Indices that have been log-transformed are marked with an asterisk (*). Parameter estimates and p-values are shown for parameters retained in most parsimonious 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. Full model was of the form: functional diversity response ~ farmer attributes [years organic (yorg) + value of ecosystem services (ves) + cognitive map connection-to-variable ratio (cv) + cognitive map density (density)]

<table>
<thead>
<tr>
<th>Model</th>
<th>AIC-retained parameters</th>
<th>Coefficient (p-value)</th>
<th>Full AIC</th>
<th>AIC</th>
<th>ΔAIC</th>
<th>Model r² (p-value)</th>
<th>Starting Equation</th>
<th>Most parsimonious equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRic*</td>
<td>(Intercept)</td>
<td>-2.77 (0.121)</td>
<td>-33.02</td>
<td>-40.51</td>
<td>3.93</td>
<td>0.151 (0.012)</td>
<td>FRic*-yorg</td>
<td>FRic*- cv</td>
</tr>
<tr>
<td></td>
<td>cv</td>
<td>30.51 (0.039)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>cv</td>
<td></td>
</tr>
<tr>
<td></td>
<td>density</td>
<td>-57.77 (0.057)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>density</td>
<td></td>
</tr>
<tr>
<td>FEve</td>
<td>(Intercept)</td>
<td>1.70 (&lt;0.001)</td>
<td>-117.1</td>
<td>-119.77</td>
<td>2.67</td>
<td>0.172 (0.009)</td>
<td>FEve-yorg</td>
<td>FEve ~ cv</td>
</tr>
<tr>
<td></td>
<td>cv</td>
<td>-11.27 (0.048)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>cv</td>
<td></td>
</tr>
<tr>
<td></td>
<td>density</td>
<td>21.04 (0.070)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>density</td>
<td></td>
</tr>
<tr>
<td>FDic*</td>
<td>(Intercept)</td>
<td>-0.12 (&lt;0.001)</td>
<td>-180.4</td>
<td>-184.62</td>
<td>4.18</td>
<td>N/A</td>
<td>FDic*-yorg</td>
<td>FDic*- 1</td>
</tr>
<tr>
<td></td>
<td>yorg</td>
<td>-0.075 (0.108)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>yorg</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ves</td>
<td>-0.188 (0.027)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ves</td>
<td></td>
</tr>
<tr>
<td></td>
<td>cv</td>
<td>-88.27 (&lt;0.001)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>cv</td>
<td></td>
</tr>
<tr>
<td></td>
<td>density</td>
<td>177.74 (&lt;0.001)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>density</td>
<td></td>
</tr>
</tbody>
</table>
but was significantly negatively associated. There was no measured farmer attribute that predicted functional divergence of the herbaceous community. However, farmer value of ecosystem services, cognitive map density and connection-to-variable ratio were all significant predictors of FDQ of the herbaceous community (model $r^2=0.423; p<0.001$). Stepwise regression found that FDQ declined with increased farmer value of ecosystem services and connection-to-variable ratio, however FDQ increased with increased cognitive map density.
Chapter 5 - Discussion

5.1 Unrecorded diversity in organic agroforestry systems

Organic agriculture has been reported to increase biodiversity in agricultural landscapes in comparison to conventional management (Hyvönen & Salonen 2002; Nascimbene et al. 2012). Previous research has determined that organic coffee agroforestry systems have greater shade-tree taxonomic and functional diversity than conventional coffee production methods (Jose 2009; Haggar et al. 2011; Toledo & Moguel 2012). This study provides insight into the previously undocumented diversity of the herbaceous community in coffee agroforestry systems. Results from this research project found that herbaceous communities not only increase species richness but also functional diversity within coffee agroforestry systems, which has been linked to efficient resource use (Storkey & Neve 2018), nutrient cycling (Méndez et al. 2010; Tully et al. 2013; Isbell et al. 2017) and resilience to disturbance (Norgrove & Beck 2016) in other agroecosystems.

The herbaceous community in these organic coffee agroforestry systems was both taxonomically and functionally diverse compared to coffee in monoculture or simplified high input agroforestry systems (Rossi et al. 2011). Overall, there were 39 herbaceous species from 20 taxonomic groups found in plots across this study. The species identified, however, only represent a portion of the more than 200 herbaceous species commonly found in coffee farms in the region (Laurito et al. 2016). Within organic coffee agroforestry systems, the herbaceous community contributed substantially to plant species richness where the only other source of diversity is coffee plants and canopy shade-trees, typically composed of one to five species (Rossi et al. 2011; Gagliardi et al. 2015; Cerda et al. 2017a). The taxonomic and functional diversity of the herbaceous community within organic coffee systems supports the growing body of research that organic agriculture provides an alternative to the perpetual decline in biodiversity within industrial agriculture systems (Jones et al. 2018; Storkey & Neve 2018). While herbaceous community diversity has been documented in temperate and Mediterranean climates (see Gaba et al. 2016), my findings contribute some of the first insights into herbaceous community diversity in tropical agroecosystems.
Interestingly, across all farms, high taxonomic and functional diversity of the herbaceous community had no measurable negative impact on coffee yield under current weeding intensities and shade-tree management practices. This may be because many herbaceous species possess either different resource acquisition traits (Smith et al. 2009) or nutrient acquisition segregation (Storkey & Neve 2018) than those of the crop. As a result, organic coffee agroforestry systems can support a high diversity of herbaceous species without declining yield (Rossi et al. 2011).

The species within the herbaceous community in organic coffee agroforestry systems have a wide range of leaf functional traits. Broad-leaf species such as *Hydrocotyle bowlesioides* had high SLA and LNC values. These species were considered beneficial ground covers and green manure by farmers, a relationship supported by similar research in Latin America (Rossi et al. 2011) and the Caribbean (Damour et al. 2014). Grasses and sedges in this study, such as *Brachiaria platyphylla* and *Cyperus tenuis* had low LNC, SLA and high LDMC values. These species are difficult to control due to their tough leaves (Labrada 1997; Pérez-Harguindeguy et al. 2013) and are less beneficial to soil as they can have slower decomposition rates than leaves with higher LNC and SLA. On a plot-scale, the mass ratio hypothesis explains that the most abundant species will determine ecosystem function (Grime 1998; Díaz et al. 2007). For example, farms with an abundance of *Physalis angulata*, a broad-leaf species, may have high levels of photosynthesis (Grime 1998; Wright et al. 2004) and nutrient cycling as chemical (CWM\_LNC) and structural traits (CWM\_SLA) that facilitate rapid decomposition will be dominant in these plots. Conversely, farms with *Paspalum fasciculatum*, a grass species, as the dominant species will likely have lower rates of decomposition as the CWM\_LNC and CWM\_SLA is low.

Overall, functional dissimilarity (FD\_Q) was the most significant functional diversity index of the impact of management on herbaceous community resource use efficiency and complementarity, as explored in the next section. Based on the large body of literature linking leaf functional traits to ecosystem processes (Díaz & Cabido 2001; Botta-Dukát 2005; Violle et al. 2007; Cadotte et al. 2011) one could expect that when the herbaceous community functional dissimilarity is high, resource-use strategies will vary and lead to higher overall function.
5.2 Farm management and attributes strongly predict herbaceous community diversity

The farms in this study that were below the regional mean size had higher herbaceous community CWM<sub>LNC</sub> and higher herbaceous community FD<sub>Q</sub> compared to larger farms. Since leaf nitrogen concentration of plant communities is one of the strongest driving forces for decomposition (Bakker et al. 2011), small farms would be expected to have enhanced nutrient cycling, soil health and microbial populations in the soil (Yadvinder-Singh et al. 2005). Integrating organic material with rapid N-mineralization potential, such as the herbaceous community with high CWM<sub>LNC</sub>, promotes closed nutrient cycles (Tully & Ryals 2017) and reduce inputs costs for farmers (Kilian et al. 2006). This has far-reaching implications as inorganic nitrogen fertilizer is the single largest source of energy use in agricultural production (Camargo et al. 2013). Smaller farms in this study also had herbaceous communities with higher functional dissimilarity (FD<sub>Q</sub>), which is comprised of species diversity and distinctness (Shimatani 2001; Lepš et al. 2006), compared to larger farms. Higher levels of functional dissimilarity suggest that the herbaceous community will have more efficient and, often, complementary use of soil water and nutrients (Loreau 1998; Holzwarth et al. 2015). Studies from temperate landscapes have found that smaller sized fields have a positive effect on diversity of herbaceous plants (Belfrage et al. 2015; Fahrig et al. 2015) and this study indicates that functional dissimilarity could support diverse herbaceous communities with lower competition for resources within tropical agroforestry systems.

While all farms in this study fell within the global standard of smallholder farms (World Bank 2003; Conway 2011; Graeub et al. 2016; Lowder et al. 2016), the decrease in CWM<sub>LNC</sub> and FD<sub>Q</sub> on larger farms posits that as private foreign investments in agro-industry promote larger-scale farms in Latin America (Chavarría 2015), plot-level nutrient cycles and resource-use efficiency may decrease. This may because on smaller farms, farmers have more time to physically engage with their crops and herbaceous communities, which may affect a farmer’s perception of functional traits and subsequent management responses (Ntshangase et al. 2018). In the Central Valley of Costa Rica, Isaac et al. (2018) found that on very small farms, farmers’ perception of leaf nutrient requirements better matched documented leaf nutritional deficiencies of coffee leaves. My research raises caution that larger-sized farms may see a reduction in previously
undocumented herbaceous community CWM\textsubscript{LNC} and \textit{FD}_Q which indicates less nutrient cycling and greater herbaceous species similarity and competition for resources.

This study found that canopy openness and light dynamics also influence herbaceous community functional diversity within coffee agroforestry systems. In this study, medium canopy openness (20-30\%) promoted the highest levels of herbaceous community \textit{FD}_Q and CWM\textsubscript{LNC} and medium levels of \textit{FE}_ve. The herbaceous community with canopy openness above 30\% had lower levels of \textit{FD}_Q and therefore likely more resource competition (Loreau 1998; Holzwarth et al. 2015) and lower levels of CWM\textsubscript{LNC} which indicates a decreased level of decomposition and nutrient cycling (Yadvinder-Singh et al. 2005). This finding is supported by studies in temperate forests where canopy openness has been found to affect niche space differentiation in the herbaceous community (Mason et al. 2013; Mouillot et al. 2013). In a clear-cut temperate forest, full canopy openness resulted in lower levels of herbaceous species functional diversity as compared to herbaceous communities within forests stands (Janěcek et al. 2013). The type of sunlight may be an important factor as well. A recent study into herbaceous plant diversity within Taiwanese conifer plantations found that herbaceous species diversity was significantly negatively correlated with direct sunlight, but not with indirect sunlight (Liu et al. 2015). Shade trees have been well documented for their beneficial role including supporting coffee yield stability (Staver et al. 2001; DaMatta 2004), nutrient cycling (Beer et al. 1998; Cerda et al. 2017a) and pest suppression (Cerdán et al. 2012) in coffee agroforestry systems. One farmer in this study highlighted the benefits of shade-tree coverage, stating that “we needed to start managing shade to help with weeds, so started to plant trees. We have found many advantages. We weed less and have more tree products to harvest” (personal correspondence June 2018).

Some level of management to facilitate light entry into the forest floor is suggested for the promotion of herbaceous communities with greater CWM\textsubscript{LNC} within temperate forests (Kusumoto et al. 2015). Canopy openness and thus light dynamics are promoted in local agroforestry guides within Costa Rica (Montagnini et al. 2015), but a specific level of canopy openness is not suggested. This research suggests a canopy openness of 20-30\% results in higher levels of herbaceous community \textit{FD}_Q, \textit{FE}_ve, and CWM\textsubscript{LNC}, which indicates higher nutrient cycling and reduced levels of competition. However, this study was limited to exploring canopy
openness only; and recognizes that shade-tree architecture and pruning can influence light transmission greatly (Beer et al. 1998) and pruning residues can also suppress herbaceous community growth (Staver et al. 2001). To understand the interaction between shade-tree traits and the herbaceous community, future studies should account for indirect and direct light transmission, shade-tree root traits and canopy architecture.

Weeding intensity did have a significant effect on herbaceous community diversity. However, the varied results suggest that the operationalization of farmer identified weeding intensities may not be effective in capturing actual on-farm practices. The findings that low and high weeding intensities resulted in the highest FDQ and CWM LDLC suggest that there may be other factors within weeding intensity levels. One potential factor is that all high weeding intensity farms were managed by women who, stated that “women never learn how to use a machete” (personal correspondence, June 2018), and therefore outsource weeding to paid labour. This high weeding intensity by outside labourers could be a result of low engagement with plants on the farm and therefore a coarser scale weeding approach (Bellamy 2011; Maharani et al. 2018), than farmers who have constant engagement with managing their herbaceous communities. Interestingly, weeding intensity did not affect coffee yield nor coffee leaf rust, therefore, there may be opportunities women farm owners to decrease labour costs by hiring weeding labour less frequency. Overall, however, more research into the impact of weeding disturbance on herbaceous community should be conducted in a controlled environment.

5.3 The role of farmer perception in driving diversity

All participants in this study indicated that ecological and health values were the main motivators for their conversion to organic coffee production but varied in their specific reasoning to convert. One participant mentioned that his primary reason for transition to organic production his enjoyment of a “greener” life, saying “me gusta lo verde.” Another farmer was motivated to leave conventional agriculture after developing persistent stomach pains from using Paraquat herbicide. Others were driven to convert to organic agriculture by family and spiritual motivations such as, “to take care of God’s garden.” The diversity of motivations for converting to organic is an indication that while farmers implemented similar organic guidelines and
practices, their convictions and backgrounds are different. Such differences may inform a diversity of connections to their farms (Kaufman & Mock 2014) and, therefore, perception of their herbaceous community.

All farmers in this study placed value on the herbaceous community’s ecosystem service provisioning (ranging from 1.9% to 7.8%), which outweighed their perception of ecosystem disservices of the herbaceous community (ranging from 0.7% to 3.0%). One farmer shared his admiration for the weeds in his herbaceous community saying that, “every plant has a role” (personal correspondence, May 2018). Farmers placed the most value on soil health benefits of the herbaceous community including “refreshing the soil/providing soil moisture” and “providing soil nutrients” such as “nitrogen fixation,” and the herbaceous community’s overall role supporting “soil health” and “soil erosion control.” Based on cognitive map analysis, organic material was the highest domain variable in 100% of farmer interviews, meaning that thematically soil organic matter was the most connected concept. This signifies that chopping weeds, pruning shade trees and leaving material to decompose is an important value held by farmers and can inform management (Lescourret et al. 2015), such as weeding practices and shade tree management. Moreover, all farmers placed higher emphasis on soil health and organic matter than coffee yield, which may be indicative of their role as land stewards (Jose 2009).

Farmer perception of the herbaceous community within their farm was related to herbaceous community diversity. Farmer cognitive map connection-to-variable ratio, an indicator of perceived interconnectedness between farm management variables (Isaac et al. 2009), was an important predictor for the functional dissimilarity, functional evenness and functional richness of their herbaceous community. Stepwise and multiple regression model analysis determined that cognitive map connection-to-variable ratio was positively related to herbaceous community functional richness, and negatively related to functional evenness and functional dissimilarity. Moreover, farmer value of ecosystem service was a significant negative predictor of functional dissimilarity. This result may be because farmers with high herbaceous community functional richness and therefore species richness (Mason et al. 2005) saw more linkages between their herbaceous community diversity and ecosystem services (Swift et al. 2004; Garcia et al. 2018) than farmers with high herbaceous community functional evenness and/or dissimilarity. Recent
research (Isaac et al. 2018), and the PCA analysis in this study, indicate that farmers do have a strong sense of crop and herbaceous community functional traits. However, functional diversity indices remain understudied (Ronchi & Silva 2006) and underutilized in practice. The gap in farmer knowledge about herbaceous community functional diversity and management indicates that more research and dissemination is needed, particularly around how herbaceous community functional dissimilarity can support resource-use efficiency while fostering biodiversity (Karadimou 2016).

Although weed management is perceived to be one of the largest barriers for farmers to shift to organic production (Lyngbæk et al. 2001), the Organic and Sustainable Producers Association (APOYA) network has not yet had the capacity to provide workshops on organic weed management (personal correspondence, July 2018). All participants in this study had attended workshops on other organic coffee production practices such as shade-tree intercropping, but none had attended a workshop focused specifically on herbaceous community management, diversity and ecosystem function. The lack of a centralized information on the herbaceous community is likely the reason that farmer perceptions of ecosystem services and disservices of the herbaceous community varied greatly across farms. However, the strong social relationships reinforced by the APOYA network allows for the diffusion of information and adoption of new techniques (Rogers 2003). With this strong base, workshops on organic herbaceous community management will be necessary to communicate practices that support soil health, coffee health and reduce farmer labour (Valencia et al. 2015).

5.4 The potential for agroecosystems service provisioning

Ecosystem services of the herbaceous community observed in this study included increased soil moisture, soil carbon and stable coffee yield. Farmers also described additional ecosystems services provided by the herbaceous community that were not measured in this study but are supported by other research within coffee agroforestry systems. These ecosystem services included erosion control (Meylan et al. 2013), pollination (Gordon et al. 2007), fostering biodiversity (Perfecto et al. 2014) and providing food for animals and medicine for human health (Soto-Pinto et al. 2002). One farmer mentioned the nutrient benefits from his herbaceous
community stating that “weeds are the cheapest manure you can find,” (personal correspondence, May 2018).

This study found key relationships between soil moisture and the herbaceous community: significant positive relationship between herbaceous community functional evenness and soil moisture and between functional dissimilarity and soil moisture. These findings are important as soil moisture and water management are critical to coffee health and yield (Chemura 2014), particularly as rainfalls in the region become increasingly unreliable (DaMatta 2004; Isaac et al. 2018) due to climate change (IPCC 2013). Coffee leaf rust was found to be negatively correlated with herbaceous community functional dissimilarity. Overall, these results support research that soil moisture is positively related to decomposition of organic matter, soil carbon, soil nitrogen cycling, coffee yield (El-Kader et al. 2010) and the suppression of coffee leaf rust (Zambolim et al. 1997).

The growth of the herbaceous community and continual integration of organic material can increase soil water storage (Minasny & Mcbratney 2018), as well as soil microbial biomass (Ghimire et al. 2017) and support long-term carbon sequestration (Karlen et al. 1994; Ghimire et al. 2017). Since one gram of soil carbon equates to 3.66 grams of CO₂ in the atmosphere (Poeplau & Don 2015), the herbaceous community should be considered in Costa Rica’s climate change goals of becoming the world’s first carbon neutral country by 2021 (Defrenet et al. 2016). Costa Rica’s elaborate payment for ecosystem service program may be able to encourage practices that foster ecosystem services (Pagiola 2008; Saadun et al. 2018). Currently, Costa Rica’s payment for ecosystem service program supports farmers who plant and conserve forests that contribute to ecosystem services including the mitigation of greenhouse gases, water cycling, biodiversity conservation and provision of scenic beauty (FONAFIFO 2000; 2005; Pagiola 2008). Recent research has shown that this program disproportionately supports large landowners and that there is an urgent need to better support smallholder farmers in gaining more equitable access to payment opportunities (Lansing 2017). This study suggests that the herbaceous community is a previously undocumented source of diversity and ecosystem service provisioning and should be considered in future development of Costa Rica’s payment for ecosystem service program.
Herbaceous community functional diversity had no measurable impact on coffee yield. While yield in organic coffee agroforestry systems is generally lower than conventional systems (Toledo & Moguel 2012), studies support the finding that organic systems can have higher weed diversity while maintaining yields (Rossi et al. 2011). Furthermore, herbaceous community diversity may contribute to more stable yields year-to-year (Yachi & Loreau 1999; Isbell et al. 2017), which can help farmers with income planning and financial management. In this study, age and variety of coffee varied between farms, which may influence yield per plant, and therefore age and variety of coffee should be held constant in future studies.

Higher herbaceous community biomass and coffee leaf rust were positively correlated, which may be due to decreasing airflow around coffee plants which can foster disease (Arneson 2000). This indicates that some optimal level of weeding is necessary to reduce disease. Farmers were well aware of this, as one farmer noted that “tall weeds can heat up the coffee plants and spread disease” (personal correspondence, June 18 2018). Management practices including low to medium weeding intensity, 20-30% canopy openness and further education around the role of functional dissimilarity within herbaceous communities, farmers can encourage the reduction in ecosystem disservice associated with the herbaceous community (Filho et al. 2013; Power et al. 2010). Exploring ways to include herbaceous community ecosystem service provisioning may promote management practices that foster herbaceous community soil carbon, soil nutrient provisioning and biodiversity.
6.1 Conclusions

While the herbaceous community is ubiquitous in organic coffee agroecosystems, it has been rarely studied and has never been looked at through a functional trait lens. My thesis aims to provide insights into how farmer perceptions and management practices impact the functional diversity of the herbaceous community and explore the subsequent ecosystem (dis)services the herbaceous community provides in coffee agroforestry systems.

As I hypothesized, the herbaceous community varied across farms and management practices. This study found that the herbaceous community is an important, yet previously undocumented, source of diversity within coffee agroforestry plots, which are typically composed of only one to five species (Rossi et al. 2011; Gagliardi et al. 2015; Cerda et al. 2017). This study found that the herbaceous community contributes to coffee system functional diversity and influences ecosystem functions including plant-soil feedbacks and nutrient cycling (Garrier & Navas 2012). Moreover, interviews demonstrated that similar to recent research for coffee leaf traits in the region (Isaac et al. 2018), the organic coffee farmers in the Central Valley of Costa Rica are aware of herbaceous community functional traits. Farmers in this study preferred herbaceous species that had high SLA and LNC as these, often broadleaf, species are easier to control and have higher nutrients and decomposition rates. Farmers perceived tall herbaceous species with low SLA and LNC, and high LDMC to be undesirable, as they are often thicker and more difficult to control and decompose more slowly. This study found that these traits can be favoured on the plot-level through management practices.

This research found that size of farm and canopy openness influenced both single-trait and multi-trait herbaceous community functional diversity. Plots below the average regional size of farm fostered an herbaceous community with higher $CWM_{LNC}$ and $FD_Q$. This research cautions that as farm-size increases, farmers will have less time to engage with their plants which could result in less functionally dissimilar herbaceous communities and therefore less resource-use efficiency within the herbaceous community. This research also found canopy light management affected the herbaceous community. Farmers who fostered 20-30% canopy openness through planting of
diverse shade-trees and annual pruning schedules (Montagnini et al. 2015) supported herbaceous communities with higher functional evenness, FDQ and CWM_{LNC}, which promotes resource-use efficiency and higher nutrient cycling. This research also found that while farmer identified weeding intensities may not be effective in capturing actual on-farm practices, weeding less than five times per year saves labour costs and can foster an herbaceous community with lower CWM_{LDMC}, which is easier to mechanically chop, and supports higher resource-use efficiency (Karadimou 2016). This may be particularly relevant for farmers who hire external labour to weed their plots frequently, as higher levels of weeding did not result in increased coffee yield or soil health.

While all farmers in this study believed that the herbaceous community provided multiple ecosystem services, they were not uniform in their values. This is likely due to farmers’ values being created from each participant’s individual experience, rather than a collective network. Interviews and cognitive mapping indicate that there are opportunities to shift farmer practices. Every farmer in this study said they would be interested in workshops on herbaceous community management and the local organic network said that they would be very happy to share research from any herbaceous community studies in the region. Workshops would be important spaces for organic farmers in the region to share their values of ecosystem services and to build a knowledge base of herbaceous community functional diversity and management to enhance sustainable farm development (Isaac et al. 2009; Valencia et al. 2015).

Beyond increasing biodiversity and eliminating chemical herbicides, this study demonstrated appropriate management practices of the herbaceous community can foster ecosystem services including increased soil moisture, soil carbon and stable coffee yields. These benefits, particularly the important role that soil carbon can play in the sequestration of atmospheric CO₂ (Poeplau & Don 2015) are especially relevant as Costa Rica aims to become the world’s first carbon neutral country (Defrenet et al. 2016). The role of the herbaceous community in ecosystem service provisioning should be considered for future growth of Costa Rica’s payment for ecosystem service program. The provisioning of services within small plots of land could inform a more accurate and equitable program.
This study aimed to provide initial insight into the herbaceous community functional diversity within coffee agroforestry systems. However, as herbaceous communities are one of the largest perceived barriers for farmers to transition to organic agriculture in the region, it is necessary to continue research into the herbaceous community, particularly from a functional trait lens to connect these communities to ecosystem functions and processes.

6.2 Areas of future research

This study focused on the herbaceous communities in organic coffee farms, however, conventional systems also have a present herbaceous community between sprays (Rossi et al. 2011). Research from orchards in Spain demonstrates that the herbaceous community within plots that have chemical weed control were as high as plots without herbicide use (Mas et al. 2007). Research into the herbaceous community before and after herbicide application would provide insight into the functional diversity of herbaceous communities within conventional coffee systems. While organic systems provide significant biodiversity and conservation benefits in comparison to coffee in monoculture (Toledo & Moguel 2012; Perfecto et al. 2014), future research into the ecosystem services of herbaceous communities within conventional plots could support more sustainable practices, such as the reduction of herbicide use, within conventional farms.

While my research provides some of the first insights into links between herbaceous community functional traits and ecosystem services within organic coffee systems, future studies with coffee variety, coffee age, fertilizer application and time since weeding held constant will help to improve the accuracy of measuring ecosystem services provided by herbaceous communities. Furthermore, this study looked at the above-ground functional traits of the herbaceous community but did not explore the below-ground functional traits. I recommend that a future study explore the root functional traits of the herbaceous community to understand how herbaceous species respond to available resources. As well, more research into shade tree light dynamics and canopy architecture will provide useful insight to the role of canopy management of the herbaceous community. Overall, further research will provide insight into how farmers can better manage their herbaceous community for complementarity and resource-use efficiency.
References


Appendices

Appendix A- List of all herbaceous species

All herbaceous species found in organic coffee agroforestry plots (n=45) in this study, listed in order of frequency. Range and mean functional traits are given.

<table>
<thead>
<tr>
<th>Species name</th>
<th>Family name</th>
<th>Region of Origin</th>
<th>Frequency</th>
<th>Range Height (cm)</th>
<th>Mean Height (cm)</th>
<th>Range LDMC (mg g⁻¹)</th>
<th>Mean LDMC (mg g⁻¹)</th>
<th>Range SLA (mm² mg⁻¹)</th>
<th>Mean SLA (mm² mg⁻¹)</th>
<th>Range LNC (mg g⁻¹)</th>
<th>Mean LNC (mg g⁻¹)</th>
<th>Range LCC (mg g⁻¹)</th>
<th>Mean LCC (mg g⁻¹)</th>
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<td>7.20-69.56</td>
<td>33.57</td>
<td>23.44-95.44</td>
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<td>353.10-630.10</td>
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<td>31.99-579.54</td>
<td>233.03</td>
<td>6.97-42.89</td>
<td>29.41</td>
<td>24.27-95.91</td>
<td>37.61</td>
<td>244.8-569</td>
<td>421.35</td>
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<td>8.33</td>
<td>36.41 - 883.33</td>
<td>173.29</td>
<td>7.52-70.78</td>
<td>35.90</td>
<td>27.85-67.59</td>
<td>36.65</td>
<td>362.90-659.10</td>
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Appendix B - Interview Questions

Interview questions used in all farmer interviews, approved by University of Toronto Human Research Ethics Program. Italicized questions were prompts used to support further elaboration on questions from farmers.

### Introduction Questions

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<td>Name of Region/Location</td>
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Please, tell me the story of your farm. *How long has it been in coffee production? Were there any crops here before? Any other details?*

How long have you been a farmer?

When and how did you decide to transition to organic production? *What was that process like?*

When did you join the APOYA network? *Are you a part of any other farmer networks here?*

Have you noticed a difference when not using herbicides on soils? *What is the size of your farm?*

### Herbaceous Community Questions

Do you do any weeding? *If so, how (chop, turn soil, mulch, burn)?*

Walk me through your weeding process. *How much time does it take? Who performs this task? Do you weed the whole farm at once?*

What are the key triggers that to encourage you to weed? *Is there a maximum threshold of herbaceous cover before you weed?*

### Preguntas Iniciales

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<tbody>
<tr>
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<td>Nombre de la Región</td>
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</tbody>
</table>

Por favor, expícame la historia de su finca. *¿Cuánto tiempo ha pasado en la producción de café? ¿Hubo alguna cosecha aquí antes? ¿Algún otro detalle?*

¿Cuánto tiempo ha sido agricultor?

¿Cuándo y cómo decidió cambiar al producción orgánica? *¿Cómo fue ese proceso?*

¿Cuándo se unió a la red APOYA? *¿Es usted parte de alguna otra red de agricultores aquí?*

¿Notó una diferencia cuando no usa herbicidas en los suelos?

¿Cuál es el tamaño de su finca?

### Preguntas sobre la Comunidad Herbáceas

¿Hace usted la chapea? *¿Si es así, como (usa machete, moto guaraña, girar la tierra, abono, quemar)?*

¿Puede llevarme a través de tu proceso de la chapea? *¿Cuánto tiempo toma? ¿Quién realiza esta tarea? ¿Chapea toda la finca a la vez?*

¿Cuáles son los factores desencadenantes clave que lo alientan a la chapea? *¿Hay un umbral máximo de cobertura herbácea antes de desherbar?*
How often do you weed? *Is it something scheduled, or is it triggered by a maximum threshold?*
Are there specific months or times of year that you weed more than others?
What do you do with the debris? *Do you leave plant material on the ground?*
Are there seasons or years when you have not weeded? *Did you notice differences in the coffee (yield/quality) in those years?*
When do you see a large growth of weeds? *After rains? Fertilization? Harvest?*
Do other management practices have an effect on weeds, *i.e. pruning?*

**Species-specific Questions**

How do you know this is a bad weed? How do you know is this a good weed? *What impacts do they have on the coffee plant?*

What are you looking for in herbaceous species that you keep (i.e. pollinator habitat, nitrogen fixer)?
Are there some you do not consider weeds? If so, why not?

**Ecosystem Service**

What are the most important services that your herbaceous community provides to your farm out of the following?

- improved soil health
- erosion control
- soil moisture regulation
- soil nutrient additions
- improved biological diversity
- medicine
- pollination
- farm beauty
- pest control

¿Con qué frecuencia chapea usted? *¿Es algo programado, o algo que hace como resultado de alcanzar el umbral máximo?*
¿Hay meses o épocas específicas del año en las que chapea más que otras?
¿Qué hace con el material orgánico? *¿Lo deja sobre la tierra?*
¿Hay temporadas o años en los que no ha limpiado? *¿Notó diferencias en el café (rendimiento / calidad) en esos años?*
¿Cuándo vea un gran crecimiento de monte? *¿Después de las lluvias? *Fertilización? *¿Cosecha?*
¿Piensa que otras prácticas de gestión un efecto sobre el monte? *(por ejemplo, la poda)?*

**Preguntas Específica de la Especies**

¿Cómo sabe que esta es una mala hierba? *¿Cómo sabe que esta es una buena hierba?*
¿Qué impacto tienen en la planta de café? *¿Qué está buscando en especies herbáceas que conserva (es decir, hábitat de polinizadores, fijador de nitrógeno)?*
¿Hay alguno que no piensa son malas hierbas? Si es así, ¿por qué no? *¿Cuáles son los servicios más importantes que su comunidad herbácea brinda a su finca de los siguientes?*

- mejor salud del suelo
- control de la erosión
- regulación de la humedad del suelo
- adiciones de nutrientes del suelo
- diversidad biológica mejorada
- medicina
- polinización
- belleza de la granja
- control de plagas
<table>
<thead>
<tr>
<th>Other management practices</th>
<th>Otras prácticas de gestión</th>
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<tr>
<td>Do you use fertilizers (compost or inorganic fertilizers)? <em>Where did you learn to make them?</em></td>
<td>¿Utiliza fertilizantes (compost o fertilizantes inorgánicos)? <em>¿Dónde aprendiste a prepararlos?</em></td>
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<tr>
<td>Any other farm management practices that affect the soil?</td>
<td>¿Alguna otra práctica de manejo que afecte el suelo?</td>
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General Questions:

What challenges and benefits do you have as an organic farmer? 

Can you provide any other information on your practices for maintaining successful coffee production?

Do you share information with different farmers? *What sorts of tools or resource are available for you to get information?* *What would be useful to you in the future?* 

¿Qué desafíos y beneficios tiene usted como agricultor orgánico?

¿Puede proporcionar otra información sobre sus prácticas para mantener una producción de café exitosa?

¿Comparte información con diferentes agricultores? *¿Qué tipo de herramientas o recursos están disponibles para que usted obtenga información?* *¿Qué te sería útil en el futuro?*