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Cacao – Arbuscular Mycorrhizal Fungi Association: A Review on Its Increased Potential in Improving the Ecology of Cacao Plantations in the Philippines

Diana P. Paguntalan[1,2]*, **Inocencio E. Buot Jr.**[2], and **Nelly S. Aggangan**[3]

[1]Division of Biological Sciences
College of Arts and Sciences
University of the Philippines Visayas
Miagao, Iloilo, Philippines

[2]Institute of Biological Sciences
[3]National Institute of Molecular Biology and Biotechnology
University of the Philippines Los Baños
College, Laguna, Philippines

Cacao (*Theobroma cacao*) is both an economically and ecologically important crop worldwide especially in the Philippines, a tropical country suitable for its growth and cultivation. The association of this crop with arbuscular mycorrhizal fungi (AMF) is an understudied field but the benefits reported from this symbiosis highlights their irreplaceable role in enhancing growth conditions by facilitating the uptake of phosphorus, increasing yield through increased plant health and productivity, and in several ecological aspects such as soil biological dynamics and ecological processes that are carried out in cacao plant community. This paper proposed the different areas of improving cacao ecology that need to gain attention in the Philippines to augment the measures being undertaken to boost the country's cacao plantations. This includes more research on areas of soil physicochemical properties, AMF genetic and functional diversity in cacao communities, and resistance to diseases of AMF-associated cacao trees. The ecology of the AMF-cacao association is an essential part of developing effective AMF inocula for the ultimate purpose of increasing the yield of cacao. Appropriate application of AMF could increase the overall yield of the country's cacao plantations and can be translated to improving food security and many other economic gains.

Keywords: arbuscular mycorrhizal fungi, cacao-AMF association, cacao ecology

INTRODUCTION

One of the most plenteous organisms found in almost all types of ecosystems such as agroecosystem, forest ecosystem, and humid ecosystem are indigenous fungi ranging from 4–13 CFU/g^{-1}, 0–8 CFU/g^{-1}, and 0–10 CFU/g^{-1}, respectively; and indigenous actinomycetes from 2–20 CFU/g^{-1}, 1–4 CFU/g^{-1}, and 1–3 CFU/g^{-1} in respective environments (Meliani *et al.* 2012). Even in extreme environments such as sub-marine, cold, saline, or even heavy-metal-contaminated habitats, 17,924 spores were classified – of which 106 species of AMF are identified from such varied environments (Oehl *et al.*

*Corresponding Author: dppaguntalan@up.edu.ph

2017). AMF are even detected in the roots of acidified glacial lake-inhabiting macrophytes (Sudovár *et al.* 2011). AMF are groups of organisms that are included in a monophyletic group within the Kingdom Fungi under the phylum Glomeromycota (Pagano 2016). The phylum Glomeromycota currently comprises approximately 150 described species distributed among 10 genera, most of which are defined primarily by spore morphology and was instituted based on rDNA phylogenies of living members (Schüssler *et al.* 2001; Redecker and Raab 2006). AMF are known to be a vital part of most terrestrial ecosystems and have been recognized to play an important role in the pathway of carbon flux in the soil-plant-atmosphere continuum through the mycelia they produce (Jacobsen and Rosendhal 1990; Johnson *et al.* 2002), ultimately affecting carbon fluxes and nutrient dynamics. Also, AMF participate in various aspects of global change and in regulating ecosystem responses. This is manifested in its ability to multiply under high levels of atmospheric carbon dioxide and decrease under man-caused nitrogen deposition (Treseder 2004).

In addition to this, AMF are known to have established relationships in no less than 200,000 species of host plants (Schüssler *et al.* 2001), indicating their lack of host specificity (Smith and Read 2008). It was believed that such a relationship played an important part in the early colonization of land plants about 460 million years ago (Redecker *et al.* 2000). Among the plant kingdom, mycorrhizal relationships are said to be the most important plant-microbe partnership that ultimately affects plant health and productivity. Added to the current concern on expensive and detrimental effects of fertilizers are changing climate conditions that require sustainable solutions for many crops. The application of AMF to several crops of economic value like cacao must be thoroughly explored.

Cacao (*Theobroma cacao* L.) is greatly utilized in many parts of the world – as with several fruit crops such as banana (Pinochet *et al.* 1997), oranges (Souza and Souza 2000), apples (Raj and Sharma 2009), guava (Ibrahim *et al.* 2010), and many others (Kumari *et al.* 2017) as a sustainable approach of enhancing soil fertility and plant health. Cacao is one of the most important crops of the world as it is the source of the most prized and highly valued product – the chocolate. It was in the Philippines that the first cacao in Asia was planted, given its strategic location in terms of trade and ideal climatic condition for growth allowing the production of about 10,000 MT by 1990s (Table 1) since its planting in 1670 (DA 2004). Three major cultivars are grown in the country. At present, Philippine cacao production stands only at 10,000–12,000 MT per industry (DA 2017) and was even reported lower by the Philippine Statistics Authority to be only approximately 7,000 tons in 2017 DTI 2017). Several factors have contributed to such a decline in cacao production, pest and disease infestation included.

Table 1. Production of cacao (MT) by region, Philippines, 1990–1999.

Region	1990	1995	1999
CAR	48	6	6
Ilocos Region	86	53	51
Cagayan Valley	53	49	99
Central Luzon	11	–	1
CALABARZON	61	52	53
MIMAROPA	81	74	45
Bicol Region	52	45	27
Western Visayas	431	203	105
Central Visayas	102	94	95
Eastern Visayas	137	121	136
Zamboanga Peninsula	470	341	334
Northern Mindanao	839	526	574
Davao Region	6,300	5,589	5,464
SOCCSKSARGEN	357	199	151
CARAGA	684	473	440
ARMM	135	104	86
Total	**9,848**	**7,927**	**7,667**

*Excerpt from "Cacao: Production, Area, and Yield Per Hectare by Region, Philippines, 1990–2003" by the Department of Agriculture (2004).

Hence, it is the goal of this paper to discuss studies on the effects of AMF and their mechanisms of action and how their associations with cacao plants affect the overall functioning of these important crops in their environment. Likewise, this paper intends to review existing studies on AMF utilization in the country and to provide recommendations on specific areas of study that need attention for the enhancement of methods and utilization of AMF in improving cacao ecology.

Scope

The current paper discusses past and present literaturethat substantially discusses findings and theoretical contributions on the role of AMF in enhancing the ecology of crops, specifically of cacao plants. Here, pieces of information from published academic journals, books, and related sources are organized to concretize the idea on how the mechanisms of action of AMF are carried out in cacao, giving emphasis on their role in many aspects of plant growth and plant interaction while identifying specific aspects of the ecology of cacao that needs more attention – especially in investigating the dynamics between AMF, cacao, and its environment.

KEY FINDINGS

AMF Diversity Pattern Associated with Cacao

Several studies have shown the density and diversity of vesicular-arbuscular mycorrhiza (VAM) fungi to be directly correlated to the changes in soil fertility and overall soil biological dynamics at different stages of cacao agroforests (Snoeck *et al.* 2010; Isaac *et al.* 2005) and relate to plant diversity in natural forest ecosystems (Musoko *et al.* 1994; Ngonkeu 2003. One study demonstrated that AMF diversity may correspond to proper cultivation practices that maintain mycorrhizal associations among cacao trees by showing that diversity of the AMF community from several cacao plantations is similar to that found in natural undisturbed ecosystems from Venezuela. Reported from this study is the presence of AMF in all studied plantations wherein variations between 14% and 69% were observed for percent root length colonization. A total of 15 AMF species were identified from spores, from which *Acaulospora scrobiculata* Trappe and *Glomus constrictum* Trappe were most frequently found on all sites (Cuenca and Meneses 1996). Relatedly, Snoeck *et al.* (2010) suggested that unfertilized cacao agroforests could be sustainable due to the temporal dynamism of VAM fungi that affects organic matter and major nutrients in the soil. The author suggested that despite low microbial and chemical soil properties at a young age, older cocoa agroforests foster greater VAM diversity and density based on the Shannon-Weaver index reporting 0.47± 0.02 in short fallow ecosystems, which is significantly higher than the 0.39 ± 0.03 index of young cacao ecosystems. This result is correlated with the high spore density of about 98 spores per g of dry soil observed in the short fallow.

Effects of AMF on Cacao as Host Plants

On cacao morphology and physiology. The most remarkable physiological effects on host plants by AMF is said to be an improved level of absorbing phosphorus. Hence, phosphorus deficit becomes the determinant factor as to the extent of mycorrhizal infection that can affect plant performance when the phosphorus level in the soil becomes limiting (Koide 1991). Cacao trees, specifically, has been reported to be largely reliant on phosphorus levels despite several studies reporting different levels of correlation depending on AMF species, the plant species, and even the source and solubility of phosphorus (Cardoso 1996; Tawaraya *et al.* 1996; Nikolaou *et al.* 2002; Bhadalung *et al.* 2005). Usually, a P-depleted zone around the roots is formed when P is taken up due to its low mobility in soils, and this is remedied by fungal hyphae (Schachtman *et al.* 1998), *i.e.,* extraradical hyphae in the case of AMF wherein P is delivered directly from the roots plant through structures called arbuscules (Smith and Read 2008). This ability of AMF to bypass the depletion zones and air-filled spores allows the host plant to be less dependent on soil moisture especially in cases of drought (Bitterlich *et al.* 2018). This advantage is achieved only when the phosphate level of the soil or media is low but sufficient since high phosphorus levels tend to allow plants to independently take up phosphorus without the aid of AMF, whereas very low phosphorus makes AMF parasitic (Miyakasa *et al.* 2003).

Morphologically, root characteristics were observed to be directly correlated with AMF associations. Increased stem diameter was observed for mycorrhizal plants with an associated increase in shoot phosphorus content, as reported by Chulan and Martin (1992). A study by Cuadros *et al.* (2011), wherein different levels of P availability was investigated for effects on the morphological characters of cacao seedlings, reported significant differences in root lengths among sampling times, thereby correlating root length growth to be directly affected by phosphorus availability and plant-mycorrhizal interactions.

On growth and nutrient uptake. The most limiting to increasing crop yields is known to be largely linked to the conditions of the soil in terms of nitrogen and phosphorus availability (Tilman *et al.* 2002) and, among other factors, the most studied aspect of how cacao respond to AMF experiments is on phosphorus acquisition. The beneficial effects of AMF associations with vegetables and many other crops have been fairly proven. In such studies, for instance, higher plant biomass and grain yields were

Table 2. General physiological and morphological effects of AMF on cacao.

Morphological	- increased stem diameter	Chulan and Martin 2002
	- root length growth	Cuadros *et al.* 2011
	- increased leaf area	Iglesias *et al.* 2011
	- increased leaf number	Tchameni *et al.* 2012
Physiological	- induction of plant defense	Graham *et al.* 1990; Wehner *et al.* 2010
	- amino acid synthesis	Hassan *et al.* 1994; McLusky *et al.* 1999
	- direct P uptake	Tchameni *et al.* 2012; Smith and Read 2008; Bitterlich *et al.* 2018

observed for many industrial crops like wheat (Al-Karaki 2004), rice (Rajeshkannan *et al.* 2009), corn (Naher *et al.* 2013), fruit crops such as banana (Grant *et al.* 2005), and an important industrial crop, palm oil (Widiastuti and Tahardi 1993) – all of which are related to more and efficient uptake of nitrogen, phosphorus, and potassium. For cacao, several studies on its associations with AMF have been done, with almost consistent similar results of increased plant health and performance that can be translated to increased plant growth and yield. A study by Oladele (2015) showed that a species of AMF, *Glomus mossae*, enhanced the establishment and growth of young cacao seedlings after being transplanted to the field from the nursery. Inoculation with varying levels of AMF yielded positive effects on several performance parameters such as plant height, leaf number, and shoot and root fresh and dry weights. In these studies, AMF inoculation from developed and established inoculum always had a positive correlation with shoot dry weight, shoot phosphorus uptake, root colonization, and acid phosphatase activity when applied with phosphate rocks of varying type. In all cases inoculation with seedlings always yielded effective in enhancing the supply of nutrients, especially phosphorus (Suparno *et al.* 2014, 2015). Added to this is the study by Droh *et al.* (2016), which compared the growth parameters of cacao among inoculants between native and exogenous AMF. In both sources, their study has shown increased biomass production and the feasible utilization of AMF species from temperate sources to be used in the tropics. To add to this, Aggangan *et al.* (2019b) correlated the enhanced uptakes of nutrients such as phosphorus and nitrogen to the improved microbial populations of phosphate solubilizing bacteria and nitrogen-fixing bacteria (NFB) in the soil due to treatment with AMF and an added biochar as amendment to the soil.

Implications of AMF Associations for Cacao Ecology

General aspects of mycorrhizal symbiosis. In 1885, Frank first used the term "mykorrhiza" to refer to the root structures of forest trees that have been fairly modified. The term, later on, became inclusive of a range of mutualistic, symbiotic associations between the roots of plants and fungi (Smith and Read 2008). Several categories then have been distinguished based on their morphology and the plant species involved. One of these categories is the arbuscular mycorrhizae, whose symbiosis is characterized by arbuscules that grow within cells through their highly branched fungal structure without entering into the plasmalemma of the host. Studies on AMF have explored several possibilities for its use and utilization. AMF mycelium association with other microorganisms has been influenced by the production of glycoproteins that are involved in the formation and stability of soil aggregates (Johansson *et al.* 2004). Added to this is on the role of AMF on bioremediation that, while it is yet to be thoroughly investigated, enhanced dissipation of polycyclic aromatic hydrocarbons or improved soil fertility by influencing soil nutrient availability and enzyme activities (Qiu *et al.* 2018) in the presence of arbuscular mycorrhizae. AMF are also found to have significant potential in gene regulation that provide protection against reactive oxygen species (ROS) through a functional arbuscular enzyme that may supply protection against ROS (Lanfranco *et al.* 2005), and in improving resistance to stress through the formation of antioxidant defense system (Kapoor and Singh 2017). Finlay (2008) outlined the several ecological aspects of mycorrhizal symbiosis enumerating one by one their important role in carbon flow, bioremediation, mediation of plant stress, their effect on plant communities and ecosystems, and their involvement in biotic interactions. According to the said author, it is because of symbiotic associations as adaptive mechanisms to varying environmental conditions that major terrestrial biomes of the world accommodate characteristic plant communities. The ability of mycorrhizal fungi to connect plants to patchily distributed nutrients ensures the flow of compounds that are needed for nutrient mobilization. For the AMF, more research is said to be needed basically because many species of AMF have not yet been investigated. However, studies such as that of Hodge (2006) suggested that – compared to other microbes – AMF should be more able to compete for nutrients theoretically, as based on his previous study in 2000 wherein enhanced decomposition and N capture from decaying grass leaves were observed in the presence of AMF. Contrary to historical trends of narrow coverage wherein effects of symbiosis are studied only on individual plants and their effect on the improved acquisition of mineral nutrients, more recent research (Finlay 2004; Lin 2015), suggest that mycorrhizal symbiosis has a wider, multifunctional role on a large scale of plant and microbial communities and on ecosystem processes as a whole.

On plant community structure and productivity. For cacao, distinct species of AMF associations provide information that translates to the ecology of the plant. One example is the reported variability among plant taxa to AMF infections that suggests an important role of the latter to the structure of how these host plants form communities (Koide 1991). The study of Davison *et al.* (2011) revealed that AMF are not randomly distributed among local taxon pools of host plants and that AMF communities are rather associated with ecological groups, *i.e.* whether the plant groups are generalists or specialists. Generalist plant groups include species of *Fragia*, *Geranium*, *Geum*, *Hypericum*, *Trifolium*, and *Veronica* whereas forest specialists include species in the genera *Galeobdolon*, *Hepatica*, *Oxalis*, *Paris*, and *Viola.* Also, findings from their study revealed that assemblages of AMF communities are a result of a gradual organization that undergoes seasonal changes. Such findings affirm the positive role of AMF in both the above and belowground ecosystem processes.

Generally, the functional diversity of AMF isolates from several experiments and the composition of their communities impacts largely several aspects of plant performance and community structure and ecosystem functions and services. Interestingly, several plant species such as *Brachypodium pinnatum*, *Centaurium erythrea*, *Hieracium pilosella*, *Lotus corniculatus*, *Prunella grandiflora*, *Prunella vulgaris*, *Sanguisorba officinalis*, and *Trifolium pratense* were directly dependent on AMF species to be successful in their environment. Another aspect of the study showed also that an increase in AMF species richness led to increased mycorrhizal hyphae density (up to almost 7 m/g soil), which improved resource use as indicated by higher plant P content (up to almost 2,000 mg/m) and lower soil P content (up to as low as 5 mg/kg soil) and, consequently, higher plant productivity – observed in increased root (up to 14 g/m) and shoot (120 g/m) biomass (van der Heijden and Scheublin 2007). Relatedly, direct evidence on complementarity among species within the AMF community and the root system it colonizes were also reported by Jansa *et al.* (2008), wherein mixed inoculation treatments of different AMF species of *Glomus* resulted to high combined root and shoot biomass for up to as high as 2,000 mg per plant. Furthermore, a study by Vogelsang *et al.* (2006) explained how the presence of specific AMF species can interact with the environment in complex ways to yield community-level responses such as in plant community productivity and diversity.

Studying AMF communities or microbial communities associated with plant groups provide a venue to acquire further knowledge on plant community interactions and has valuable implications in determining the success of invasions of biotic components such as AMF in plants.

As mediators of ecosystem responses. AMF communities are also known to be mediators of ecosystem responses, such as in the case of elevated nitrogen deposition wherein AMF communities tend to shift in response to high levels of nitrogen and results to lower P benefit to their host plant, consequently reducing net primary productivity in P-limited ecosystems (Treseder *et al.* 2017). Several other studies support such findings (Treseder and Allen 2002; Egerton-Warburton *et al.* 2007), as there exists an important trade-off between physiological traits of AMF genera and host plants (Johnson *et al.* 2003; Treseder 2005). To add, a study by Soumaila *et al*. (2012) investigated the population dynamics of AMF associated to cacao fields in the region of Yamoussoukro and reported that all cacao fields studied were found to have widespread spores of AMF but were of different densities of spores among study sites. The researcher related this result to environmental factors that affect AMF spore density, composition, and distribution.

Cacao-AMF Association Studies in the Philippines

Studies on interaction and effects of the special association between cacao and AMF in the Philippines are scarce in terms of exploring the different aspects of the symbiotic relationship between the said organisms. In the Philippines, local studies include that of Aggangan and Jomao-as (2019), who reported enhanced nutrient uptake and alteration of bacterial populations as good indicators of improved growth performance of cacao seedlings, indicating a good effect of AMF and biochar applications. The same results were reported on sterilized and unsterilized soils and implied improvement in crop yields by enhanced growth performance and improved soil chemical properties (Aggangan *et al.* 2019a). Relatedly, the growth, nutrient status. and NFB populationin the soil rhizosphere were found to improve when AMF amended soil was combined with biochar from bamboo or sugarcane bagasse and biofertilizer (Aggangan and Jomao-as 2019). To add to this, changes in the diversity of prokaryotes in the rhizosphere of cacao seedlings grown in acidic soil was reported, wherein genera of operational taxonomic units were induced by amendments of AMF and biochar and benefited the overall growth of cacao seedlings through enhanced nutrient cycling (Aggangan *et al.* 2019b).

Challenges Ahead

From an ecological perspective, it is a requisite to emphasize the need to understand the role of AMF and how their utilization can address future demands in maintaining plantations of one of the most important crops of the country, cacao, should sustainable agriculture be the ultimate goal. From the many studies conducted on AMF utilization, specifically in cacao, the authors have seen how the potentials created in these associations relate to many aspects of existing issues of food security and environmental preservation. Threats of food insecurity and environmental degradation due to the use of harmful chemicals and fertilizers can be both mitigated with the potential use of appropriate methods of utilizing AMF to these economically important crops. In the Philippines, relatively few studies have been done to investigate the use of AMF in all aspects of its use and potential. The ecological aspects of cacao-AMF associations are also an unpopular coverage of studies in the country. The need for integrative approaches is emphasized to address the factors that limit the security of implementation of AMF in crops that promote benefits and prevent uncertainties for plant productivity. Three major improvements arise from this review as to the aspects of cacao ecology that need more study in the Philippines (Figure 1).

The first issue is the effect of AMF on soil structure and properties. In varied environments, soil properties are one of the major determinants of plant growth. The addition of AMF requires a thorough knowledge as to the proper conditions where they can stimulate plant growth since the addition of AMF to cultivation systems actually add complexity and is not constantly functioning to mitigate the limitations in plant growth. The addition of AMF adds cost and demand for plants, and it is very important for researchers to determine the soil constraints and atmospheric conditions that affect mycorrhizal impact in plants (Bitterlich *et al.* 2018). For instance, plants with AMF associations are known to be dependent on phosphorus levels but corresponding levels of nitrogen is also a determinant in regulating symbiotic intensity and growth responses (Nouri *et al.* 2014). Consequently, leaf C assimilation is affected by AMF-mediated changes in the host plant (Augé *et al.* 2015). In the Philippines, however, this is lacking especially in cacao agrosystems. The investigation of major elements such as nitrogen, phosphorus, and potassium in cacao-planted soils and how these affect the dynamics of AMF response are needed. Further investigation also on the effects of AMF on soil properties – which is fairly studied across countries (Miller and Jastrow 2000; Leifheit *et al.* 2014), such as on soil aggregation (Bitterlich *et al.* 2018), surfactant effects (Rillig *et al.* 2010), soil microchannels (Miller and Jastrow 2000), and water retention (Bitterlich *et al.* 2018) – is needed in the Philippines. A related issue in agricultural practices that have led to soil degradation and loss of productivity inflates the great need for practices that maintain the fertility of soils with good physical properties. The cost of using fertilizers and pesticides in terms of sustainability often remains unmeasured. These practices often lead to loss of natural ecosystems and hamper the ability of such a system to provide goods and services. It is known that these practices likewise increase nutrients in both ground and surface waters that lead to the degradation of aquatic habitats and soil quality (Tilman *et al.* 2002). One of the major solutions for such problems requires a significant amount of increase nutrient-use efficiency through a variety of practices and innovations, one of which is the utilization of AMF and its widely explored use in increasing nutrient uptake in plants. Studies in the Philippines should be directed towards this step to minimize adverse environmental and economic impacts of the use of fertilizers, and investigate the influence of fungicide residues on soil AMF *in situ* in cacao agroforests.

Another aspect of cacao ecology that can be further explored in the country is the genetic and functional diversity of associated AMF species and how this affects ecological processes that are carried out in the

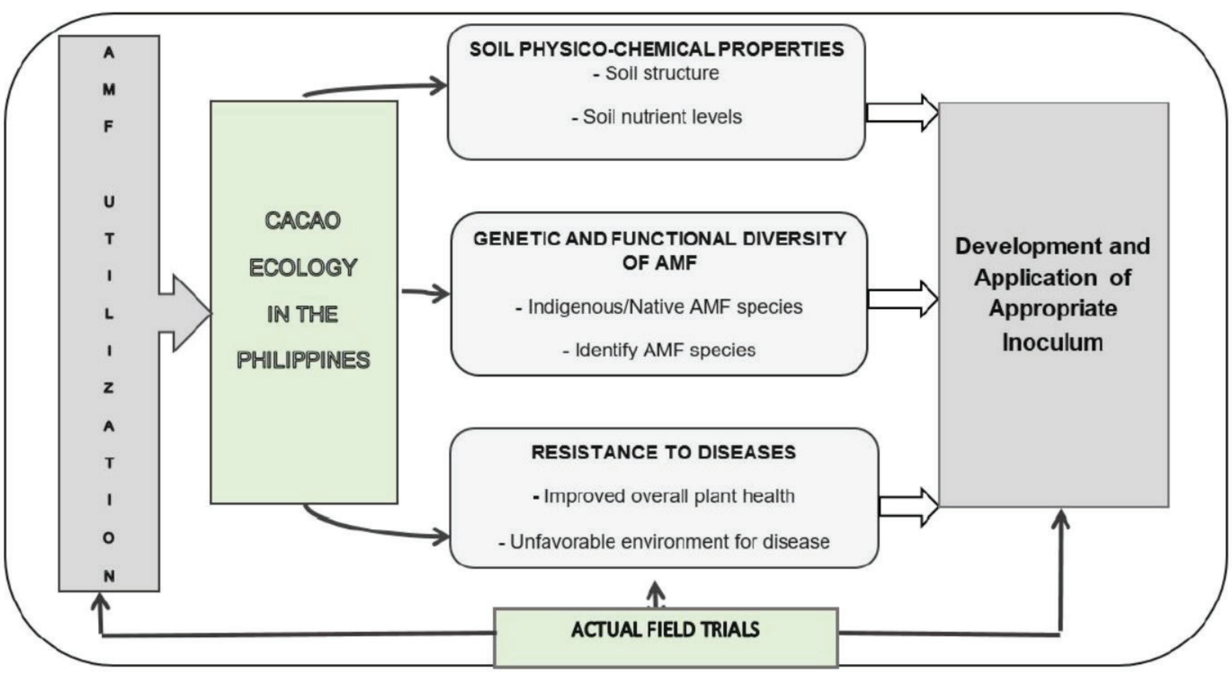

Figure 1. Simplified schematic model showing aspects of cacao ecology that need more study to reinforce the ecological resilience of Philippine cacao agrosystems.

cacao community. Several ecological studies have poor evaluations of AMF functional diversity due to the overlooked importance of co-studying the genetic diversity of AMF. Alarcón *et al.* (2012), in their review, highlighted the same thing by isolating AMF from several regions of the Mexican Republic and expounded in their paper the beneficial effects in the overall study of the different ecosystems and agrosystems in their country. The exploration of genetic variations among AMF species will help explain the different roles they have on several plant species, as well as in terms of their compatibility with host plants (Allen *et al.* 2001). Molecular studies are sufficiently being undertaken (Gómez-Leyva *et al.* 2008; Ortega-Larrocea *et al.* 2010; Kuppusamy 2015; Krishnamoorthy *et al.* 2017), but none so far has been done in the country for AMF species associated with cacao. Furthermore, qualitative and quantitative investigations on AMF species that are specifically useful for cacao plants and their characterization will allow further knowledge on how their interaction with both the host and the variable factors that make up their areas of distribution can be directly useful for the development of suitable inoculum that can optimize beneficial impacts on cacao under varied settings. While the evidence for the ecological importance of AMF is extensive, specific roles of every AMF species are still to be thoroughly explored. The identification and characterization of endogenous and native AMF species may contribute to the largely unknown functional significance of uncultured AMF and explore their impact on ecosystem functioning since individual AMF species are known to affect plant growth variedly, and this can be related to specific matching between AMF and host plants (Streitwolf-Engel *et al.* 1997; van der Heijden *et al.* 1998). Specifically, the quantification of several AMF types is often overlooked aspect but will serve very important information in determining which species are rare and which are abundant, as it is known that the largest impact in an ecosystem is a function of dominant species (van der Heijden and Scheublin 2007). This is yet an underdeveloped aspect of AMF utilization in the country due also to the many challenges posed in AMF identification and quantification.

Lastly, one of the many factors that affect the yield is the presence of crop diseases and pathogens. The role of the environment and the susceptibility of the host in the disease triangle emphasizes the fact that increasing host resistance and manipulating the environment to become unfavorable for disease development is a good measure to prevent losses from crop diseases. Philippine cacao production presently stands only at 10,000–12,000 MT per industry (DA 2017) and was even reported lower by the PSA to be only approximately 6,000 tons in 2015 (DTI 2017), and one of the many factors that have contributed to such decline is the infection of diseases among cacao trees. Several studies have explored the role of AMF in combating cacao diseases. A study by Nana *et al.* (2016) revealed that the simultaneous application of two species of AMF and a natural flavonoid improved the susceptibility flavonoids content were observed resulting in higher tolerance against infection. Another study by Tchameni *et al.* (2011) showed a significant seedling growth of cacao to one of the most devastating diseases it is exposed to, the black pod rot. Improved growth and enhanced biosynthesis of total phenol and increased phosphorus uptake were reported, as well as increased resistance against *Phytophthora megakarya* for cacao seedlings inoculated with two species of AMF (*Gigaspora margarita* and *Acaulospora tuberculata*) or in combination with a saprophytic fungus (*Trichoderma asperellum*). A related study by Tchameni *et al.* (2012) reported a significant decrease in disease severity for cacao seedlings inoculated with AMF species, *Gigaspora margarita*, *Glomus mossae,* and their relatives observed reduction in disease severity to increased synthesis by the leaves of soluble amino acids. The same observations were reported by Herre *et al.* (2007) wherein foliar damage from *P. palmivora* was reduced in cacao, and this was attributed to mycorrhizal associations. The utilization of AMF and its direct effect in increasing plant tolerance to infection of pathogens need to be a study of interest in the country. Surprisingly, very few studies have been conducted on the role of AMF in controlling cacao diseases.

It is also suggested that more actual field trials should be conducted to monitor consistent promising results so as to maximize the adoption of mycorrhizal technology. Very few have been published on actual field experiments especially in the country, as it is very simplistic to assume that one would always get consistent increases in crop yield when AMF is introduced to an already established AMF community (Rodriguez and Sanders 2015). Plus, very little is known to the establishment of AMF as they adapt to varying environmental conditions (Johnson *et al.* 2013).

CONCLUSION

The interactions between plants and their biotic components make up much of how plants can maximize nutrient uptake and tolerate abiotic stress. The association between cacao and AMF is a widely studied field and offers a promising scope of knowledge that will allow the improvement of cacao agrosystems. In the Philippines, further development of suitable AMF inocula, specific for cacao, that can be integrated with existing agricultural technologies is needed in response to the existing need to boost the country's cacao industry. Ecological aspects of this goal can be initiated by identifying and quantifying endogenous species associated with cacao fields, investigating the physicochemical properties of fields to relate these factors to the community of AMF and predict plant responses, and exploring further the use of AMF in hampering the threats posed by diseases in cacao plantations that may affect the overall productivity of these systems. Investigating the ecological aspects of AMF and cacao associations will guide sustainable practices and innovations and minimize environmental degradation.

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