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Spatio-temporal dynamics of the coffee berry borer (*Hypothemus hampei*): proposing a simulation tool for planning management and control strategies at multiple spatial scales

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Summary

Loss of agricultural production due to pest damage is of growing concern due to global climate change, deforestation and agricultural intensification. The coffee berry borer (CBB: *Hypothenemus hampei*; Coleoptera: Curculionidae: Scolytinae) is an important insect pest that affects coffee cultivation and causes great economic losses worldwide, threatening the food security of small coffee farmers who completely depend on that crop. Control strategies against this pest are focused on the plot level and the landscape context is globally ignored. However, the landscape and the degree of connectivity might play an important role in the spread of the pest and should be considered in control strategies from a holistic approach. In this thesis, we set out to develop a *Spatio-temporal dynamics of the coffee berry borer: proposing a simulation tool for planning management and control strategies at multiple spatial scales.* This work arises because of the need to integrate the empirical and local knowledge of farmers in a simulator that serves as an effective tool for making informed decisions in the management of the CBB.

During the literature review, we realized the paucity of specific information on the interactions between landscape and CBB management. Therefore, we set out to ask questions and design studies to understand the mechanisms that act at different scales and how these can influence the incidence of CBB in coffee plantations. Our approach focused on considering CBB management beyond the plot and examining interactions between plot management characteristics and the surrounding landscape on pest dynamics. To achieve this, we carried out a series of field work, including *Assessing the joint effects of landscape, farm features and crop management practices on berry damage in coffee plantations*; studies on *Interactions between landscape connectivity and pest management*; and studies to *Quantify the movement of the Coffee Berry Borer at the interface between coffee plantations and adjacent land uses*. Through these studies, we gained a more complete understanding of the interaction between management, landscape, and the incidence of bored berries.

The results of the three empirical studies suggest the importance of considering the landscape context when searching for management strategies to control CBB. We found consistent evidence that factors operating at the landscape level were as important as those

operating only at the plot scale and that landscape connectivity has a direct effect on incidences of bored berries. Coffee plots, with connectivity in the landscape and that are managed, had a higher incidence of bored berries than the plots that were not connected and managed. In addition, we showed the importance of adjacent land uses in the dispersal of the CBB even though the dispersing CBB population is approximately 4% of the population that moves within coffee plantations.

The results obtained have provided valuable information to understand and think about more effective control strategies adapted to the characteristics of the surrounding landscape. We hope that this work, especially the ABM-CBB, serves to evaluate CBB management scenarios in a collaborative environment with producers. This work seeks to promote the adoption of sustainable management practices to control the pest and to contribute to improving coffee growing in Latin America. Our work should contribute to the advancement of knowledge in the field of the ecology and control of CBB and of other insect pests in general, promoting an ecological sustainability approach in pest management.

Keywords

Agent, agroecosystem, pest management, management strategies, landscape connectivity, dispersal, farm

Résumé

La perte de production agricole due aux dommages causés par les ravageurs est de plus en plus préoccupante en raison du changement climatique mondial, de la déforestation et de l'intensification de l'agriculture. Le scolyte des baies du caféier (CBB : *Hypothenemus hampei* ; Coleoptera : Curculionidae : Scolytinae) est un insecte ravageur important qui affecte la culture du café et provoque d'importantes pertes économiques dans le monde entier, menaçant la sécurité alimentaire des petits producteurs de café qui dépendent entièrement de cette culture. Les stratégies de lutte contre ce ravageur se concentrent à l'échelle de la parcelle et le contexte paysager est globalement ignoré. Cependant, le paysage et le degré de connectivité peuvent jouer un rôle important dans la propagation du ravageur et devraient être pris en compte dans les stratégies de contrôle à partir d'une approche holistique. Dans cette thèse, nous avons entrepris de développer un outil de simulation de la dynamique spatio-temporelle du scolyte des baies du caféier pour planifier des stratégies de gestion et de contrôle à plusieurs échelles spatiales. Ce travail découle de la nécessité d'intégrer les connaissances empiriques et locales des agriculteurs dans un simulateur qui serve d'outil efficace pour prendre des décisions éclairées dans la gestion du scolyte du caféier.

Au cours de l'analyse de la littérature, nous nous sommes rendu compte du manque d'informations spécifiques sur les interactions entre le paysage et la gestion du scolyte. Nous avons donc entrepris de poser des questions et de concevoir des études pour comprendre les mécanismes qui agissent à différentes échelles et comment ils peuvent influencer l'incidence du scolyte dans les plantations de café. Notre approche a consisté à considérer la gestion du scolyte au-delà de la parcelle et à examiner les interactions entre les caractéristiques de la gestion de la parcelle et le paysage environnant sur la dynamique du ravageur. Pour ce faire, nous avons réalisé une série de travaux sur le terrain, notamment pour évaluer les effets conjoints du paysage, des caractéristiques de l'exploitation et des pratiques de gestion des cultures sur les dommages causés aux baies dans les plantations de café. Nous avons aussi conduit des études sur les interactions entre la connectivité du paysage et la gestion des ravageurs et des études visant à quantifier le mouvement du scolyte des baies du caféier à l'interface entre les plantations de café et divers usages des

sols adjacents. Grâce à ces études, nous avons acquis une compréhension plus complète de l'interaction entre la gestion, le paysage et l'incidence des baies scolytées.

Les résultats des trois études empiriques suggèrent l'importance de prendre en compte le contexte paysager lors de la recherche de stratégies de gestion du scolyte. Nous avons trouvé des preuves cohérentes que les facteurs opérant au niveau du paysage sont aussi importants que ceux opérant uniquement à l'échelle de la parcelle et que la connectivité du paysage a un effet direct sur l'incidence des baies scolytées. Les parcelles de caféiers qui sont connectées au sein du paysage et qui sont gérées ont une incidence plus élevée de baies scolytées que les parcelles qui ne sont pas connectées mais qui sont gérées. En outre, nous avons montré l'importance de l'utilisation des terres adjacentes dans la dispersion du CBB, bien que la population de CBB qui se disperse représente environ 4 % de la population qui se déplace à l'intérieur des plantations de café. Les résultats obtenus ont fourni des informations précieuses pour comprendre et réfléchir à des stratégies de lutte plus efficaces et adaptées aux caractéristiques du paysage environnant. Nous espérons que ce travail, en particulier l'ABM-CBB, servira à évaluer des scénarios de gestion du scolyte dans un environnement de collaboration avec les producteurs. Ce travail vise à promouvoir l'adoption de pratiques de gestion durables pour lutter contre le ravageur et à contribuer à l'amélioration de la culture du café en Amérique latine. Notre travail devrait contribuer à améliorer les connaissances dans le domaine de l'écologie du CBB et notamment de sa gestion et de celle de d'autres insectes ravageurs en général, en promouvant une approche écologique et durable.

Mots clés

Agent, agroécosystème, lutte contre les ravageurs, stratégies de gestion, connectivité du paysage, dispersion, exploitation agricole

I. Introduction

Pests are a constant threat to the food security of smallholders due to losses in agricultural production, with devastating economic impacts, especially in regions where agriculture is an important source of income. Savary et al., (2019), estimate global annual crop losses due to pest between 17 and 23%in wheat, maize, rice, potato, and soybean crops. Agricultural intensification with large extensions of monoculture, and the constant use of pesticides have altered the ecological balance of production systems, favoring the adaptation of pests and expanding their distribution areas, which is reinforced by the global exchange of products and global warming (Anderson et al., 2004; IPCC Secretaria, 2021; Savary et al., 2019).

Alternatives to counteract the use of agrochemicals in pest and disease management resulting from the rapid intensification of modern agriculture (Tilman et al., 2002) have been developed. These management alternatives aim at reducing the ecological, social, and economic impact of conventional pest management based on pesticide use. Integrated pest management (IPM) is an alternative to the use of pesticides marked at economically permissible damage thresholds for their control (Elliott et al., 2008; Metcalf & Luckman, 1975), IPM is directed towards holistic management that allows incorporating different spatial scales focused on different management approaches such as host resistance, biological control, cultural practices, physical or mechanical control, trapping, in addition to chemical management. Ecological intensification should be incorporated into the IPM which requires optimal management of ecosystem functions and biodiversity to reduce the impact of pesticides and pest control.

To implement management alternatives such as ecological intensification, a large body of knowledge is produced and supports the importance of biodiversity conservation and of the associated ecosystem services for pest control (Bianchi et al., 2006; Sánchez et al., 2022). Recognizing the role of landscape configuration and composition in the provision of ecosystem services provided by biodiversity associated with crops and adjacent land uses (Estrada-Carmona et al., 2022; Gámez-Virués et al., 2012; Kebede et al., 2019; Perovic et al., 2010; Qiu, 2019) it is likely pest management must consider multiple spatial scales.

1. Landscape ecology: An essential tool in pest management

The inclusion of multiple spatial scales and the acknowledgment that landscape complexity plays an important role in pest management, favor the use of the entire methodological body of landscape ecology (Rusch et al., 2011). Landscape ecology is a discipline that focuses on the study of the interactions of the spatial patterns of ecosystems (natural or anthropogenic; structure) at different scales, their processes (functions), and the landscape changes (Forman and Godron, 1986; Turner, 1989).

1. 1 Landscape metrics

Landscape metrics have been developed to quantify landscape structure and change, and they are usually grouped into composition and configuration metrics. Composition metrics are not spatially explicit and can be measured at the class (land use) or landscape level and represent the variety and abundance of elements that shape the landscape (Turner and Gardner 2015). Configuration metrics are spatially explicit and can be measured at the patch, class, or landscape level and represent the spatial characteristics and distribution of the elements (Gustafson and Parker, 1998; McGarigal and Marks, 1995).

At the patch level, the metrics are individually defined for each landscape element (e.g., area, shape). At the class level, metrics are defined for all landscape elements of the same type, along with additional properties that result from the spatial configuration of these elements of the same type (e.g., average distance). At landscape level: metrics are calculated on the whole landscape with additional properties resulting from the spatial configuration of all the elements that compose it (e.g., diversity).

An important concept in landscape ecology is the matrix. The matrix refers to the most connected and extensive class (land use) in the landscape. The matrix influences the connectivity, the mobility of the species and the dynamics of the different classes that make up the landscape (Forman and Godron, 1986).

Both components of landscape complexity, composition and configuration, should be considered to assess how they contribute additively or interactively to pest suppression (Haan et al., 2020) and contribute to management practices. A variety of composition and configuration metrics have been used to assess the relationship between pests, natural enemies or control strategies with landscape complexity (Chaplin-Kramer et al., 2011)..

Metrics of landscape composition are usually used to understand the response of natural enemies or pests. They generally correspond to the proportion of crops or other land uses (natural or semi-natural habitats), but metrics of landscape diversity such as Shannon's diversity index, Simpson's or Shannon's equity, and heterogeneity index are also often used as a measure of landscape composition that combines the types of land uses (or crops) and their proportion (crop diversity) around a focal crop (Aristizábal and Metzger, 2019; Kebede et al., 2019; Nicholson and Williams, 2021; Ricci et al., 2019; Rusch et al., 2013; Sánchez et al., 2022; Vilchez-Mendoza et al., 2023).

In the other hand, the most used configuration metrics are edge density (edge length per unit area), contagion (a measure of the degree to which landscape elements cluster together, with higher values resulting from landscapes with a few large, contiguous patches, and lower values from landscapes with small and dispersed patches is same a high fragmentation) (Figure 1), grain index (a measure of the degree of openness of the landscape), and different aggregation indices (Beasley et al., 2022; Martin et al., 2013). Metrics that measure landscape complexity are usually related to the abundance or diversity of natural enemies, presence or abundance, and pest damage (p e., Aristizábal & Metzger, 2019; Kebede et al., 2019; A. Rusch et al., 2013).

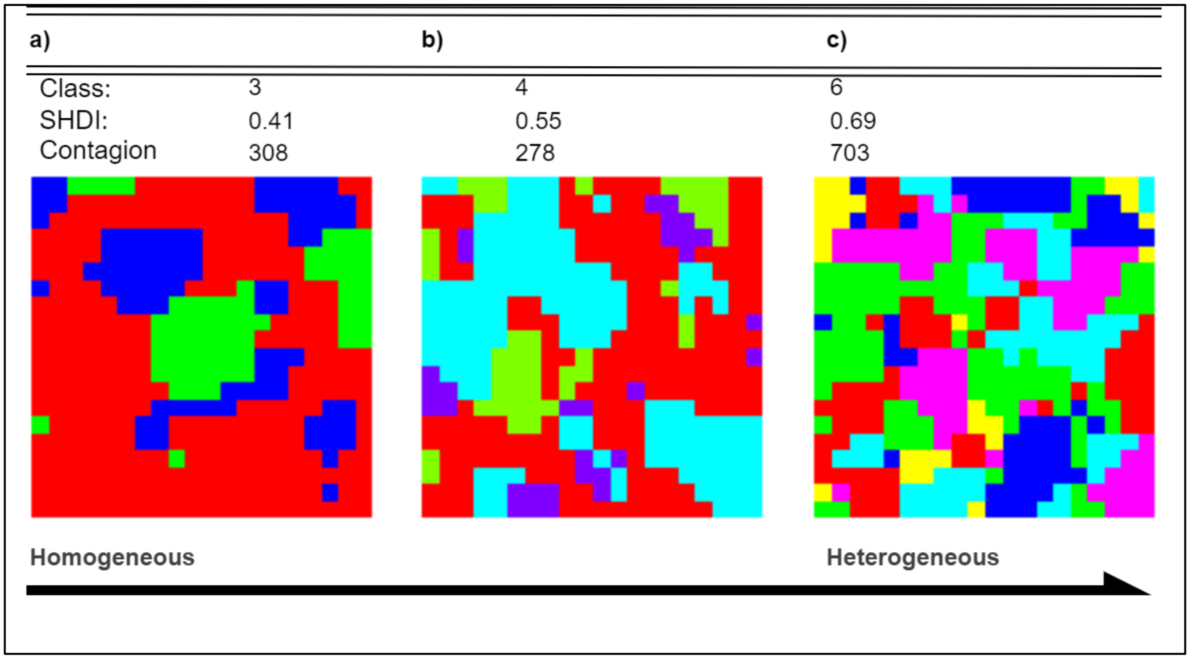

Figure 1. Landscape complexity gradient where the colors represent the different classes (land uses) that make up the landscape. a) The figure shows a complexity gradient from ***a*** *to* ***c*** *and three landscape-level metrics that measure configuration and composition. The number of classes in the landscape is a simple measure of landscape composition. In contrast, the form and arrangement (e.g., contagion) is a measure of landscape configuration.*

Usually, measures of landscape complexity (configuration and composition) are calculated based on a land use map, where concentric circles with a fixed radius around the focal patches are generated. The radius of these buffers is typically considered based on knowledge of the biology of the species, mainly on its dispersal capacity as a function of the perception of the pest or natural enemy to its environment (Haan et al., 2020). In some cases, concentric circles of different radii are used to assess the perception of the pest to different landscape features measured at different scales (Thies and Tscharntke, 1999). Studies considering multiple scales have shown that that specialist pests or natural enemies are often influenced at smaller scales than generalist species (Chaplin-Kramer et al., 2011) (See chapters 1 and 2).

1. 2 Landscape ecology and crop pest regulation

Hypotheses have been proposed to explain the relationships of pest and natural enemies with landscape complexity

The **resource concentration hypothesis,** Root (1973), is focused on crops and proposes that polycultures reduce the density of specialist herbivores by interrupting olfactory signals. This mechanism of irruption to the olfactory signals of herbivores may be true for those with low dispersal capabilities. However, when the pest has long dispersal capabilities, irruption by crop diversity may not be sufficient to reduce its densities in the crop of interest. O'Rourke & Petersen, (2017), consider that the Root's resource concentration hypothesis (may contribute to clarifying the role of landscape complexity. They propose that in more complex landscapes additional interconnected mechanisms increase the difficulty of dispersal and the risk of pest mortality, directly suppressing pest densities in comparison to less complex landscapes, Furthermore, these authors propose that greater dispersal may have a higher energetic cost by decreasing the physical capacity of herbivores depending on their biological characteristics (diet, habitat specialization, strategies, and dispersal ability) (O'Rourke & Petersen, 2017).

Pest suppression at landscape scales may also be due to mechanisms beyond the role of natural enemies **(enemy hypothesis)**. Theres is increasing evidence that landscape complexity can contribute to pest control and favor the persistence of natural enemies (pest control ecosystem service) and other organism (e.g., associated services pollination) (see Chaplin-Kramer et al., 2011; Karp et al., 2018; Tscharntke et al., 2016; Veres et al., 2013), but the mechanisms that explain the relationships of pests and natural enemies with the complexity of the landscape are still not clear and may be complex to evaluate. Tscharntke et al., (2016), suggest different hypotheses to understand why natural habitats around crops may not contribute to improve biological pest control in agriculture:

1) it may be a product of the abundance and diversity of prey for natural enemies (**prey diversity hypothesis**)

2) natural enemies may have sufficient refuge and resources in crops (**refuge hypothesis**)

3) the edge effect is negative for natural enemies, as an inverse response to the spillover hypothesis (**edge effect hypothesis**)

4) there is a lack of landscape connectivity between the crop and natural habitats (**connectivity hypothesis**)

5) biological pest control may respond to mechanisms suggested by the resource concentration hypothesis extended to landscape context (O'Rourke and Petersen, 2017) for natural enemies (**enemy hypothesis**)

6) the spatial and temporal context hypothesis, which indicates that factors such as spatial scale and ecological interactions, may influence the effectiveness of natural habitats for pest control.

Currently, there is a need to better understand the interconnected mechanisms between landscape complexity, natural enemies, and pests, based on functional diversity approaches to trophic interactions and spatiotemporal variations of pests and natural enemies (Haan et al., 2020; Karp et al., 2018; O'Rourke and Petersen, 2017; Tscharntke et al., 2016). It is also important to understand how management practices associated with the studied crop and surrounding crops (e.g., agrochemical application, biological, mechanical, or cultural control), and landscape complexity can modulate pest control.

1. 3 Landscape connectivity and pest management

Pests and natural enemies use the landscape to move (disperse) in search of resources or colonize new habitats. The ease with which they can move through the landscape is known as landscape connectivity (Merriam 1984). Understanding how the complexity of the landscape (composition and configuration) facilitates the movement of organisms is fundamental to management plans. The direction of relationships between connectivity and ecosystem service provision will depend on the service in question. For example, pest regulation should increase as predator movement across the landscape also increases, and therefore reduced landscape connectivity for a pest or a disease vector may increase pest and disease regulation (Mitchell et al., 2013).

Kindlmann & Burel, (2008) consider that connectivity should be seen as a function of the degree of complexity of the landscape and the characteristics of the organism. In fact, the dispersal capacity of a species is not a constant trait but depends on the complexity of the landscape and the availability of resources (Goodwin and Fahrig, 2002) and therefore depends on the response of the organism to the structure of the landscape.

Arthropods move specifically in the landscape due to olfactory cues that induce dispersal and cause directed movement driven by resource availability. Physical constraints imposed on movement by the internal structural complexity of the patch or landscape, act as a barrier to limit olfactory signals, and increase energy expenditure the presence of predators. Harnessing wind action to transport, as well as patch or landscape complexity may impede wind action to pests' movement. Risk of injury or death (physical attrition or high predation pressure) may require movement behavior aimed at minimizing risks (Gámez-Virués et al., 2012; Goodwin and Fahrig, 2002; O'Rourke and Petersen, 2017). These mechanisms are mainly influenced by the landscape matrix, given that they facilitate or impede movement, and even facilitate predation.

Metrics that measure landscape complexity and often used as proxies for landscape structural connectivity, e.g., edge density (Martin et al., 2013), contagion index, grain index (Vilchez-Mendoza et al., 2022), or number of patches which measures the degree of landscape fragmentation, or the distance from the focal crop to other patches of the same crop or different land uses (e.g., semi-natural habitats) (Aristizábal and Metzger, 2019; Berger et al., 2018). This approach is limited for the understanding of mechanisms that stimulate pest movement, as these metrics do not consider the organism's dispersal ability or how they perceive the landscape matrix. The lack of linking landscape complexity and physical characteristics of organisms (e.g., dispersal ability) in studies assessing the role of landscape connectivity may be insufficient for predicting the movement of organisms and may even lead to erroneous conclusions about the role of the landscape in facilitating or impeding the movement of organisms (Goodwin and Fahrig, 2002; Minor and Urban, 2008).

Different metrics and tools have been developed to specifically measure or evaluate landscape connectivity that consider the dispersion capacity of the pest or natural enemies or how they perceive the landscape matrix. These metrics are separated into structural (connectivity as a function of the landscape; metrics based on minimum cost trajectory models) or functional (connectivity as a function of landscape and organism movement ability; based on graphs).

1. 4 Approaches to measure landscape connectivity

The measurement of landscape connectivity are indispensable tools for the development of pest management plans at multiple spatial scales. On the one hand, the modeling of landscape connectivity can improve the understanding of how landscape connectivity can favor or not the arrival of natural enemies or pests, which landscape elements can be intervened to favor or not connectivity in the landscape, which habitats can generate resistance in the movement of pests (Moreno et al., 2022) or useful tools to identify the specific areas for (e.g, application of insecticides) (Guo et al., 2022). On the other hand, the use of landscape connectivity indices based on these methods can be estimated around a focal patch using concentric circles to relate them to characteristics of pest and natural enemy populations measured in the focal patches, like the analysis approaches used to assess the relationship of landscape complexity. Landscape connectivity can be measured based on a graph or circuit theory.

1. 1. 1. Graph theory

To improve the understanding of landscape connectivity, metrics based on graph theory, also known as network analysis, have been developed to functional connectivity mo(Bunn et al., 2000; Laita et al., 2011; Minor and Urban, 2008; Pascual-Hortal and Saura, 2006)Galpern et al 2011. A graph or network models the relationships among patches of habitat and is composed of nodes (patches) and edges (links; landscape matrix). Nodes represent patches of habitat defined for a focal species, and edges represent connections among nodes, which suggest the potential for movement or dispersal of a focal species, being nodes connected by links when distance (Euclidean or cost distance) between them is below some ecologically relevant movements threshold for the organisms (Galpern et al. 2011). Patch-based graphs are models of functional connectivity because their links represents a functional response of the organisms of the landscape, rather than structural features of the landscape or as corridors (Galpern et al. 2011). A wide range of metrics can be calculated for each graph to characterize the connectivity of the entire graph (global level), of its subparts (component level) or of its basic elements (nodes and links) (Galpern et al 2011, Foltête et al 2021; Pascual-Hortal and Saura, 2006). For example, measure of connectivity for the entire graph may be the number of components (set of connected nodes) in the graph, at component level the number of connected nodes or total area in those connected nodes, at node or link level metrics exists that quantify the different ways in which individual landscape elements can contribute to overall habitat connectivity and availability in the landscape(Minor and Urban, 2008; Pascual-Hortal and Saura, 2006) Galpern et al 2011. The estimation of functional indices requires information on the dispersion capacity of the organism under study.

1. 1. 2. Circuit theory

McRae et al., (2008) propose to apply circuit theory to assess landscape connectivity. Circuit theory is based on considering an organism as random walkers; it assumes that individuals moving through a landscape do not know relative resistance beyond their immediate surroundings (Dickson et al., 2019; Laita et al., 2011; McRae et al., 2008). The circuit structure is similar to graphs, but edges (landscape matrix) are replaced by resistors, which area function of the probability of movement of the organism between patches to be connected (conductance or resistance), i.e. represent the ease of movement or the number of dispersers exchanged between nodes (Bunn et al., 2000). Moreover, circuit methods incorporate multiple pathways connecting nodes (multi graph approach),

Circuit-based connectivity modeling only requires a raster that identifies the patches to be connected (nodes) and a raster that defines the matrix in terms of resistances or conductance resistance represents the isolation or cost of movement between patches, while conductance is the inverse of resistance.

Connectivity measures in circuit theory are simple: they can indicate the travel time of a random walker and show how effectively the surrounding landscape configuration routes dispersal between origin and arrival patches (resistance distance), the degree of movement expected for random walkers (cumulative current); a high cumulative current indicates a high flux of organisms arriving at the patch (McRae et al., 2008). Following electrical circuit theory, voltage measures the probability that random walkers starting from any patch in the network can arrive at their destination (dispersal success) before others (McRae et al., 2008).

Circuit-based connectivity can serve as an index of functional connectivity and may subsequently be correlated with indicators of natural enemies or pests at the focal plot level, such as their abundance or the degree of damage caused. One approach is to estimate the amount of accumulated current (representing the number of organisms arriving at the patch) or voltage (representing the probability of arrival) around the focal plot using a concentric circle. This can be a valuable metric for understanding the dynamics of natural enemy and pest populations.

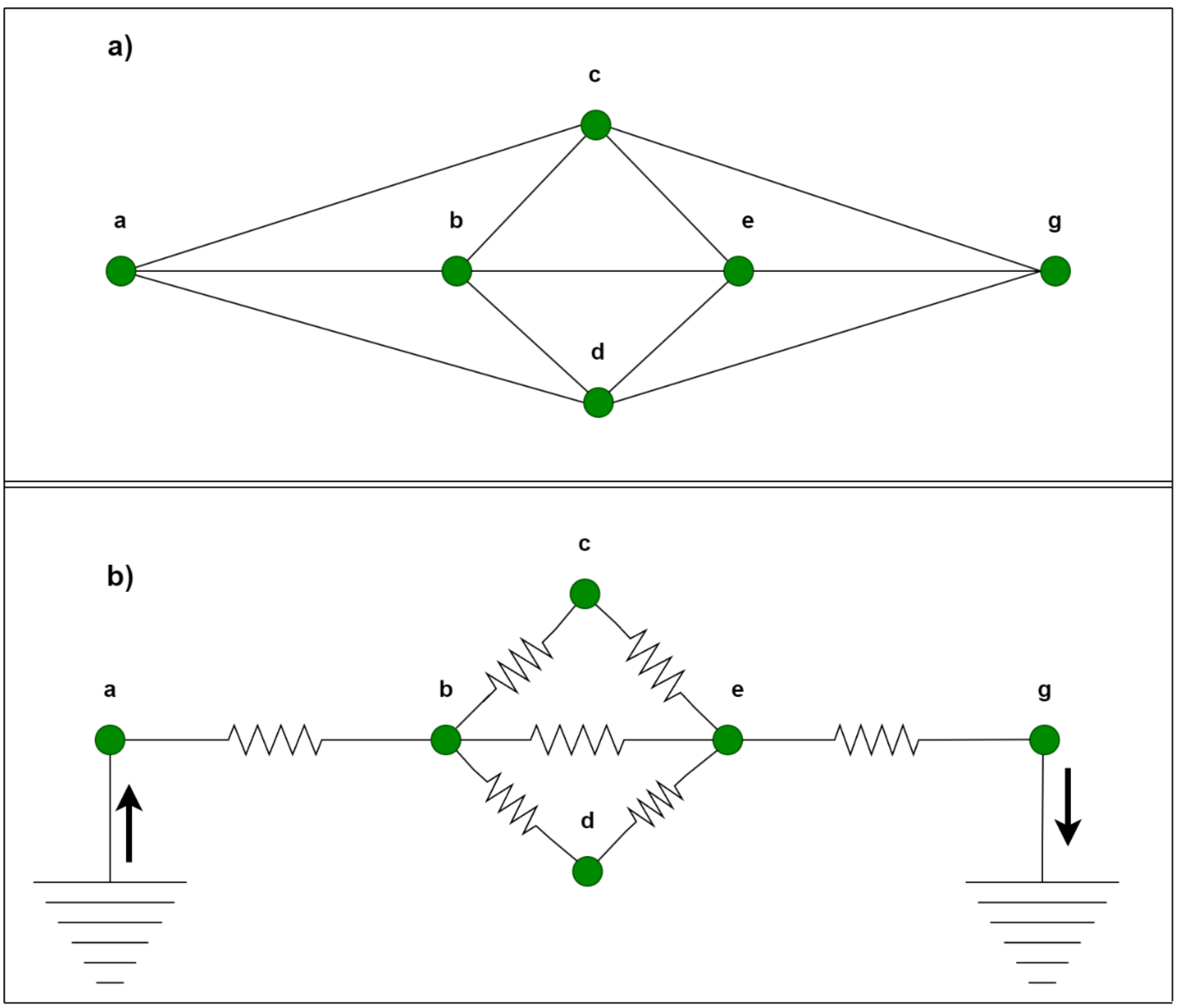

Figure 2. Approach to measure landscape connectivity. a) representation of a graph defined by six nodes (a,b,c,d,e,f) and 11 links (ab, ac, ad, bc, bd, be, ce, cf, de, df, ef) y b)

*representation of a circuit with **a** current source at node and with node **g** connected to ground. The nodes represent the random walk of currents with resistors in their movement.*

The methodological body of landscape ecology and the development of specific metrics tools to measure connectivity can contribute to improving the management approach historically focused on a plot scale, and design management plans that consider the spatial scale, the landscape elements that contribute to facilitating the flow of natural enemies and preventing the movement of pests (Schellhorn et al., 2015). In this context, it is possible to reexamine the sizes of cultivated plots, the distance between cultivated plots and redesign homogeneous agricultural landscapes into heterogeneous landscapes that allow reducing damage caused by pests, minimizing management costs and the use of pesticides in favor of well-being of producers and the environment.

2. Agent based modelling

The knowledge generated by understanding the effect of the landscape (configuration and composition) on pests and natural enemies can contribute to considering actions to modify certain elements of the landscape that favor natural enemies and reduce the impacts of pests or diseases. However, studying or applying pest or disease management at multiple spatial scales (plant, plot and landscape) is not an easy task given the multiple interactions that can emerge from these complex agrolandscapes and external factors that influence its spatiotemporal dynamics (Rebaudo et al., 2014; Rebaudo and Dangles, 2015). Management decisions depend on the owners of the fields, the economic benefit they perceive, and the social relationships between them (e.g., the decisions of a farmer to manage his crop may depend on the management decisions of his neighbors or vice versa), relationships with the environment and external factors (e.g., market, public policies).

Understanding the interactions that arise from these complex systems can be studied or evaluated through simulations of simplified representations of the system under study. In simulation models, farmers' management decisions can be evaluated considering the environment to seek plausible solutions to control pests and diseases; empirical knowledge and farmers' experience can also be incorporated into them. A powerful simulation tool is agent-based modeling (ABM). This is an ideal methodological framework for the study of pest management at multiple spatial scales developed in a virtual environment, allowing complex systems to be represented (Liu et al., 2016; Rebaudo et al., 2014; Rebaudo and Dangles, 2013).

Agent-based models (ABMs) are a set of autonomous entities called agents that act by constraints or rules and that interact with each other in a dynamic environment (Bousquet and Le Page, 2004), resulting in changes in the global dynamics of the system. Agents do not have an assigned control hierarchy and can self-organize, based on intra- and interspecific interactions, adjusting their behavior based on changing environmental conditions.

ABMs are a bottom-up simulation approach that can represent complex systems and capture non-linear relationships or interactions, offering greater realism, detail and adaptability, characteristics that differentiate them from equation-based simulation models (Bommel et al., 2016).. However, the non-representation of ABM through mathematical expressions (equations) makes it difficult to communicate, creating a kind of "black box" for many researchers and a limitation for its reuse (Grimm et al., 2006). To clarify and improve the communication of ABMs in the scientific literature, Grimm et al., (2006), propose a standard protocol to describe ABMs in a series of guidelines with a logical order (Polhill et al., 2008). The protocol called ODD (Overview, Design concepts, and Details) has had rapid adoption in the scientific community (Grimm et al., 2020, 2010). The use of Unified Modeling Language (UML) can be a useful tool to graphically accompany the description of the ODD using diagrams that represent the structure of the ABM or the dynamics of the system (Bommel et al., 2016; Muller and Bommel, 2007).

The articulation between empirical knowledge and the experience of farmers for the search for management alternatives for the coffee berry borer (CBB) at landscape level beyond the plot scale is framed in this research through empirical research and the development of an ABM in coffee landscapes of Central America. The ABM has proven to be an excellent tool for the simulation of complex socio-ecological systems, due to its flexibility in considering the producer, the crop, and pests as agents that interact with each other and their environment (Lustig et al., 2019; Rebaudo et al., 2014; Rebaudo and Dangles, 2015, 2013).

3. Case study: Coffee berry borer management in Central America

3. 1 The coffee cultivation

Coffee cultivation originated in Ethiopia and is currently grown in more than 60 countries in tropical and subtropical regions. It is an important agricultural activity in many parts of the world, especially in tropical countries such as Brazil, Colombia, Vietnam, Indonesia, and Ethiopia, among others. Two species of coffee are cultivated: Arabica coffee (*Coffea arabica*), considered of higher quality with approximately 62% of the total coffee production, but susceptible to diseases, and Robusta coffee (*Coffea canephora*), with greater resistance to disease and lower quality. Coffee cultivation requires an average annual temperature between 18-28 °C and annual rainfall of around 1500 mm, although this varies according to the variety and the place of cultivation. Specifically, *Coffea arabica* grows at an altitude of between 600 and 2000 meters and development from bud to fruit takes place in several stages and lasts between 8 and 9 months.

Currently, coffee farmers face challenges or this crop cultivation, including price volatility (Avelino et al., 2015; Jha et al., 2011), diseases and pests, and climate change (Avelino et al., 2015; Bilen et al., 2023). Because vegetative growth, flowering and fruiting are closely linked to climatic conditions, increase in temperatures die to climate change threatens the food security of many families that depend on the crop by reducing the optimal production conditions (loss of yields) and increasing the incidence of pests such as the coffee berry borer (CBB), which is increasingly present in areas where previously it was limited by low temperatures.

It is estimated that around 25 million households depend on coffee cultivation (Vega et al., 2003). Approximately, 70% of the cultivated area is managed by smallholders with areas less than 10ha (Jha et al., 2011). About 41% of the coffee area is estimated to be managed without shade, 35% with sparse shade, and only 24% with diversified shade (Jha et al., 2014). In Central America, the coffee activity is carried out by small farmers (less than

7ha), with very few inputs due to their low economic resources (Avelino et al., 2015). Most of the coffee growing system is associated with shade trees and depends on the objectives of the coffee farmers. The diversity of coffee plantations varies from low shade level and simplified systems (only one species associated to coffee) to coffee plantations with 60% shade and diversified with many associated tree species (Figure 3). Commonly coffee farmers select shade trees for their benefits (i.e., nutrients, wood, or fruits).

Shaded coffee plantations are often referred to as coffee agroforestry systems. These agroforestry systems can provide habitat for a wide variety of plant and animal species, including natural enemies of pests and diseases (Armbrecht and Gallego, 2007; Johnson et al., 2010; Larsen and Philpott, 2010; Martínez-Salinas et al., 2016; Perfecto and Vandermeer, 2006). Trees in the system can augment nutrients, regulate microclimatic conditions, improve the quality of coffee berries, and provide farmers with multiple sources of income (Haggar et al., 2011; Koutouleas et al., 2022; Padovan et al., 2018; Youkhana and Idol, 2010).

Regarding coffee pest and diseases, in recent years, Central American countries have been confronted with an epidemic of coffee rust, a fungal disease caused by *Hemileia vastatrix* Berk and Broome (*Basidiomycota*, *Pucciniales*) that affects coffee leaves. Worldwide, coffee production is also heavily affected by the coffee berry borer (CBB), *Hypothenemus hampei* Ferrari (Coleoptera: Curculionidae).

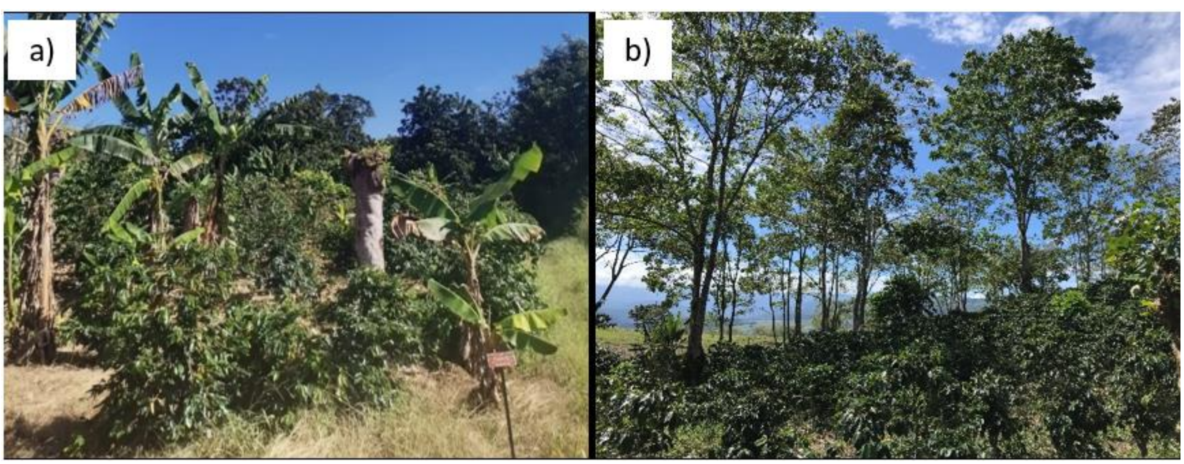

Figure 3. Coffee agroforestry system. a) the coffee with association of poró trees (Erythrina sp.) b) coffee with association of laurel (Cordia alliodora).

3. 2 The Coffee berry borer the most important pest of coffee

3. 2. 1. Losses and danger

The coffee berry borer (CBB) (*Hypothenemus hampei*; Coleoptera: Curculionidae: Scolytinae) a small beetle native to Africa, is the most important pest in coffee cultivation, found in all producing regions (Baker et al., 1992) and causing losses of around US$500 million (Vega et al., 2002). The CBB perforates the coffee berry, to reproduce in the endosperm, causing the premature drop of the berry, loss of fruit quality and even total loss.

3. 2. 2. Coffee berry borer biology

The coffee berry borer (CBB) perforates the berry when it reaches 20% of dry weight, creating galleries in the endosperm (Bergamin, 1943; Jaramillo and Guzmán, 1984; Ruiz-Cárdenas, 1996; Salazar et al., 1994). It is known that the CBB prefers berries with a dry weight higher than 27% (150 days after flowering) and they start oviposition 4 or 5 days after fruit colonization. The CBB goes through four main stages of development (egg, larva, pupa and adult) inside the berry, lasting approximately 28 to 34 days. The egg stage corresponds to the 13% of their development time, while 41% corresponds to the larva stage. At the larva stage the CBB feeds on the endosperm of the berry causing damage or total loss. Then the pupal stage lasts 28% of the development time, while the immature adult stage corresponds to the 16% of the development time, before becoming sexually reproductive adults (Baker et al., 1992a; Bergamin, 1943; Damon, 2000; Jaramillo et al., 2009b; Mendes, 1949)

At the adult stage males can live between 20 and 87 days, while females can live an average of 157 days (Baker et al., 1992a). The male to female ratio is 1:10 (Ruiz-Cárdenas, 1996). Males are smaller, have atrophied wing muscles, and remain inside the berry all their lives (Bergamin, 1943; Damon, 2000). The females have developed wings facilitating their dispersal, and they are responsible for the colonization of berries. Females are able to oviposit from 31 to 74 eggs, and have between 2 to 9 generations in a single berry if they are not removed (Bustillo Pardey, 2006; Damon, 2000; Jaramillo et al., 2009).

When the female CBB emerges from the berry, it disperses in search of olfactory signals to find berries with a higher content of volatile compounds (Ruiz-Diaz et al., 2023) and later integrates the visual stimuli (color, shape, and size) to select a suitable berry (F. Mathieu et al., 1997). It is presumed that once a coffee berry borer colonizes a berry it releases pheromones exerting a greater attraction to the rest of the dispersing females (Mendoza Mora J.R, 1991; Rainho, 2015), explaining the aggregation patterns of the affected berries found in the field (Baker, 1984). Colonization can occur in a generation of berries from the same infected plant, between berries from different plants (Baker, 1984), or disperse to new coffee plantations. The CBB can disperse freely or by wind action, reported dispersal distances range from 30 m to 348 m (Castaño et al., 2005; Gil et al., 2015; Leefmans, 1923) (See figure 3 in chapter 4).

3. 2. 3. Relationship of the coffee berry borer with environmental variables

The environmental temperature is the most important factor in the development of the CBB. It determines the reproduction pattern and accelerates physiological processes: for each degree centigrade that the temperature increases, the development time is shortened by an average of three days, generating a greater amount of generations in less time (Azrag et al., 2020; Baker et al., 1992; Bergamin, 1943; Damon, 2000; Jaramillo et al., 2009, 2011; Mendes, 1949). The thermal amplitude of the CBB is between 15 and 32°C, with an optimum of 25°C (Azrag et al., 2020; Jaramillo et al., 2009a). The CBB can survive outside its thermal range, however, its development stops, and it cannot oviposit. On the other hand, relative humidity is related to the fertility of the CBB; maximum fecundity is recorded between 90 and 93.5% relative humidity. In addition, relative humidity stimulates emergence to search for new berries when it exceeds 90% RH (Baker et al., 1994; Baker et al., 1992).

Precipitation is related to the emergence of the CBB. After prolonged periods of drought and rain events causes the massive emergence of the CBB in residual berries from the previous harvest. However, prolonged periods of rain or high rainfall can cause their death, inducing the decomposition of the endosperm of the berries.

3. 2. 4. The coffee berry borer and agroforestry systems

Tree shade in coffee systems has been a matter of controversy regarding berries infestation and CBB population densities. Some authors have documented a higher incidence of infested berries in coffee plantations with shade than in full sun (Bosselmann et al., 2009; Mariño et al., 2016; Oliva et al., 2023; Teodoro et al., 2008), while other authors do not record differences (Monterrey, 1991; Soto-Pinto et al., 2002), or a greater infestation of berries in full sun than in shade (Johnson et al., 2010). Regarding CBB populations inside the berries, it has been observed that coffee plants under shade register a lower CBB population inside the berries than in full sun (Bagny Beilhe et al., 2020; Mariño et al., 2016), while (Oliva et al., 2023) find opposite results.

The contradictions or antagonism generated by tree shade on the incidence of bored berries and CBB populations (Bagny Beilhe et al., 2020; Mariño et al., 2016; Sanchez et al., 2012), may be due to a mixture of factors, including the environmental conditions of the coffee-growing areas and the different architectures of the agroforestry systems in terms of tree composition, density, shade management, height and canopy opening (Merle et al., 2022; Staver et al., 2001). The synergies generated in agroforestry systems favor the production of larger and heavier grains than in systems under full sun (Bosselmann et al., 2009; Bote and Struik, 2011), generating a greater attraction of the CBB to colonize larger berries, but also, shade trees contribute to the presence of natural enemies (Aristizábal and Metzger, 2019; Armbrecht and Gallego, 2007; Karp et al., 2013; Kellermann et al., 2008; Martínez-Salinas et al., 2016; Perfecto et al., 2004; Philpott et al., 2009). Shade trees in agroforestry systems also contribute to the regulation of environmental temperature and relative humidity, two environmental variables that directly influence the biology of the CBB (Damon, 2000). It is known that shade trees reduce the environmental temperature between 1 and 8 °C in comparison to coffee plantations in full sun (Barradas and Fanjul, 1986; Jaramillo-Robledo, 2005; Mariño et al., 2016; Siles et al., 2010; Vaast et al., 2006), while relative humidity increases between 5 and 20%(Mariño et al., 2016; Olivas et al., 2023).

Figure 4. Shade gradient in coffee agroforestry systems and its effect on the microclimate. a) coffee in full sun, b) coffee with medium tree shade, c) coffee with high shade. A gradient of structural complexity generated by the trees in the system is also shown.

3. 2. 5. Landscape and coffee berry borer

Information about the relation between the landscape and the CBB is scarce. The importance of the surrounding landscape is recognized in the provision of natural enemies of CBB, e.g., ants and birds (Aristizábal and Metzger, 2019; Armbrecht and Gallego, 2007; Johnson et al., 2010; Karp et al., 2013; Kellermann et al., 2008; Martínez-Salinas et al., 2016; Perfecto et al., 2004; Philpott et al., 2009). Furthermore, it has been suggested that land uses adjacent to coffee plantations can impede or facilitate the movement of CBB (Avelino et al., 2012; Olivas et al., 2009). By understanding the mechanisms that underly the relationships between the CBB and the landscape (e.g., connectivity, refuge or enemy hypothesis), and how it interacts with local-scale factors (plot characteristics and management), we can identify synergies between management and the landscape, that allow the integration of multiple spatial scales for better effectiveness in the management of the CBB for economic benefits to farmers and environmental sustainability.

Figure 5. Coffee plantations surrounded by pastures and forests. Coffee systems in Central America vary between full sun, medium shade and high shade systems.

3. 2. 6. Management of the coffeeberry borer

The management of the CBB is challenging due to its entire life cycle taking place inside the coffee berries. Initially, insecticides like endosulfan and chlorpyrifos were utilized, but their effectiveness was limited as they needed direct contact with the CBB, which only happens when the insect is entering the berry. Furthermore, these agrochemicals pose risks to human health and the environment, leading to their discontinuation (Aristizábal et al., 2016; Villalba-Gault et al., 1995).

Integrated management of the CBB combining different practices, including cultural practices, has been proposed in Latin America (Aristizábal et al., 2016; Benavides et al., 2012; Dufour, 2009). Cultural practices, take place during the harvest and are related to an efficient collection of berries, that is, avoid leaving ripe, overripe, or dry berries on the plant and harvest more frequently. Also, in places where there are insignificant flowers, it is recommended to carry out granting, which consists of removing ripe, overripe, or dry berries on the plants. It is also recommended to prune coffee trees to facilitate handling and harvesting. Then, sanitary harvesting is the cultural practice with the greatest impact since removing residual berries on the plant reduces the CBB population that will colonize the next crop (Benavides et al., 2012; Bustillo Pardey, 2006; Cure et al., 2020).

The importance of considering the provision of natural enemies in the control of the CBB is suggested (Aristizábal and Metzger, 2019; Armbrecht and Gallego, 2007; Karp et al., 2013; Kellermann et al., 2008; Martínez-Salinas et al., 2016; Perfecto et al., 2004; Philpott et al., 2009). It is known that the use of nematodes, entomopathogenic fungi (*Lecanicillium lecanii, Beauveria bassiana*) and insects parasitoides (*Cephalonomia stephanoderis, Nasuta prorops*, and *Karnyothrips flavipes*) (Chapman et al., 2008; Jaramillo et al., 2009b) can be efficient. The application of *Beauveria bassiana* has been a widely used, but with inconsistent results, since it depends on factors such as the strain, concentration, virulence, environmental conditions, and application efficiency (Aristizábal et al., 2016). Finally, a specific trap with semi-chemical attractants has been developed to capture CBB (Damon, 2000; Jaramillo et al., 2009a). The location, the number of traps, and the timing of deployment (period of the year) are important components to take into consideration for the control of the CBB. Jaramillo (2010)recommend locating them between 30 and 160 days after flowering depending on the temperature conditions of each site.

There is a large amount of knowledge produced around CBB and a unified agreement on its management (IPM), mainly focused on a local or plot level view. However, the understanding of how the surrounding landscape and its interactions with management practices affect CBB is still limited. Some mechanisms, such as the diverse effects in the literature on biological control and controversies about the impact of shade, remain unclear, possibly due to the complexity of multiple interacting factors beyond the plot scale that are difficult to verify in observational studies. The use of simulation, as a tool that integrates existing empirical knowledge, can provide a more complete and clarifying view of management strategies. This would include consideration of spatial scale at multiple levels and facilitate interaction with local stakeholders, allowing for more effective and holistic management of the CBB.

3. 2. 7. Simulation tools

Empirical studies evaluating the dynamics of the CBB are complex and expensive to implement, especially when the objective is to include different aspects that influence the dynamics of the CBB, for example, management practices, structure of the plantation and even the surrounding landscape. Simulation modeling based on differential equations has been developed to understand the dynamics of the CBB and its management (Cure et al., 2020; Gutierrez et al., 1998; Montoya et al., 2009; Rodríguez et al., 2013). These mechanistic models efficiently capture biological aspects of the CBB and its interaction with the environment and berry phenology but are limited to a plot scale.

Contrary to this modeling approach, agent-based models (ABM) offer a bottom-up simulation paradigm that connects agents to the system (see chapter 4).

There is a need to develop a simulation tool that links the knowledge generated and extends the proposed mechanistic approaches, considering the lack of cooperative farmer-to-farmer management strategies to control CBB.

4. General objectives

In this study, a simulation tool for the spatio-temporal dynamics of the CBB based on multi-agent models is proposed and developed. The tool goes beyond the models developed by Cure et al., (2020), Gutierrez et al., (1998), y Rodríguez et al., (2013), as it incorporates the landscape context and the facility for farmers or extension technicians to interact with the system as one more agent.

For the development of the multi-agent based CBB model we aimed to fill some gaps on the joint effects of landscape, farm characteristics and crop management practices on CBB damage to coffee berries. We first investigated these effects using a variance partitioning approach (Chapter 1). We also explored the role of landscape functional connectivity, plot characteristics and management performed by farmers on the incidence of bored berries, and the role of different land uses on landscape permeability for CBB movement using circuit theory (Chapter II). Finally, we set out to understand the movement of CBB between coffee plantations and adjacent land uses over a coffee production cycle (Chapter III). We present the conceptual model using a unified modeling language (UML). The rules governing the model are based on empirical information, published research and the work developed in this research.

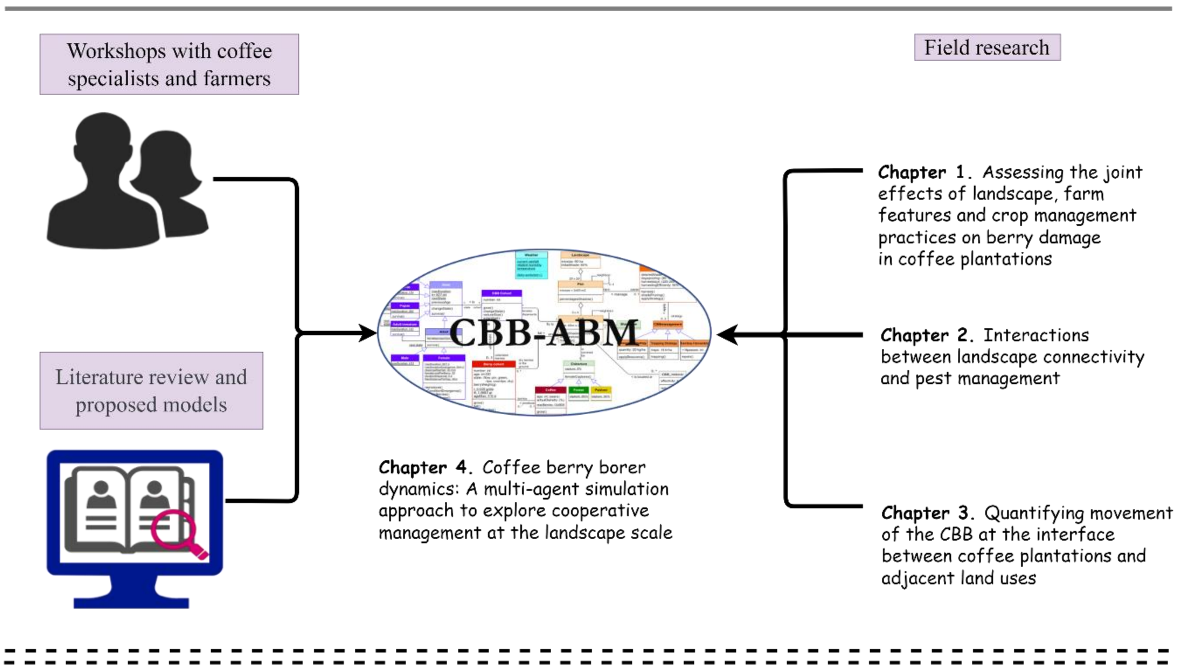

Figure 6. Development scheme of the general objective of this research.

II. Chapter I. Assessing the joint effects of landscape, farm features and crop management practices on berry damage in coffee plantations

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The chapter focuses on showing the importance of management and plot characteristics and landscape configuration on the number of bored berries using a variance partitioning approach. These results demonstrate that it is not possible to evaluate the damage caused by the CBB without considering the global context of all the factors that occur at different spatial scales.

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Assessing the joint effects of landscape, farm features and crop management practices on berry damage in coffee plantations

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5. Abstract

Coffee berry borer (CBB) (*Hypothenemus hampei*; Coleoptera: Curculionidae: Scolytinae) is a major insect pest affecting coffee cultivation that causes large economic losses worldwide. Characteristics related to its life cycle makes it very difficult to control. Usually, CBB control measures are carried out at plot scale, with almost no actions taken at wider landscape scales. It is unclear how plot level control strategies and landscape factors act alone or in combination to influence CBB infestation levels. We evaluated the joint effects of crop management at the plot level, of farm features, and of landscape structure at different spatial scales on CBB infestation in 50 Costa Rican coffee farms. On five plants in each farm, we estimated the maximum number of infested berries during the fruiting period. We measured three separate groups of variables related to plot management practices, farm features and landscape structure. To assess their single and joint contributions, their relative importance, and the effects of these variables on the number of infested berries we used the variance partitioning approach of the RandomForest algorithm.

When evaluating the groups of factors separately, we found that crop management explained 35% of the variability of number of infested berries, farm features 42% and landscape structure 27%. The joint contribution of all three groups of variables explained 48% of variability of the number of infested berries. However, when we assessed the single contributions of each set of variables, i.e., when controlling the other two set of variables, we found that farm features explained 17% of the variance of the number of infested berries, landscape structure 6% and crop management practices only 3%. The larger amount of the variance explained by the joint effect of crop management practices, farm features, and landscape structure suggests that to develop a pest management strategy at a local scale it is important to consider the effect of both local and landscape factors affecting pest abundance. The integrated CBB management plan should consider influences at multiple spatial scales and a coordinated action among farmers that share the same landscape would be beneficial.

Keywords: Agroecosystem, coffee berry borer, multi-scale, pest and crop, RandomForest, variance partitioning.

1. Introduction

On-farm practices, as well as landscape composition and configuration, significantly affect arthropod diversity and abundance (Attwood et al., 2008; Bianchi et al., 2006; Chaplin-Kramer et al., 2011; Clough et al., 2007; Flores-Gutierrez et al., 2020; Pereira et al., 2012). Intensively managed agroecosystems, such as monocultures with frequent pesticide applications, have reduced overall arthropod diversity (Attwood et al., 2008). Landscape composition and configuration can promote pest control through the conservation of pests' natural enemies (Haan et al., 2020; Librán-Embid et al., 2017; Lindell et al., 2018; Martin et al., 2019; Milligan et al., 2016). Natural enemy populations can be reduced by homogeneous landscapes with low percentages of natural cover, which might be associated with availability of food resources, nesting locations, or refuges, all of which are frequently more abundant in heterogeneous landscapes (Chaplin-Kramer et al., 2011; Flores-Gutierrez et al., 2020; Martin et al., 2019).

Farm management and the life histories of individual pests and their enemies can modulate landscape effects (Karp et al., 2018, 2013; Rusch et al., 2013) Djoudi et al., 2018). Landscape composition and configuration might directly affect a pest's population dynamics by facilitating or obstructing their movement and thus changing the pest´s foraging behavior (Bhar and Fahrig, 1998; O'Rourke and Petersen, 2017). Multiscale approaches are important to understand population dynamics and trophic interactions. Understanding how these interactions contribute to natural pest control can help shift pest management strategies from a local process that is repeated many times within a cropping season, to a more holistic approach that considers multiple factors and scales for action (plot, farm, landscape) (Qiu, 2019; Rusch et al., 2011; Salliou and Barnaud, 2017).

In this study, we develop a multiscale approach to study pest damage using as our test case the coffee berry borer (CBB), *Hypothenemus hampei* (Coleoptera: Curculionidae), the most important coffee insect pest in the world. The coffee berry borer is present across all coffee growing regions of the world, with records of its presence up to 1500 m elevation (Agegnehu et al., 2015; Jonsson et al., 2015; Asfaw, 2019). Inadequate management of CBB infestations has caused major economic losses across the globe due to the pest's direct impacts on coffee yield and quality (Baker et al., 1992b; Chain-Guadarrama et al., 2019; Damon, 2000). Its range is limited by its thermal tolerance, with an optimal development thermal range between 15 to 27°C, and a maximum temperature tolerance around 32°C (Azrag et al., 2020; Jaramillo et al., 2010). Larval development occurs exclusively within the coffee bean. Female flight is mainly responsible for the species' spread when adults move to colonize surrounding coffee resources. These biological characteristics make CBB difficult to control (Damon, 2000).

Integrated Pest Management (IPM) programs for control of CBB have been proposed that would combine cultural, biological, chemical control, and post-harvest sanitation practices (Aristizábal et al., 2016). Development of effective CBB IPM programs requires detailed knowledge of the population dynamics of the target pest and its natural enemies. Over the last 30 years, CBB population dynamics have been intensively studied due to the severity of the economic losses CBB causes to small and medium size coffee farmers worldwide (Jha et al., 2011). However, most studies on CBB ecology and its control have focused on assessing infestations and the effects of management strategies at the plot level

(Aristizábal et al., 2016; Bagny Beilhe et al., 2020; Johnson and Manoukis, 2020; Mariño et al., 2016; Rodríguez et al., 2013; Román-Ruiz et al., 2018). Additional research has focused on understanding the contribution of natural enemies in controlling CBB populations to inform development of conservation biocontrol strategies (Armbrecht and Gallego, 2007; Kellermann et al., 2008; Martínez-Salinas et al., 2016; Perfecto et al., 2004) Morris and Perfecto, 2016). However, many of these strategies have been largely based on parasitoid releases (Rodríguez et al., 2017) or the application of entomopathogenic fungi (Bustillo et al., 1999). More recently, studies have focused on understanding the effects of the surrounding landscape's composition on CBB control, focusing mainly on a landscape's positive effects on boosting natural enemy populations (Aristizábal and Metzger, 2019; Chain-Guadarrama et al., 2019; Karp et al., 2013; Kellermann et al., 2008) Boesing et al., 2017; Escobar-Ramírez et al., 2019).

For instance, in Southeast Brasil, Aristizábal and Metzger, (2019) reported that incidence of infested coffee berries increased as the distance between sun coffee plantations and forest patches increased. Karp et al., (2013) found that percentage of on-farm forest cover was a significant predictor of the rate of removal of adult CBB females by birds, with higher forest cover being associated with higher pest control. The presence of forests around coffee plantations could affect CBB numbers either by enhancing predation rates on CBB by natural enemies or by limiting dispersal and colonization of surrounding coffee plantations by CBB adults. Studies on direct effect of landscape context on CBB life cycle, dispersion and incidence are scarce but see Avelino et al., (2012), Román-Ruiz et al., (2018) and Mosomtai et al., (2021). In coffee plantations in Colombia, Castaño et al., (2005) found that CBB adults tend to disperse up to 30 m and colonize nearby coffee plantations. In Costa Rica, Avelino et al., (2012) found that forest cover acted as a dispersal barrier, such that CBB infestation was less intense in coffee plantations surrounded by high forest cover.

Coffee growing and pest control are affected by changes environmental factors that operate at local and landscape scales and which influence CBB population dynamics. However, these scale-dependent interactions remain mostly unexplored despite their importance for coffee IPM. It is unclear how these factors act alone or in combination to moderate CBB infestation levels. Therefore, the aim of this study was to assess the effects of (1) crop management practices implemented at the plot scale (i.e., CBB control actions, pruning), (2) environmental variables believed to operate at the plot scale (i.e., degree of shade, coffee density) and (3) factors that act at landscape scale (i.e., factors related to the structure of the surrounding landscape) on CBB infestation levels. Considering an estimated average CBB dispersal range (ca 140 m, Oliva et al. 2011), we expected that factors occurring at the plot scale would have the greater effect on the CBB infestation rate. We also expected that factors favoring host plant availability, a location with a suitable climate for CBB development, and vegetation factors facilitating CBB dispersion at both the plot and landscape scales would increase the incidence of CBB infestations.

In the field of ecology, variance partition approaches have been developed to assess the relative importance of multiple factors explaining beta diversity or variation in species abundance. Such approaches contribute to diversity conservation strategies, as well as to the understanding of patterns of organization among organisms through community assembly theories. Different modeling strategies such as general linear and generalized mixed (variance components) models and multivariate techniques (e.g., redundancy analysis, partial mantel tests) are useful tools to partition the total variance of a response variable (uni or multivariate) into multiple explanatory factors (i.e., environmental or biological), separating the unique and share effects of measured factors (Chevan and Sutherland, 1991; Legendre and Legendre, 1998; Walsh and MacNally, 2007; Legendre, 2008; Olea et al., 2010).

We used a variance partitioning approach to i) investigate the effect of unique and joint contributions of crop management practices, plantation characteristics, and landscape structure on the number of infested berries; ii) assess the relative importance of these factors on the number of infested berries, and iii) estimate the type of effect of the different factors occurring at the different scales on the variation of the number of infested berries.

2. **Material and methods**

2. 1 Study area

This study was performed in 2009, within the limits of the Volcánica Central Talamanca Biological Corridor (Lambert 553500-599500 W y 190900- 224200 N), located in the Cartago province of Costa Rica, in the Turrialba, Jiménez, Paraíso and Alvarado counties (Figure 7). Annual average temperature in the study area varies between 24 and 29°C, with an average relative humidity of 85% and an annual precipitation of 2600 mm (Brenes, 2009). The biological corridor comprises 114,485.22 ha, of which 51% is in forest, 24% in pastures, 4% in sugar cane, and 8% used for coffee cultivation (Brenes, 2009). Coffee (*Coffea Arabica* L.) (Catuai and Caturra varieties) is mainly grown in coffee agroforestry systems, in which poró (*Erytrina poepigiana* Walp.) and laurel (*Cordia alliodora* Ruiz & Pav.) are the predominant shade trees in the coffee plantations. Harvest occurs between July and December, peaking typically around November. A variety of management types are used in the region, from conventional management, certified organic, and other certification programs, including the Nespresso AAA sustainable quality program, the Rainforest Alliance, Utz, and Starbuck`s (CAFNET project, 2009).

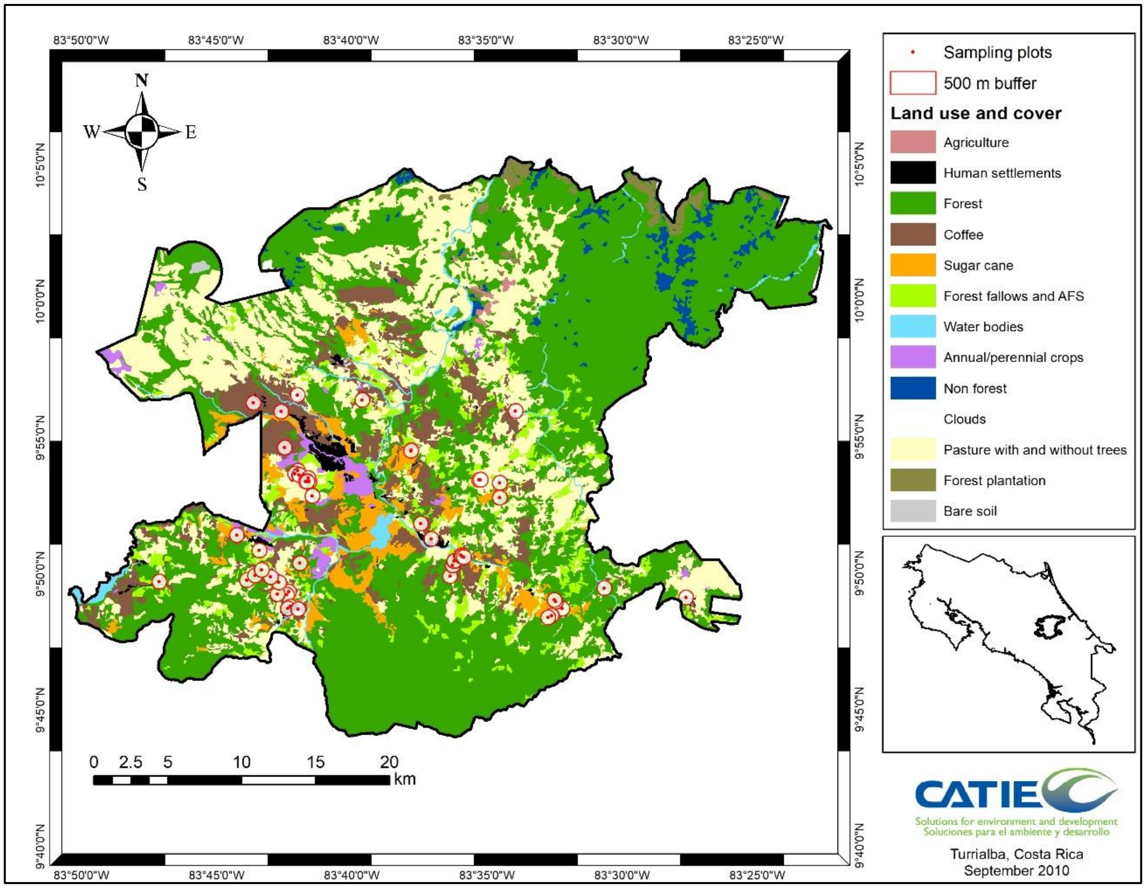


Figure 7. Distribution of sample farms in the study area. Buffers represents the maximum scale at which landscape metrics were estimated (500 m radius).

2. 2 Site selection

The coffee plantations used as study sites were selected by choosing plantations located in different landscape areas that varied in their landscape complexity (from coffee-dominated landscapes to localities where the coffee plantations were highly fragmented) (Avelino et al., 2012). Fifty coffee plantations were selected along a gradient from 613 to 1259 m.a.s.l., with different landscape structure and with different farm management (see description below). Inclusion was also based on farmers' willingness to collaborate with the study and allow access to their farms throughout the year. At each farm site, a plot (average size of 217 m^2) was chosen that was comprised of eight rows of 15 coffee bushes each.

2. 3 Characterization of farm features

In the demarcated plots on each farm, we estimated the density of the coffee plants per ha from measurements of the distances between rows and between plants within rows. The height of the coffee trees was estimated at five plants distributed in the form of a cross. In the selected plants, the number of productive nodes per plant was estimate; we counted the number of fruiting nodes present on all productive branches that contained at least 20 fruiting nodes. To characterize the shade conditions on each farm (for the selected plot), we categorized farm plots into four shade groups: (1) shade of legumes tree only, (2) shade of legumes trees and other trees species, (3) shade of bananas (Musaceae) and (4) the absence of leguminous trees or Musaceae (this type also includes plots with lack any shade). The percentage of shade cover was measured with a spherical densitometer twice, one measure taking in May and another one in September based on the time when shade trees were pruned. For each selected coffee plant, four measurements with the spherical densitometer were made cardinal direction. To characterize the degree of shade in the plot, we averaged the measured values. Elevation in meters above sea level (m.a.s.l.) was recorded using a GPS (table 1). Finally, the age of the coffee system was provided by the farmers (Romero-Gurdián, 2010).

2. 4 Estimation of landscape metrics

A land use map was obtained from the photointerpretation of a mosaic of one-meter resolution aerial photographs taken in 2005. The classification process was supported by validation in the field performed in a 500 m radius surrounding each sampling plot in 2008 (Avelino et al., 2012). The landscape surrounding each sampling plot was characterized within concentric circles (buffer) of different sizes (100, 150, 250, 300, 350, 400, 450 and 500 m radius) that represent landscapes of different proximity to the study plot (Thies and Tscharntke, 1999; Steffan-Dewenter et al., 2002; Avelino et al., 2012). In each landscape circle, the percentages of area covered by coffee, forest, sugar, cane, or pastures were estimated. Two other landscapes indices were calculated: the Shannon Evenness Index (SHEI) and the grain index. The SHEI measures the ratio between the actual Shannon's diversity index and the theoretical maximum of the Shannon Evenness Index (SHEI) and is calculated as follows:

$$SHEI = \frac{-\sum_{i=1}^{m}(P_i * \ln P_i)}{\ln m}$$

where Pi is the proportion of land use in class I, and m the number of land use classes. The index ranges from 0 (when only one patch is present, in this case coffee) to 1 (when the proportions of all classes are equal) (McGarigal and Marks, 1995).

The grain index characterizes the openness of the landscape (measures the degree of aggregation), which in our case was estimated as the distance between centers of land patches classified as coffee. The distances were categorized into four classes (class 1 and 2 represent the shortest distance, and class 3 and 4 the longest distances between coffee cells) which are equidistant between the minimum and maximum image cell distance according to the buffer (Max. distance – Min. distance/4). For each class, all cells are counted (Betbeder et al., 2015). Then the following equation was applied to calculate the landscape grain index:

$$grain\ index_i = \frac{(C3_i + C4_i)}{(C2_i + C3_i)}$$

where C1, C2, C3, and C4 are the frequency of cells in each of the distance classes for the i^{th} sampling point. The grain index for coffee provides fine-scale information about how the sampling plots are aggregated degree with respect to surrounding coffee area. A high grain value (coarse grain) label implies the existence of an open pattern to the landscapes. The grain index was calculated every 10 m from 50 m of buffer to 100 m of buffer, then every 50 m.

2. 5 Characterization of crop farm management

To characterize farmers CBB management we interviewed them about their use or not of traps for CBB, chemical insecticides, application of the entomopathogen *Beauveria bassiana*, the use or not of shade trees pruning and if used, the annual pruning frequency, and the number cycles of cutting of non-crop vegetation (weeding) (Table 1). Another activity, sanitation harvesting, which consists of collecting remnant berries in the plant after harvest, were evaluated by counting the number of remnant berries on the ground below plants and on branches in February 2009 (after the 2008 harvest period). We made the assumption that the higher the number of remnant berries that we collected, the lower the number removed by sanitation harvest would have been. Farmers follow Icafe recommendations to implement CBB traps and B. bassiana application, i.e., 20 traps/ha after harvesting or even during the harvest season, and B bassiana application around 60-80 days after flowering, and up to three times a year in regions such as Turrialba where multiple flowering events occur.

Table 1. Type of management variables and plots evaluated in each of the farms.

Set of variables	Variable	Type of variable	Type of variable specifies
Farm features	Elevation in meters above sea level (m.a.s.l)	Quantitative	Continuous
	Number of young leaves	Quantitative	Discrete
	Age of the coffee system	Quantitative	Discrete
	Number of fruiting nodes	Quantitative	Continuous
	Plant height	Quantitative	Continuous
	Variety	Categorical	Nominal
	Distance between coffee rows	Quantitative	Continuous
	Distance between coffee plants	Quantitative	Continuous
	Density of coffee plants	Quantitative	Continuous
Crop management practices	% Shade	Quantitative	Continuous
	Shade type	Categorical	Nominal
	Pruning of shade trees	Quantitative	Frequency
	Type of pruning	Categorical	Nominal
	Number of weeding cycles	Quantitative	Frequency
	Chemical insecticide application	Categorical	Binary
	Beauveria bassiana application	Categorical	Binary
	Coffee berry borer traps use	Categorical	Binary
	Remnant infested berries (sanitation harvest)	Quantitative	Discrete

2. 6 Estimation of number of CBB-infested berries per plant

Within each plot, five coffee plants were distributed in a cross shape pattern were selected at each sampling period (see below). Plants corresponded to healthy and productive coffee bushes, homogeneous in height and architecture, separated by a distance of 5-15m between them. On each plant, four branches with berries were selected, choosing one each from four vertical strata within the plant, for a total of 20 branches sampled per plot and a minimum of 200 fruits suitable for CBB infestation per plot. On each sample branch, we counted the number of visibly infested ("bored") coffee berries (ones with a visible hole at the apex of the berry where the adult CBB entered). We then counted the total number of fruiting branches per coffee plant and estimated the total number of infested berries per coffee plant as the ratio (Avelino et al., 2012).

Sampling of the number of CBB-infested berries per plant was done four times between May and November 2009: once at the end of the dry season when mature berries (May), twice during the rainy season (berry maturation period) (July and September), and once at the peak of harvest (November). Given that the phenology of different coffee varieties caused the time of peak harvest to differ among farms, we decided to use the maximum of infested berries per plot as a response variable for statistical analysis in all four sampling periods.

2. 7 Data analysis

To assess the relative contribution of landscape metrics, plot characteristics, and management practices on the variable "maximum number of infested berries (as described above), we used a Random Forest algorithm (Breiman, 2001). Random forest is a recursive technique of use of binary trees for classification or regression tasks to obtain precise predictions (Breiman, 2001).

This algorithm is most useful for data sets with high dimensionality and redundancy problems in the explanatory variables since each tree in the forest is trained on a random subset of the total data training set. The approach can capture nonlinear relationships well.

This technique allows one to identify the most important variables using a measure of mean decrease in accuracy and the mean decrease in mean square errors.

A recurrent issue in studies where landscape metrics are estimated in nested concentric circles of different size, is a high redundancy in estimated landscape metrics within these landscapes at different scales, which carries collinearity problems between explanatory variables. Although Random Forest is a robust algorithm to deal with collinearity, high redundancy in metrics calculated at different landscape extensions results in changes in the order of the variables' importance each time a model is run. To consistently identify the most important landscape variables from data calculated at different radius sizes, we ran all possible models, combining the extension while maintaining one variable of each estimated metrics in each model. The total number of estimated models was 826,686. The selection of the best model was based in the determination of the pseudo-coefficient (R2) estimated from mean square error. For each combination, the number of solicited of trees grown was 500, with 100 permutations (Breiman, 2001).

We used a partial regression tree to determine the relative importance of management, plot, and landscape context characteristics on the maximum number of infested berries (Legendre, 2008). Hereafter the term "table of variables" will be used to refer to any of the set of variables corresponding to landscape metrics, plot characteristics, or management practices.

We started by constructing regression trees for each table of variables separately to determine the level of variability in the maximum level of infested berries that was explained by each table of variables, without controlling for any other table of variables. We then, modified the regression trees by considering the explanatory variables contained in two tables of variables (landscape + plot, landscape + management, and plot + management). Using the residuals of these models as the response variable, we separately adjusted the regression trees for each table of variables to determine the unique contribution of each table of variables while controlling for the other two table of variables (partial model; landscape| plot+management, plot| landscape+managament and management| landscape+plot). Finally, we constructed a regression model in which we combined all tables of variables (complete model). Using the results of this last model, we assessed the relationship between each explanatory variable and the maximum number of infested berries through partial graphs. In summary, with the results of all models, we were able to determine how much of the variation in the maximum number of infested berries was explained by the joint or unique contribution of each table of variables (Figure 8).

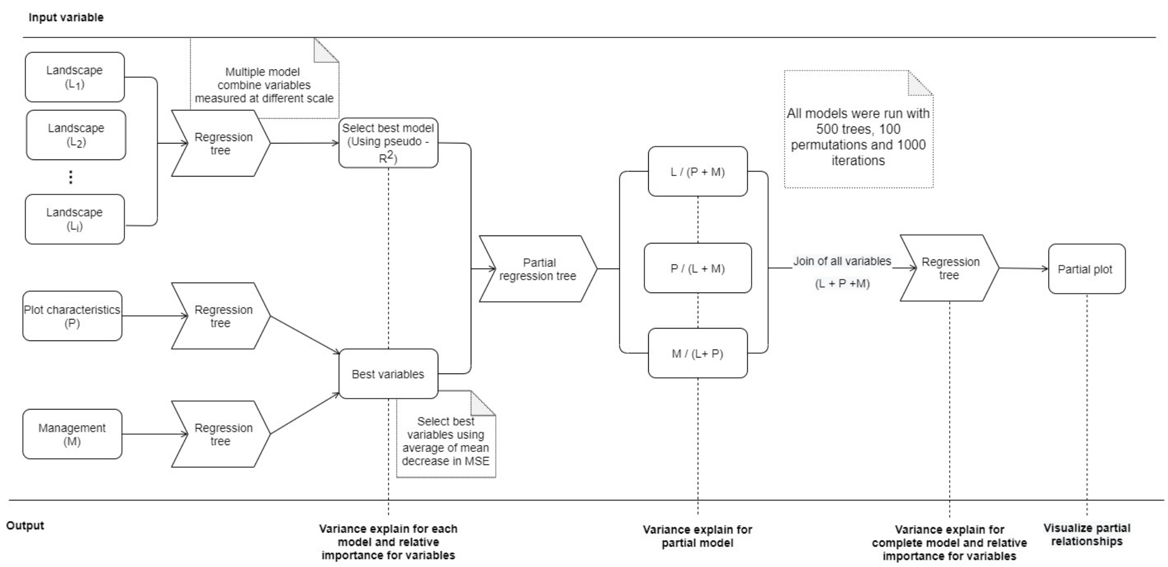


Figure 8. Workflow of the analysis to assess the relative contribution of all variables (management, plot characteristics and landscape) on maximum number of infested berries using Random Forest algorithm. L1, Li = Its combination of landscape metrics for each model. MSE = Mean Square Error

All models were run using 500 trees and 100 permutations. Moreover, we ran 1000 iterations of each model to estimate the average importance of each variable and the average percentage of variation from all models. Running 1000 iterations ensured the stability of explained variance estimations. Partial graphs were generated based on these 1000 iterations. To avoid the effect of extreme values and normalize the data on infestations, in all models the data on the maximum number of infested berries were transformed to its natural logarithm (1+Y). All explanatory quantitative variables were scaling and centering. All analyses were performed using the software R 3.6.1 (R Core Team, 2019) and the RandomForest library (Liaw and Wiener, 2002). Graphs were built using the ggplot library (Wickham, 2016).

3. **Results**

3. 1 Characterization of management types, plots, and landscapes

The average maximum number of infested berries per coffee plant was 55 (± 95.13 SD), with a maximum of 533. In five plots, there were no infested berries. Fourteen percent of all farmers interviewed did not prune the shade trees in their coffee plantation, while 72% pruned at least twice each year and 12% did so three times each year. Fourteen percent of farmers applied chemical insecticides on their coffee plants, 28% used *B. bassiana* and 26% used CBB traps. In 15 plots, there were no remnant infested berries, but in the other plots, there were from 1 to 31 left over infested berries per plant. Nearly half (48%) of the farmers weeded their coffee plantations at least twice each year, two farmers did so up to six times, and only one farmer did no weeding.

Plots were distributed in elevations between 613 and 1182 m.a.s.l., with an average elevation of 871 m.a.s.l. Plantation age varied from 3 to 50 years, with an average age of 19. The density of coffee plants varied from 3,185 to 9,520 plants per hectare, with an average of 5571. The distance between rows was between 1 and 2.16 m, while the distance between plants varied from 0.72 to 1.61 m. The percentage of shade over the plots varied from 0 to 59. Shade was provided most commonly (49%) by species of Musacea (bananas), while leguminous trees in association with other species were used in 30% of the plots, and leguminous trees alone in 17%. Only two plots had no shade cover at all. The number of fruiting nodes varied from 7 to 676 nodes per plant.

The landscape surrounding the study area was mainly composed of coffee plantations, from 65.6% of land area at 100 m to 40.1% at 500 m. The percentage of surrounding land determined as coffee plantation decreased as the radius of the buffer surrounding the plot increased (Table 2) because the percent of the landscape in forest increased at larger spatial scales. The percentage of land in pasture or sugar cane was less sensitive to the size of the radius used outward from the plots to define the landscape. The landscape Shannon evenness index increased with the size landscape radii, indicating that the landscape become more heterogeneous at larger scales. The grain index also greatly increased with landscape size, indicating that when the radii of the concentric circles around plots increased, the coffee landscape became more open (extensive) (Table 2).

Table 2. Mean and standard deviation of each of the landscape metrics calculated at different landscape extensions and used to explain variation in the maximum number of coffee berries infested by coffee berry borer (Hypothenemus hampei).

Buffer (m)	% Coffee	% Forest	% Pasture	% Sugar cane	Evenness index	Grain
50	-	-	-	-	-	0.09 ± 0.21
60	-	-	-	-	-	0.10 ± 0.20
70	-	-	-	-	-	0.11 ± 0.20
80	-	-	-	-	-	0.13 ± 0.20
90	-	-	-	-	-	0.14 ± 0.20
100	65.63 ± 27.57	4.38 ± 10.96	9.11 ± 13.81	16.25 ± 24.65	0.61 ± 0.29	0.16 ± 0.21
150	57.52 ± 29.25	8.99 ± 15.13	10.59 ± 14.00	17.79 ± 25.74	0.61 ± 0.23	0.23 ± 0.23
200	51.60 ± 28.88	13.91 ± 17.03	11.47 ± 13.11	17.94 ± 24.31	0.65 ± 0.21	0.30 ± 0.26
250	47.89 ± 28.45	16.94 ± 17.87	11.69 ± 12.19	18.10 ± 22.68	0.67 ± 0.21	0.35 ± 0.27
300	45.44 ± 28.07	19.34 ± 18.11	11.73 ± 11.59	17.75 ± 20.99	0.67 ± 0.20	0.39 ± 0.27
350	43.63 ± 27.56	21.14 ± 17.71	12.10 ± 11.18	17.29 ± 19.42	0.69 ± 0.19	0.42 ± 0.28
400	42.24 ± 27.25	22.65 ± 17.50	12.41 ± 10.82	16.86 ± 18.10	0.70 ± 0.19	0.45 ± 0.27
450	41.01 ± 26.82	23.98 ± 17.40	12.75 ± 10.71	16.47 ± 17.06	0.69 ± 0.18	0.46 ± 0.27
500	40.09 ± 26.22	24.99 ± 17.31	12.86 ± 10.54	16.21 ± 16.28	0.70 ± 0.18	0.47 ± 0.27

3. 2 Contribution of management practices, plot characteristics and landscape metrics to CBB infestation levels

The model including only management practices as variables explained 35% of the variability of the maximum of number of infested berries. The number of remnant infested berries and the frequency of shade tree pruning were the only variables contributing to the explained variance (Figure 9a). The frequency of plot weeding, the use of *B. bassiana*, the use of coffee berry borer traps, and the application of insecticide did not show any contribution.

The model including only the plot characteristics as variables explained 42% of the variability of the maximum number of infested berries. The number of fruiting nodes and elevation were the most important variables explaining the variance, followed by the distance between plants and plant density (Figure 9b). Shade characteristics of the plot (type and percentage) did not have any significant contribution to the explained variance and neither did the age of the plantation, the variety of coffee, the height of the plants, or the distance between rows.

The model including only the landscape metrics as variables explained 27% of the variability of the maximum number of infested berries. The best explanatory variable combination was composed of the percentage of pastures at 250 m, the Shannon evenness index at 500 m, the percentage of forest at 300 m, the grain metric at 300 m, the percentage of coffee at 400 m, and the percentage of sugar cane at 150 m (in order of importance) (Figure 9c).

Finally, a combination of variables from the three tables (landscape + plot + management) in the most complete model explained 48% of total variability of the maximum number of infested berries. The variables with the greatest weight were plot elevation, the number of remnant berries (i.e., sanitation harvest) and number of fruiting nodes, followed by landscape metrics such as percentage of pastures at 250 m and Shanon evenness index at 500 m. Variables making smaller contributions were the variable’s grain at 300 m, the percentage of coffee at 400 m, the percentage of sugar cane at 150 m, the distance between plants, and the plant density. In this model the least important variables were the frequency of shade tree pruning and the percentage of forest at 300 m. The contribution of this latest variable was more important than the contribution of the percentage of coffee at 400 m, the grain at 300 m, and the percentage of sugar cane at 150 m in the landscape metrics model (Figure 9d).

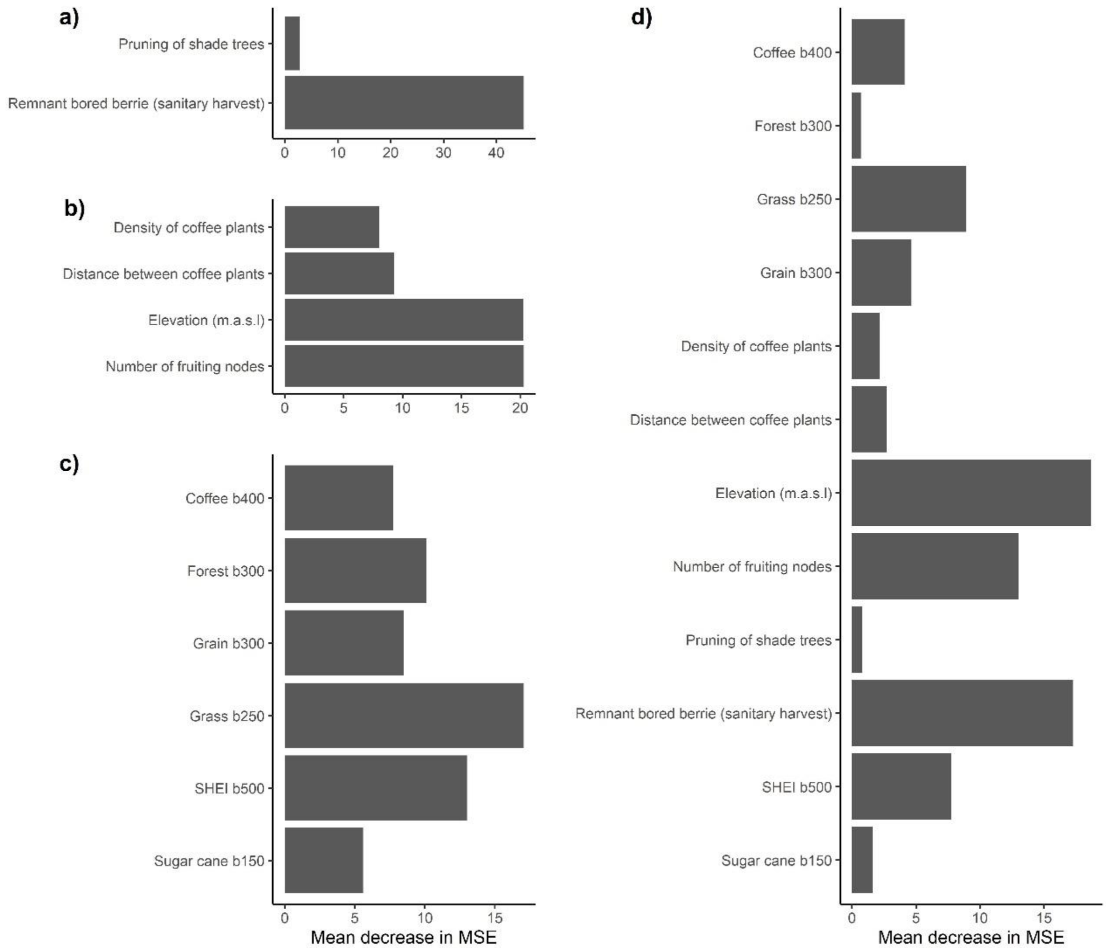


Figure 9. Relative importance of explanatory table of variables. (a) management, (b) plot characteristics, (c) landscape and (d) landscape+plot+management in explaining the variance of maximum of bored berries.

3. 3 Unique contributions of each table of explanatory variables and joined variance

Partial models indicated that the plot characteristics considered alone, i.e., when controlling for landscape and management tables, only explained 17% of the 42% of the explained variability of maximum number of infested berries obtained with the plot model. Landscape metrics alone explained only 6% of the 27% of explained variability of the landscape model (Figure 10). Management strategies alone explained 3 % of the 35% of explained variability of the management model. Indeed, 48 % of the total variability is due to the joined contribution of plot, management, and landscape characteristics.

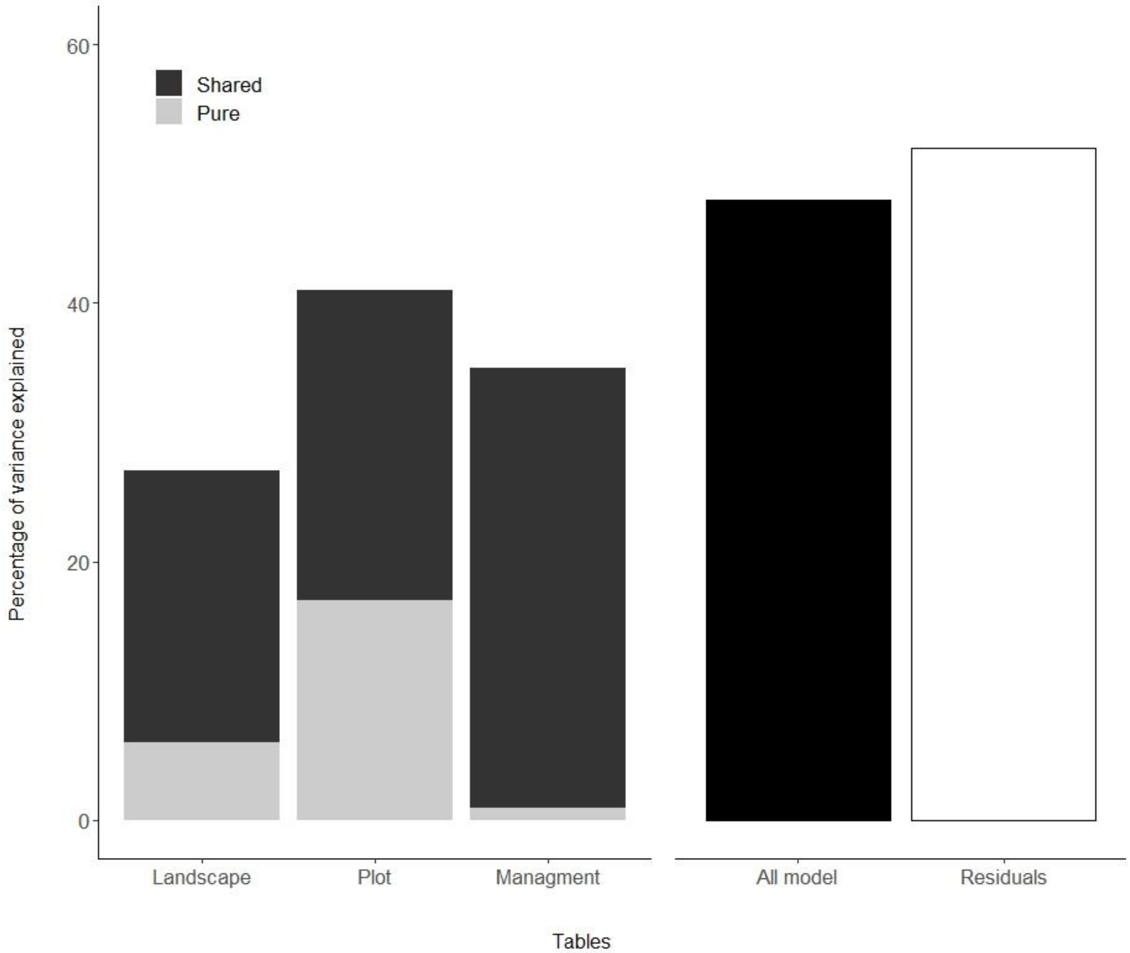


Figure 10. Pure (light grey) and shared (dark grey) contribution of landscape, plot and management table of variables, as the total explained (black), and the unexplained (white) variation of infested berrie

3. 4 Partial relationships

The maximum number of infested berries was negatively related to elevation, to increase in the percentage of land in pastures at 250 m, to Shannon evenness index at 500 m, to distance between plants and to the percentage of forest at 300 m. In contrast, the maximum number of infested berries showed positive relationships with the number of remnant bored berries, the number of fruiting nodes, the percentage of coffee at 400 m, and the frequency of shade tree pruning. The planting density and grain index showed a quadratic relationship, while the percentage of sugar cane was highly variable with a negative trend (Figure 11).

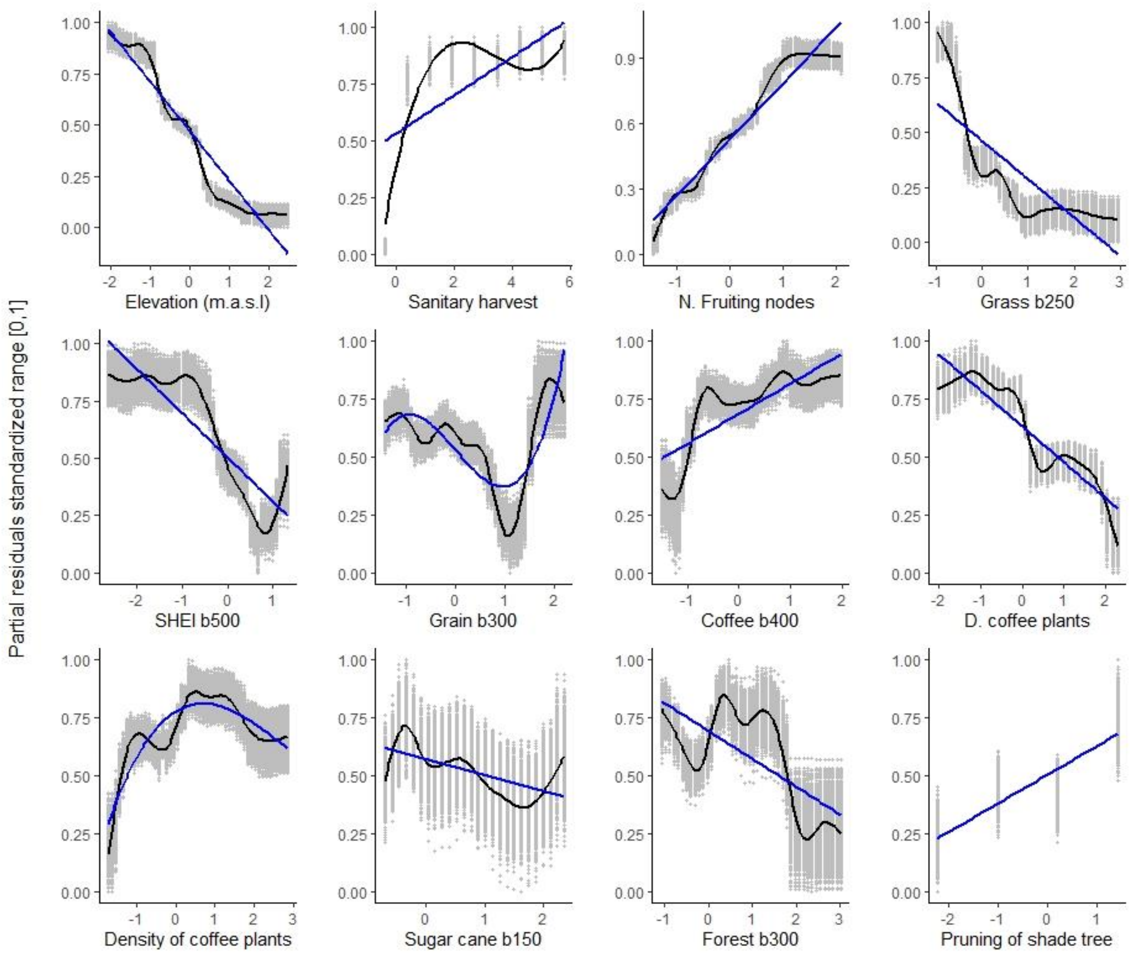


Figure 11. Partial relationships between maximum of infested berries and each of the management, plot and landscape variables that maximize the explained variance. Black line is the average of the relationship based on the 1000 iterations of the models. Blue line indicates the trend of the relationship.

4. Discussion

In our study, we used a multiscale approach to assess the effect of crop management practices at plot scale, of environmental variables believed to operate at plot scale, and others operating at the landscape scale, as well as their joint contributions on the incidence of berries infested by CBB. We found consistent evidence that factors operating at the landscape level were as important as those operating at plot scale only (including crop management practices) to explain the incidence of infested berries in coffee systems. Crop management practices, plot characteristics and landscape characteristics had interactive effects that reduced the number of infested berries. We found that plot and landscape characteristics favoring coffee plant concentration (like higher number of fruiting nodes, percentage of coffee area) and CBB dispersion (landscape homogeneity based on Shannon Evenness Index and grain index) are correlated with higher maximum numbers of infested berries. We also found that plantations at higher altitudes were less affected by CBB.

We found that the portion of the variance of the maximum number of infested berries that was explained by joint effects of each group of variables (management, landscape context and plot characteristics) was more important than the part of the variance that was explained by each group's single effects. This result emphasized the importance of considering different spatial scales in order to explain the variation of the level of infested berries at the plot scale. Considering each group of variables separately, more than half of the explained variance was due to joint contribution among all the variables. This was most obvious for the group of variables related to management, which only explained 3% of the total variance. Our results confirmed that to develop a pest management strategy at the local scale, it is important to consider the effects of both local and landscape factors on pest abundance (Rusch et al., 2011).

At the plot scale, the most important variables (to explain the level of infested berries) were elevation, number of fruiting nodes, planting density, and the distance between plants. Surprisingly, there was no effect of the percentage of shade or the shade type on CBB infestation levels. More shaded systems have often been reported to increase CBB infestation levels (Bosselmann et al., 2009; Mariño et al., 2016) in comparison with full sun systems, even though some studies failed to find clear effects due to the interaction between shade and other components of the system (Soto-Pinto et al., 2002, Teodoro et al., 2008). Mariño et al. (2016) observed higher infestation rates under shade conditions, with fewer individuals inside berries. Indeed, shade tends to buffer temperatures and to maintain humidity close to the optimum for CBB survival (Damon, 2000). In our study, the absence of an effect of shade could have been due to temperature and humidity in the study area. Turrialba temperature varies between 24 and 29 °C and its average relative humidity is 85%, both favorable for CBB with an optimal development thermal range between 15 to 27°C (Jaramillo et al., 2010; Azrag et al., 2020) and close to 90% relative humidity (Baker et al. 1992). Moreover, the level of shade considered in the study (between 0 and 59%) might have not been sufficiently contrasting to observe significant difference.

We also showed how certain management practices, including whole-farm sanitation harvest and pruning of shade trees, explained the variability of maximum number of infested berries, while others, such as number of cycles of weeding, use of CBB trapping, applications of chemical insecticides, and the use of *B. bassiana*, did not. Timely harvest of coffee and the collection of residual fruits on the plants (i.e., whole-farm sanitation) are important practices known to reduce local CBB populations that would otherwise be available to colonize berries in the next CBB generation in a plantation (Vega et al., 2009; Johnson et al., 2020). A recent study based on a simulation model of control of CBB confirmed that intensive harvesting of coffee was the most effective control practice for reducing CBB infestations in Colombia and Brazil (Cure et al., 2020). Moreover, the use of CBB traps and of *B. bassiana* applications could also be efficient practices to control CBB population when they are adequately deployed (Vega et al., 2009; Aristizábal et al., 2016; Escobar-Ramírez et al., 2019; Johnson et al., 2020). To be efficient, traps have to be used during the flight periods of female CBB during the period when coffee bushes are in their unproductive season. In addition, these traps are more effective when used in coffee regions with a marked dry season and clustered flowering events, as CBB massive emergence occurs in short windows of time. This is not the case of our study area where rain is present across all year resulting in multiple flowering events and a longer period of fruit availability *Beauveria bassiana* is also more efficient under shade conditions, which produce higher humidity rate that favor the growth of this entomopathogen fungus. In our analysis, we could not provide detailed information on the use of CBB traps and of *B. bassiana*. This lack of information could partly explain the absence of effect of these strategies as farmers may not implement them appropriately. However, farmers follow Icafe recommendations to implement these management practices (e.g. 20 traps/ha after harvesting or even during the harvest season, http://www.icafe.cr/wp-content/uploads/revista_informativa/Revista-I-Sem-07.pdf) so we assume that those farmers who declared to follow Icafe recommendations were doing them correctly.

Our study confirmed for the first time that there was an effect of a certain configuration landscape metrics (i.e., grain index at 300 m and Shannon evenness index at 500 m) that significantly affected the maximum number of infested berries. We also found significant effects on CBB infestation levels for other landscape composition metrics (i.e., % of land in forest, coffee, pasture, or sugar cane), in line with results of Avelino et al. (2012), with the exception that they did not find any significant effect of land area in sugar cane on the incidence of infested fruits and the action scales were not the same. In fact, Avelino et al. (2012) found a significant influence of the percentage of landscape in coffee at 150-200 m of in pasture between 100 and 350 m, and of forest at 150 m, whereas in this study we found significant effects for these land use types at 400 m, 250 m and 300 m, respectively. The main differences between our works and Avelino et al. (2012) were in relation to the land area in coffee and forest. These differences with our works, may be caused by the fact that Avelino et al. (2012) explored simple linear relationships between the incidence of infested berries and landscape composition metrics, but did not consider the covariation of the other metrics, including the configuration metrics (grain index and Shannon evenness index). Among the five most important explicative variables of bored berries incidence, there are two from plots (altitude, number of fruiting nodes), one from management (remnant fruits) and two from landscape (% of pasture 250 m, SHEI). Our study confirms the finding that some landscape characteristics can override the impact of field level management practices (Kebede et al., 2019).

The relationships between variables occurring at different spatial scales and the incidence of infested berries are largely explained by CBB's biological traits. These relationships can occur at different scales, favoring the incidence of the infested berries, or not. At the plot scale, variables like the number of nodes with berries, the distance between plants, and the density of coffee plants are important variables explaining the maximum number of infested berries that can be directly related to fruit production and availability, and to the resource concentration hypothesis (Root, 1973). At the landscape scale, positive partial relationships with the percentage of the landscape in coffee and the highest grain index and negative partial relationships with the landscape percentages of forest, pasture, and sugar cane, and the Shannon evenness index, suggest that homogenous landscapes dominated by coffee favor CBB. More heterogenous landscapes can act as barriers inhibiting CBB displacement such that dispersing CBB female adults would expend more energy searching for coffee plantations, causing an increase in mortality (O'Rourke and Petersen, 2017).

Pests with limited dispersal capabilities, such as CBB, may be more affected by landscape diversification than robust dispersing species when resources are limited, For CBB limited resources occur as after harvest. In contrast, plots that are adjacent with other coffee plantations (which is characterized by the grain index) would experience decreased time spent in dispersal to find new, adequate coffee habitats.

The partial relationships found between the maximum number of infested berries and landscape or plot variables are in agreement with O'Rourke and Petersen's (2017) extension of the resource concentration hypothesis of Root (1973) to a landscape scale. This extension of Root's hypothesis predicts that herbivorous insects will be more abundant in large patches of their host plants because these patches are easier to locate, and herbivores will stay longer in big patches (Root, 1973). On the one hand, the observed influences of factors such as number of berry nodes, the distance between plants, the density and percentage of land devoted to coffee all support the idea of resource concentration acting at a local scale (Root, 1973). On the other hand, landscape factors such as the Shannon Evenness Index, the grain index, the percentage of the landscape in forest, pasture, or sugar cane support importance of landscape-scale mechanisms. In addition, heterogenous landscapes can increase the abundance and diversity of generalist natural enemies (e.g., birds, ants) in surrounding areas devoted to other uses (Bianchi et al., 2006), and such diverse landscapes can favor top-down regulation of crop pests (Aristizábal et al., 2019; Escobar-Ramírez et al., 2019). The presence of forest in the landscape can favor ant and bird populations and hence their regulation of pests.

Elevation had the greatest weight towards explaining the variance of the maximum number of infested berries. Low altitude coffee areas are characterized by higher temperatures, as well as higher relative humidities, which can influence the thermal tolerance of CBB (Jaramillo et al., 2009, Hamilton et al., 2019, Giraldo-Jaramillo et al., 2018), as well as the availability of resources (Damon, 2000). Indeed, it is known that Arabica coffee, grown at low elevations, is very attractive to *H. hampei*, possibly due to a weakening of the plant, which grows best at altitudes above 1200m. Our study was conducted at low altitudes (between 613 and 1182 m) that are close to the minimum needed to cultivate Arabica coffee.

We also found a positive partial relationship between the maximum number of infested berries and the frequency of shade tree pruning. Current IPM recommendations for CBB control in Central America include pruning to ventilate the coffee plantation and facilitate the penetration of sunlight, which would increase the speed of drying of any residual berries that have fallen to the ground, thus reducing the survival of any CBB stages present in these berries. Our results, indicate otherwise. A higher frequency of pruning of coffee shade trees can increase temperature and lower relative humidity, favoring CBB by shortening its developmental time and increasing adult female emergence (Baker et al., 1992). Shaded areas can also promote survival of *B. bassiana* and consequently increase CBB mortality. Moreover, since shade trees can enhance predation on CBB through habitat provision for natural enemies (Morris and Perfecto, 2016; Karp et al., 2013; Martínez-Salinas et al., 2016; Aristizábal and Metzger, 2019), it may be that frequent pruning may reduce favorable habitat for CBB predators. However, shade effects on CBB are still to be better clarified, for example Mariño et al. (2016) found a higher incidence of infested berries in plots under shade, but with a lower total population of CBB per berry. Finally, shade tree pruning may interact with other practices, and it is related with other pests and diseases such as coffee leaf rust, and management decisions by farmers must consider these interactions.

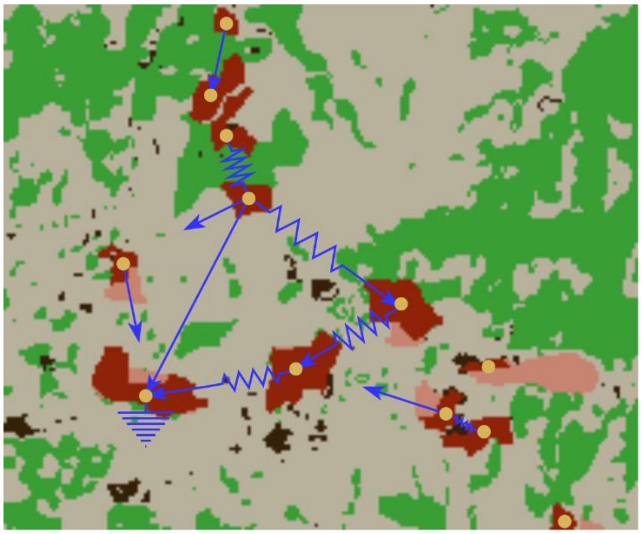
5. **Conclusions**

This study allowed us to identify factors that contribute to the reduction of the number of infested coffee berries in our study region. We showed that more heterogeneous landscapes, with more forest and less aggregated coffee plots, combined with a lower coffee plant density (i.e., plants with greater distance between them), a lower pruning frequency, and good sanitation harvest practices (that reduce the number of residual coffee berries after harvest) result in fewer infested berries. Based on our findings, we think that an integrated and area wide CBB management plan should consider influences that act at multiple spatial scales as well as the coordinated action among farmers that share the same landscape. Coordinated management decisions for pest control among neighbor farmers would result in an efficient control of pest populations, particularly for mobile pest like CBB, a reduction in production costs and a reduction of the negative impacts of crop production to the environment. Our results confirm that to develop a pest management strategy at local scale it is important to consider the effect of both local and landscape factors affecting pest abundance. The recognition of the importance of heterogenous landscapes and coordinated control and management among farmers should be accompanied by the development of incentives that encourage farmers to do so (Brévault and Clouvel, 2019).

Our approach to analysis is a good approximation to understand the response of the CBB to its environment at different spatial scales. This approach is widely used in the field of ecology and conservation biology to assess the independent or combined effects of environmental factors that contribute to the patterns of ecological communities.

III. Chapter II. Interactions between landscape connectivity and pest management

This chapter focuses on showing the importance of landscape connectivity on CBB movement and its interaction with management on the incidence of bored berries. To characterize the degree of functional connectivity of the landscape, we use metrics based on graph and circuit theory. We present a novel approach to associate circuit-based connectivity with the incidence of bored berries. The approach is based on the simulation of different resistance scenarios of the land uses that make up the landscape matrix in the movement of the CBB, an approach to that proposed by (Moreno et al., 2022)



Interactions between landscape connectivity and pest management

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1. Introduction

Recognition of the influence of landscape-scale factors on pests and diseases has led to the implementation of holistic management approaches at multiple scales. However, gaining a better understanding of the complexity of the landscape matrix and the various factors and interactions at different scales that affect the distribution, dispersion and development of pests and diseases is crucial for creating efficient control strategies (Rusch et al., 2011; Schellhorn et al., 2015). The reconfiguration of a landscape to promote pest control presents significant challenges, requiring a long-term perspective for effective pest management. The integrated pest management approach at a landscape scale has emphasized the use of trap crops (Sequeira 2001), insecticides that do not harm beneficial insects, and the coordination of pest control practices at the landscape level (e.g., coordination of insecticide applications) (Hendrichs et al., 2007, Lloyd et al., 2010).

Comprehensive pest control strategies at multiple spatial scales through landscape reconfiguration can include measure such as the inclusion of live barriers, scattered trees or restoration of semi-natural habitats to hider pest movement and provide refuge to natural enemies. These measures can work in synergy with control practices at the plot level and the socio-environmental characteristics of the landscape. Understanding "when," "where," and "what" elements of the landscape that influence pest and disease control require insight into their movement and the impact of different land uses on pest and disease colonization and dispersion (Moreno et al., 2022; Vilchez-Mendoza et al., 2022).

Moreno et al. (2022) propose the use of graph theory (Bunn et al., 2000) as a tool to analyze the influence of different types of land use on the movement of two pests in olive crops. The authors put forth 18 hypotheses based on resistance values for the different land uses impacting on the movement of pests to identify land uses that facilitate or impede movement and the spatial scale at which the barrier/corridor effects are detected. By using this tool, they suggest that it is possible to plan the landscape composition for pest control. This research direction is crucial for understanding the pest management approach at multiple spatial scales, evaluating the role of the spatial patterns of the different land uses beyond the provision of natural enemies.

Our study, conducted in a coffee landscape in Costa Rica, Central America, aimed at contributing to this research direction by evaluating the significance of plot-scale management and the landscape context in facilitating or impeding the movement of the coffee berry borer (CBB). Coffee landscapes in Central America are dynamic and complex, characterized by a matrix of land uses interspersed with small patches of annual crops, coffee, pasture, and natural habitats such as forests, riparian forests, and forest fallows.

The coffee berry borer is the most significant pest in coffee cultivation, causing economic losses by perforates the berries and affecting both the quantity and quality of production (Chain-Guadarrama et al., 2019). This pest completes its life cycle inside the berry (Baker et al., 1992a), only the mated females leaving the fruits to colonize new berries, making this stage susceptible to control practice (Benavides et al., 2012; Damon, 2000). The CBB can colonize a coffee plantation through transport of infected berry or its innate ability to disperse. Gil et al. (2015) found that 90% of the dispersing CBB within a coffee plot reach a distance of no more than 40m, while Olivas et al. (2011) observed that in land uses surrounding the coffee plantation, the CBB can move up to 140m, with dispersal at even greater distances favored by the wind (Baker, 1984).

The role of the landscape's configuration and composition influencing the CBB has been demonstrated through the provision of natural enemies or action as a barrier to the pest's movement (Karp et al., 2013; Avelino et al., 2016; Aristizábal & Metzger, 2019; Vilchez-Mendoza et al., 2022a). Given the CBB's resource specialization on coffee berries, the pest waits inside remaining berries on plant or in the soil after harvest, a period that can last up four months, depending on the precipitation regimen of the coffee production sites, which define the fruiting phenology (De Alvin, 1960; Damon, 2000; Benavides et al., 2012).

Sanitary harvest, involving the collection of residuals berries from the ground and plants after havers, is the most important practice for controlling the CBB (Benavides et al., 2012; Cure et al., 2020; Pardey, 2006). However, economic constraints may prevent many farmers from implementing this practice, particularly during periods of low coffee prices in the international market. The resulting neglect of coffee plantations can lead to focal points of infestation that disperse to neighboring plantations in the next fruiting cycle. Even a low percentage of infested berries (>5%) can significantly impact the overall quality of the production, potentially leading to rejection or reduced sale prices.

The aim of this study was to examine the influence of connectivity of the landscape between coffee plots and agricultural practices on the incidence of infested berries. Drawing on previous knowledge of the impact of landscape structure, particularly the percentage of forest versus coffee and landscape heterogeneity (Vilchez-Mendoza et al., 2022), these metrics were taken into account when selecting the study landscapes. We assessed the impact of different land uses by employing circuit theory to simulate different dispersal scenarios. Based on these scenarios, we calculated indices, graph-based functional metrics and landscape configuration metrics to evaluate their relationship with infested berries.

Our hypothesis suggests that there is a synergistic relationship between CBB management and landscape connectivity in the incidence of infested berries. Specifically, we hypothesized that plots not connected with CBB management (under certain distance thresholds) would exhibit a lower incidence of infested berries compared to connected plots, regardless of CBB management practices.

2. **Methodology**

2. 1 Study area

The study was carried out in the year 2020, in the Canton of Turrialba, located in the Central Biological Volcanic Corridor of Talamanca (CBVCT), situated in southeastern of Costa Rica on the Caribbean slopes of Central cordillera (Figure 1). This area offers climatic conditions that favors CBB development, with an annual rainfall of 2700 mm and an average temperature of 22°C. Wind direction is oriented east/northeast during all the year with an annual average speed of 10km/h (National Meteorology Institute, SA). The CBVCT is part of the Mesoamerican Biological Corridor (MBC). The CBVCT spreads over 114 451,46 ha and presents a matrix of various land uses. The predominating land cover is forest (52%), followed by pastures (24%) and then by minor agricultural land uses including 8.5 % of coffee and 4% of sugar cane (Figure 12Figure 1).

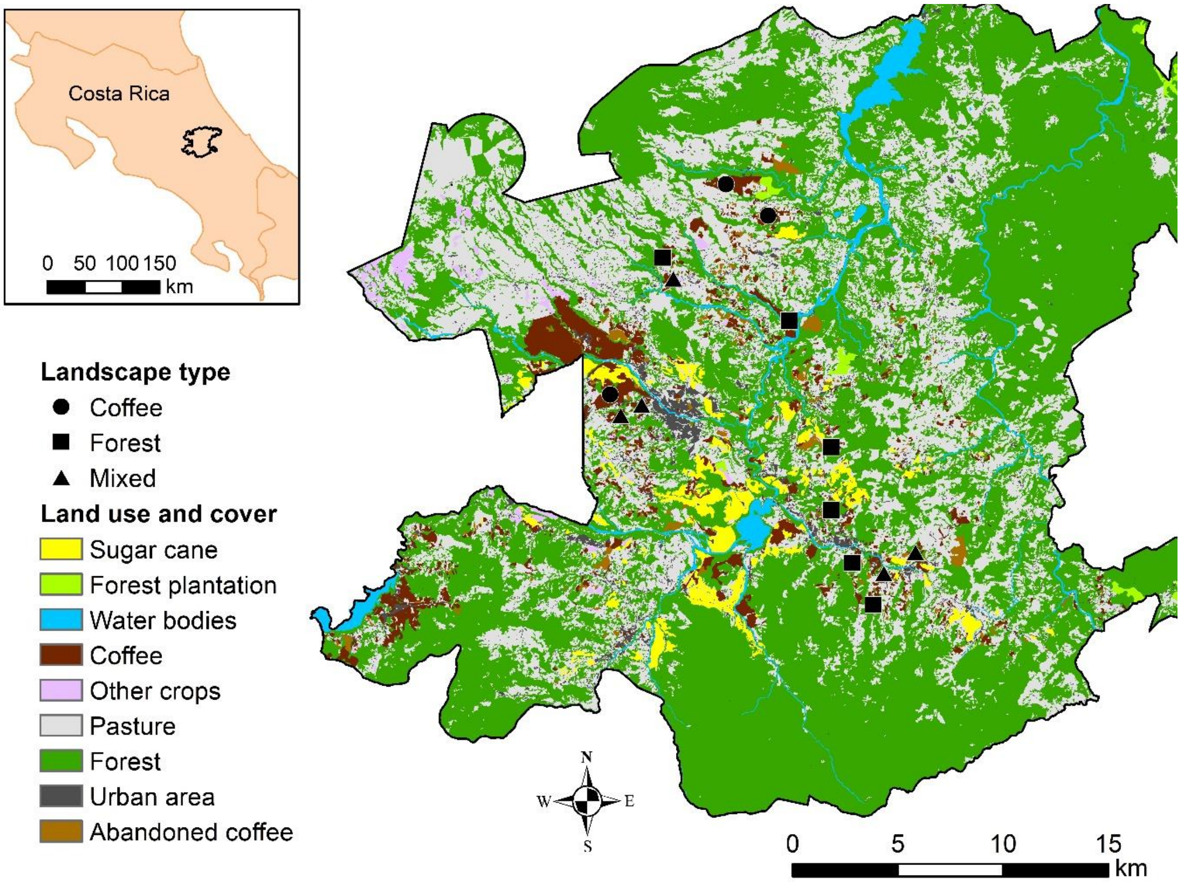


Figure 12. Location and main land uses of the study area. Location and main land uses of the study area. Classification map of the 14 landscapes selected after the field work. The point shape indicates the type of landscape where the plot is located: square = forest; circle = coffee; heterogeneous triangle.

2. 2 Procedure for the selection of site

The aim of this section was to select landscapes based on a gradient of forest-coffee elements and fragmentation, along with the identification of coffee plots within these landscapes. The selection process involved the development of a 2018 land use map, which was achieved by combining a land use map derived from the classification of Sentinel 2 images (10m resolution) developed by Amante (2020) with a spatial database of coffee plantations in the study area from 2012 to 2018, created by Coffee Institute of Costa Rica (ICAFE). The comparison of these datasets enabled the enhancement of mapping for coffee plantations within the Sentinel 2 map, including coffee plantations, abandoned coffee plantation present in 2012 but absent in 2018 was verified in the field and reclassified as “abandoned coffee plantation”. To ensure accuracy, any salt and pepper effects in the final lands use map was eliminated by aggregating the pixels in the closest land uses, thus preventing bias in the estimation of the aggregated landscape metrics.

Second, to analyze the landscape composition and configuration, we utilized the sliding windows method included in the Chloe 4.1 freeware (Boussard and Baudry, 2014), This approach involved forest, coffee, and pasture, along with two metrics of landscape fragmentation within 500m radius windows across the entire map, with a 500m offset. We focused on areas with elevations lower than 1500m, as coffee plantations are not typically found above this altitude. The 500m radius windows size was chosen to ensure consistent coverage of the CBB population, considering the pest dispersal capability of up to 140m from coffee plot edges (Olivas et al., 2011, Gil et al., 2015, Avelino et al. 2012).

The two-fragmentation metrics calculated were the Shannon Evenness Index (SHEI), which measure the degree of representation of different land uses, and the Heterogeneity of fragmentation (Hetfrag), a measure the compositional heterogeneity of land-use types (Burel, Francois & Baudry, 2013). These metrics provided insight into the distribution and variability of different land-use types within the landscape.

Subsequently, we classified each window (referred to as “landscapes”) based on the landscape metrics calculated. This classification resulted in “forest landscapes” with over 40% forest cover and low SHEI and Hetfrag index values, “coffee landscape” with over 40% coffee cover and intermediate SHEI and Hetfrag index values, and “mixed landscapes” with 20-40% coffee area and high SHEI and Hetfrag index values. Additionality, we considered two elevation categories using a threshold of 850 masl, as the number of infested berries is inversely related to elevated (Vilchez-Mendoza et al., 2022).

We applied these criteria related to landscape composition, configuration and elevation, while also considering the spatial correlation effect and the presence of at least three coffee plantations within each landscape, resulting in the selection of 14 landscape (three coffee landscapes, six forest landscapes, and five mixed landscapes). Within these landscapes, we identified 66 active coffee plots where all field activities were conducted, with the participation of willing farmers (refer to Table 3 and Figure 12).

Table 3. Number of selected plots, landscape type, and elevation category

Type of landscape	<= 850 masl		> 850 masl	
	N. Landscapes	N. Plots	N. Landscapes	N. Plots
Coffee	1	7	2	5
Forest	3	11	3	18
Mixed	3	17	2	8

2. 3 Sampling of bored berries

In each of the 66 selected plots, we collected coffee berries in five productive coffee plants to estimate the percentage of bored berries. We carried out four sampling events from August to November 2020 (mid August, September, October and November) coinciding with the period of highest availability of suitable berries for CBB infestation. In each sampling event. Different coffee plants were selected for each sampling event, and from each plant, we selected one branch with the presence of suitable berries and collected all the berries. The berries were then categorized as ripe, green, and dry, and the number of bored berries per category was counted. We estimated the percentage of bored berries for each category based on the total berries collected. The maximum percentage of bored berries per plot was used as the variable of interest, considering the harvests carried out by the farmers and the variation of the maximum berries in the study area.

2. 4 Characteristics of the plots and management

To collect information about CBB damage perceived by farmers, we designed a structured interview with closed questions (Table 2) about the specific control practices against CBB and other pests and diseases, the farm characteristics, and the management of coffee plot. In total, 56 farmers, who were owners or managers of the 66 plots, were interviewed.

Farmers were questioned about CBB presence in the plots and percentage of induced damage. The damage unity could be either a percentage of the total production or a fraction of boxes that were penalized by the coffee post-harvest center. Additionally, we asked for the presence of other pests and disease in the coffee plot (e.g., coffee rust (Hemileia vastatrix), green coffee scale (Coccus viridis), Anthracnose (Colletorichum gloeosporioides) or American leaf spot (Mycena citricolor)), and their relative importance (in term of damage) in comparison with CBB.

Then, there were specific questions on the use of control practices against CBB like biological control (with *Beauveria bassiana*), CBB traps, sanitary harvest, insecticides (chemical control) or others. Information on the quantity of inputs applied, the period of application (before the coffee tree flowering or fructification, as soon as the first rain comes), the frequency of sanitary harvest and the satisfaction rate of the farmer was also collected. If farmers did not implement any control strategy, we asked for the possible limitations to use these practices such as price, efficiency, lack of time or knowledge. We also gather information on the control of other pests and diseases (use of chemical or other) and the type of weed management practices (none, mechanical, chemical, or cultural by means of pruning waste and high shade cover condition) and its annual frequency.

Regarding farm characteristics and biodiversity use, we asked for the presence and type of other crops, the presence, and types of associated trees (fruits, shade), their approximate number/density, and the reasons why they planted trees (shadow, organic matter, erosion control, timber use, natural enemies' attraction, etc.). This last information gave an interesting clue about the perception of tree importance within coffee plantations. Specific questions about the coffee plants were also asked like coffee varieties, age (or a range from the youngest to the oldest plant) and the density of the plantations (Table 4).

Finally, we collected information about annual frequency of coffee pruning and practices of coffee leaf thinning, that is generally realized two or three months after pruning, to improve the tree productivity. We also inquired about the timing of shade tree pruning, which is typically carried out either once a year after the final harvest at the end of the year (AHY) or at the beginning of the next year before the first harvest (BF)

Table 4. Synthesis of management variables and representation codes.

	Variable	Category	Unit of measurement
Plot characteristics	Varieties	CR_95, Caturra, Marsellesa (Mars), Obata, Catuai, Catimor, centroamericano (CAF1)	Binary [0,1]
	Number of coffee plants per hectare	Density	Quantitative
	Pruning	By rows coffee pruning (LCP), Selective coffee pruning (SCP)	Binary [0,1]
	Suckering	*Deshija*	Binary [0,1]
	Tree pruning season	After the harvest of the year (AHY), Before flowering (BF),	Binary [0,1]

		Before the ripening of the berries (BRB), Not pruned (NP)	
	Shade trees pruning	Regular shade tree pruning (RSP) Drastic shade tree pruning (DSP)	Binary [0,1]
	Types of shapes trees	Banana (*Musa sp.*), Poro (*Erythrina peppigiana*), Laurel (*Cordia alliodora*), fruit trees, other trees	Binary [0,1]
	CBB presence	CBBP	Binary [0,1]
Management strategies	Control of CBB	Apply: insecticide, Beauveria, Trap, picking, others	Binary [0,1]
	Management of differentiated plots in a plantation	MDL	Binary [0,1]
	Frequency of weed control	FWC	Number
	Diseases	Rust, American Leaf Spot (LS), Anthracnose (Antracn), other diseases (OD)	
	More damage than CBB	MDCBB	Binary [0,1]
	Apply other insecticide	AOI	Binary [0,1]

2. 5 Structural and functional landscape connectivity measures

In order to evaluate the role of the landscape in facilitating the dispersion of the CBB between plots and its impact on the prevalence of bored berries, we conducted an analysis of landscape metrics for each of the 66 plots. Three structural connectivity metrics were computed within 500m radius buffers around each plot: the contagion index, the Intercalation and Juxtaposition Index (IJI), and the edge density (ED) specifically for the coffee class.

The contagion index, which measures landscape aggregation based on cell adjacencies, reflects the likelihood of two random cells belonging to the same class. It is influenced by both the dispersion and intercalation of classes. For instance, a landscape with low class scattering (high proportion of similar adjacencies) and low intercalation (unequal distribution of pairwise adjacencies) would result in a high contagion value. We hypothesized that a high contagion index corresponds to a well-connected landscape, potentially leading to a higher incidence of bored berries, particularly in areas dominated by coffee plantations.

The IJI index, which quantifies coffee aggregation and describes class mixing (salt and pepper effect), is inversely related to landscape connectivity. A higher landscape connectivity result in a lower IJI index. Additionally, the ED index characterizes the aggregation of land uses, with lower values indicating higher connectivity.

We computed five different metrics of functional connectivity based on graph theory (the number of components (NC), the Class Coincidence Probability (CCP), Landscape Coincidence Probability (LCP), Expected cluster size (ECS), Area-weighted flux (AWF) (Table 5). These metrics consider the dispersal distance of the CBB. They are supposed to be more consistent in finding relationships between connectivity and the presence of the studied species than structural metrics (Table 5). Those metrics were estimated for different thresholds of CBB maximum dispersion distance (40, 60, 100, 150 and 200m) according to previous studies (Avelino et al., 2012; Gil et al., 2015; Olivas et al., 2011). To calculate the indices, we used the Iconnect library (Mestre and Silva, 2021) of the packages R (R Core Team (2022) to calculate the indices.

Table 5. Connectivity metrics based on graph theory and using different CBB dispersion distances.

Metric	Description	Relation
Number of components (NC)	Number of interconnected coffee patch groups in the landscape	>NC less connected <NC landscape + connected
Class matching probability (CCP)	The probability that two randomly chosen points (pixels) belong to the class coffee.	CCP > landscape + connected
Landscape coincidence probability (LCP)	The probability that two randomly chosen points (pixels) belong to the same group of coffee patches.	LCP > higher connectedness
Expected component size/clusters (ECS)	The expected size of the group of patches taking a random point. Value increases with smaller and less isolated groups, even as habitat decreases	ESC> higher connectivity

Area-weighted flux (AWF)	Area-weighted motion flow between all patches. It is a probabilistic measure of dispersion between two patches.	AWF > higher probability of dispersal

To understand and test the role of the different land uses elements in facilitating or retaining the dispersion of the CBB between coffee plots we calculated another connectivity index based on circuit theory for different scenarios (reflecting a less or high resistance of the different landscape elements to the CBB dispersion). Circuit theory allowed us to consider the resistance of the landscape matrix to the movement of the species. The three following scenarios were tested:

I. Coffee plantations facilitate the CBB dispersion (0 % resistance), pasture and sugar cane don't impact CBB dispersion (50% resistance) and forests elements don't allow the dispersion of the CBB (barrier 99% resistance)
II. Coffee plantations facilitate the CBB dispersion (0 % resistance), pasture and sugar cane and forests elements don't impact CBB dispersion (50% resistance).
III. Coffee plantations facilitate the CBB dispersion (0 % resistance), pasture and sugar cane don't impact CBB dispersion (50 % resistance) and forests elements are unfavorable to the CBB dispersion (80 % resistance) (allow passage with less resistance to scenario 1).

Theoretical weights were assigned to three scenarios, with scenario 1 and 3 being the closest to reality according to Avelino et al. 2012. Firstly, we created three friction maps (per scenario) with their respective resistance values for each land use to simulate the dispersion of CBB. Secondly, we applied the circuit landscape algorithm on the different friction maps to quantify the cumulative current (CBB) reaching the studied coffee plots (Dickson et al., 2019; Shah and McRae, 2008).

This algorithm is independent of the maximum dispersal distance. The nodes to be connected in the circuit corresponded to the 66 plots studied. We ran 66 circuits, each corresponding to a focal node (a coffee plot) that receives electric current (amperes) from the rest of the nodes (the other coffee plots) (modes = all-to-one). Each node sends electric current towards the focal node, meaning CBB migrates from each coffee patch towards the focal node.

In the circuit network, the current flow encounters resistors in its path, determined by the friction values assigned to the different land uses. The friction maps were created by assigning resistance values to patches of forests, pastures, sugar cane, and coffee plantations (active and abandoned) across the entire study area. We then calculated the maximum current received by each focal node, generated a 100 m buffer around the centroid of each focal node, and summed the current. This buffer ensures the average area of the plot size.

The current reaching the focal node corresponds to the CBB reaching the coffee plot; hence, the higher the value, the greater the connectivity of the coffee patch.

2. 6 Data analysis

To combine management variables and plot characteristics (local metrics), we performed Non-Metric Multidimensional Scaling (NMDS). Prior to the NMDS we scaled all variables (Table 4Table 4. Synthesis of management variables and representation codes.) to [0, 1] and used the Chord distance. Chord distance is an euclidean distance over a data table where the rows are pre-standardized to a normal distribution. The most important axes of the NMDS were used as the management, variety, and shade descriptors (Figure 6). We selected the three main axes of the ordination (where the plots were ordered) according to the weight of the variables.

Then, for the landscape metrics, we performed a principal component analysis to evaluate the degree of redundancy among the connectivity metrics and to order the sampling plot in a gradient of different measure of connectivity.

To evaluate the effect of landscape connectivity metrics, management, plot characteristics, and their possible interactions on the percentage of bored berries, we fit mixed generalized linear models (glmm) with binomial distribution and logit link function. To control for the lack of independence of the plots induced by altitude (2 levels) and landscape (14 levels), we considered to include them in the model as a random effect (Stroup, 2013).

To avoid redundancy of functional connectivity indices based on graphs and circuits (for each metric estimated in graphs we use five measures of dispersion thresholds), we fit all possible models (fixed part of the model) combining the axes in each model: plot and management characteristics, structural metrics, and functional connectivity metrics. In fact, models must have at least one predictor variable for each connectivity metric with one of the maximum dispersal distance thresholds and one connectivity metric based on circuit theory (Figure 13).

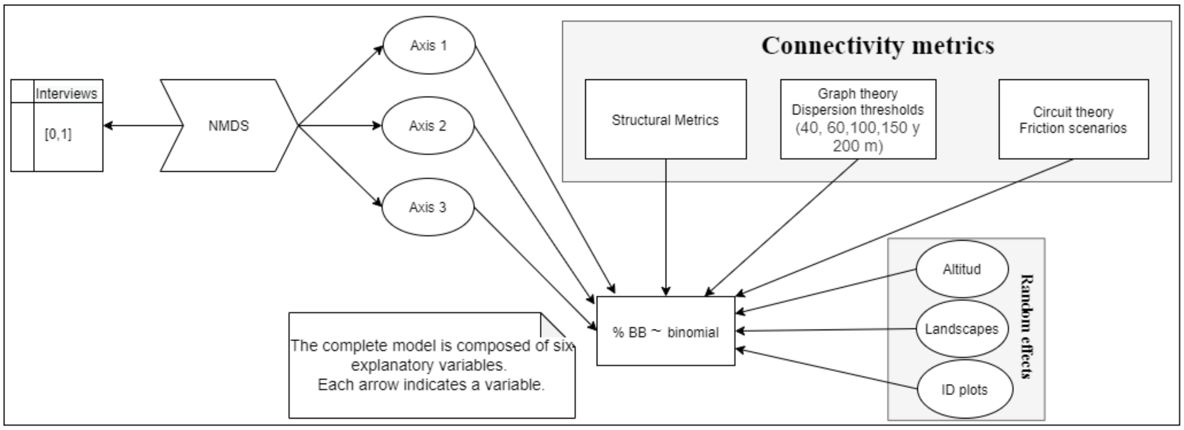


Figure 13. Representation graph of data analysis. Selection of the 15 models using the AIC and BIC criterion. Only one connectivity metrics for each box enters in each model.

We selected the 15 models that best explain the percentage of bored berries using the BIC and AIC information criteria. Finally, with the 15 selected models, we performed forward elimination (manually), evaluating for any lack of fit (quadratic terms or interactions). All analyzes were conducted in R 4.2.1 software (R Core Team, 2022). We used the metaMDS with global solution call function from the vegan (Oksanen et al. 2022), library. We used the glmer function from the lme4 library (Bates et al. 2005) to perform glmm. The diagnostics of the models were performed using the DHARMa (Hartig, 2022) library.

3. Results

We collected 29027 berries in the four sampling events. Ripe berries represented 50% (14399 berries), the green berries 45% (13041 berries) and dry berries 5% (1587 berries). The availability of dried berries decreased over the sampling time; the other states fluctuated.

In general, similar averages were recorded for all sampling events. However, for green berry, the percentage of bored berries was lower in November, and for dried berry, the percentage decreased in October and November (Table 6).

Table 6. Percentage of bored berries by category and sampling event. The value is Average [Minimum, Maximum].

Sampling event	Green berry	Ripe berry	Dry berry	Total
1 (August)	14 [3, 29]	20 [0, 47]	4 [0, 18]	38 [9, 93]
2 (September)	16 [3, 36]	18 [5, 33]	6 [0, 24]	39 [13, 84]
3 (October)	17 [1, 40]	19 [1, 40]	2 [0, 6]	38 [2, 68]
4 (November)	7 [0, 14]	22 [3, 52]	2 [0, 16]	30 [4, 75]

The maximum of the total (green, ripe and dry) bored berries incidence in the 66 plots was between 2 and 93% with an average of 36.25%. Only nine plots recorded proportions of bored berries above 60% and only four plots recorded less than 10% (Figure 14).

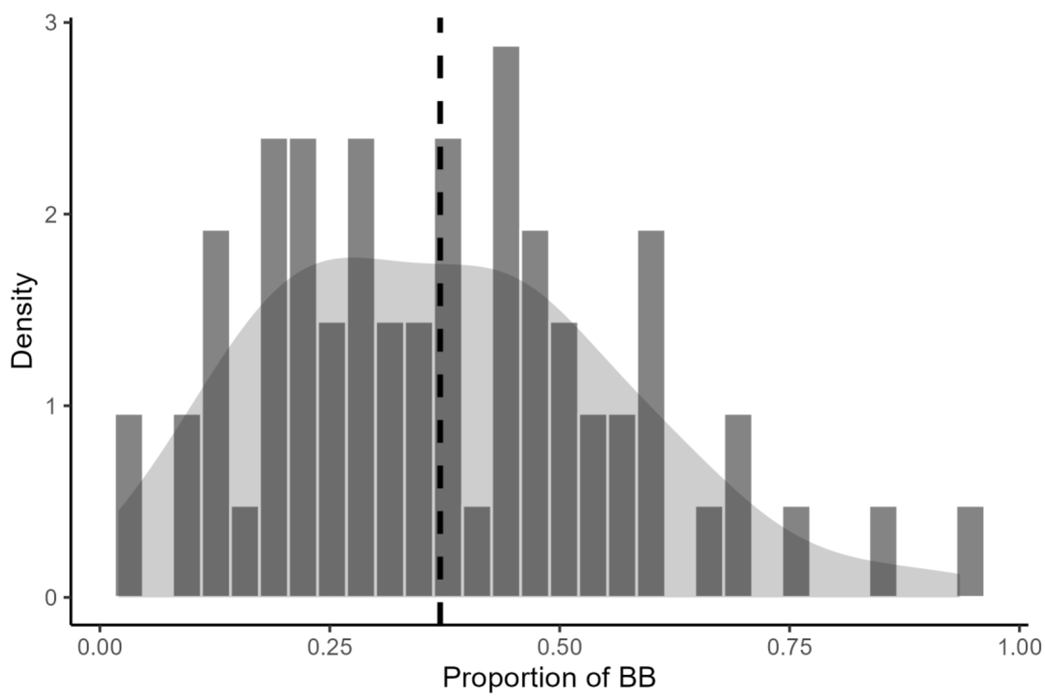


Figure 14. Distribution of proportion bored berries (BB) in the 66 plots. The grey area represents the density function.

3. 1 Characterization of the plot

In the study, farmers planted five varieties of coffee. Thirty-six percent of the plots had the Caturra variety; CR95 and Obata were reported in 24 plots, Catimor in 14 plots, Catuai and Marsellesa in 10 plots, and centroamericanoF1 in only two plots. A single variety of coffee was reported in 32 plots, and a maximum of five varieties were reported in two plots. In the other plots, there were between two and four varieties of coffee. The coffee plantation density was between 1,000 and 10,000 plants per hectare, with on average 4647 plants per ha. Pruning of the coffee plants was reported in 95% of the coffee farms among with 78% was selective pruning and only 13% was linear pruning. In 95% of the plots weeding was applied.

Ninety-two percent of the plots had shade trees associated with coffee plants. The shade trees strata present in the plots can be monospecific (16% of the plots) or a mixture of different tree species (77% of the plots). Shade trees strata was composed mainly of banana (*Musa sp.)* for four plots, Poró (*Erythrina poeppigiana*) for 46 plots, Laurel (*Laurus nobilis*) for 45 plots, berries trees for four plots and other species. In 53 plots, shade trees were pruned: 35 plots were characterized by regular pruning and 22 plots by drastic pruning. Shade trees pruning was done once to three times a year. For 43% of the plots, shade trees were pruned after the end of the harvest, for 56% of the plots before the ripening of the berries and for 33% of the plots before flowering. Three, two and one pruning per year were carried out in 17, 18 and 18 plots respectively.

3. 2 Perception of CBB damage and management

The farmers reported the presence of CBB in 37 plots (eight farms located in coffee landscapes, 16 in heterogeneous landscapes and 8 in forest landscapes). Only 13 farmers reported that damage represent between one and 28% of their production with an average of 17% of damage, the other farmers did not respond. Forty three percent of farmers consider that the damage caused by other pests and diseases is greater that the damage caused by the CBB (three farms located in coffee landscapes, 15 in heterogeneous landscapes and 11 in forest landscapes). Leaf spot was the main disease mentioned by 71% of farmers, Rust by 68% and Anthracnosis by only 9%. Regarding management of CBB, 33 plots received some type of management (nine farms located in coffee landscapes, 14 in heterogeneous landscapes and 10 in forest landscapes). In 21 plots the farmers used CBB traps, in 16 plots they used to apply *Beauveria bassiana* and to apply insecticides, and in only seven plots the farmers did sanitary harvest. Three plots combined all these practices to control CBB (traps, Beauveria, insecticides and sanitary harvest); two plots combined traps, Beauveria and insecticides; 14 plots combined at least two management practices (traps and Beauveria or insecticide and traps) and 14 plots applied only one practice. Some farmers (31%) make a different management of their plots based on their specificity. On average they did weeding control three times per year, mainly using chemical inputs (71%).

3. 3 Multivariate ordination of management and plot characteristics

The ordination stress was 14%, indicating a reasonable solution. The NMDS 1 (Figure 15) separates the plots (negative values) in farms that had mainly Catimor, CR_95 and Obata varieties and where the farmers performed selective pruning (SCP) of the coffee plants. In addition, the shade trees strata were composed mainly of banana, Laurel and poró, they performed regular pruning (RSP) of the shade trees before flowering (BF), and after the harvest of the year (AHY). The farmers on this part of the axis, considered that other diseases caused more damage than CBB (MDCBB). On the other extreme of NMDS 1 (positive values), the coffee plantations were mainly composed of Caturra, the plots had other trees species, farmers performed drastic shade tree pruning (DSP), they mentioned presence of CBB (CBBP), applied insecticide and other insecticides (AOI), they used Beauveria, traps and they conducted a different management per lot (MDL). The farmers also reported the presence of rust and other diseases (OD).

On the NMDS 2 (Figure 15a), farms were mainly differentiated by presence of CBB (CBBP) (positive value) and presence of rust and the perception that other diseases cause more damage than CBB (MDCBB) and perform drastic shade tree pruning (DSP) (negative value). Farms reporting presence of CBB, also applied Beauveria, traps, and other insecticide (AOI). The coffee shade in the plots with presence of CBB is composed of

Laurel, and the farmers used to prune shade before flowering (BF), and they applied a different management per plot (MDL).

The NMDS 3 is less discriminant and separates the plots by coffee varieties mainly Catimor and Caturra for negative values, and Obata, CR_95 and Catuai for positive ones (Figure 15b). With respect to landscape types, there is no clear management gradient for the plots according to the type of landscape.

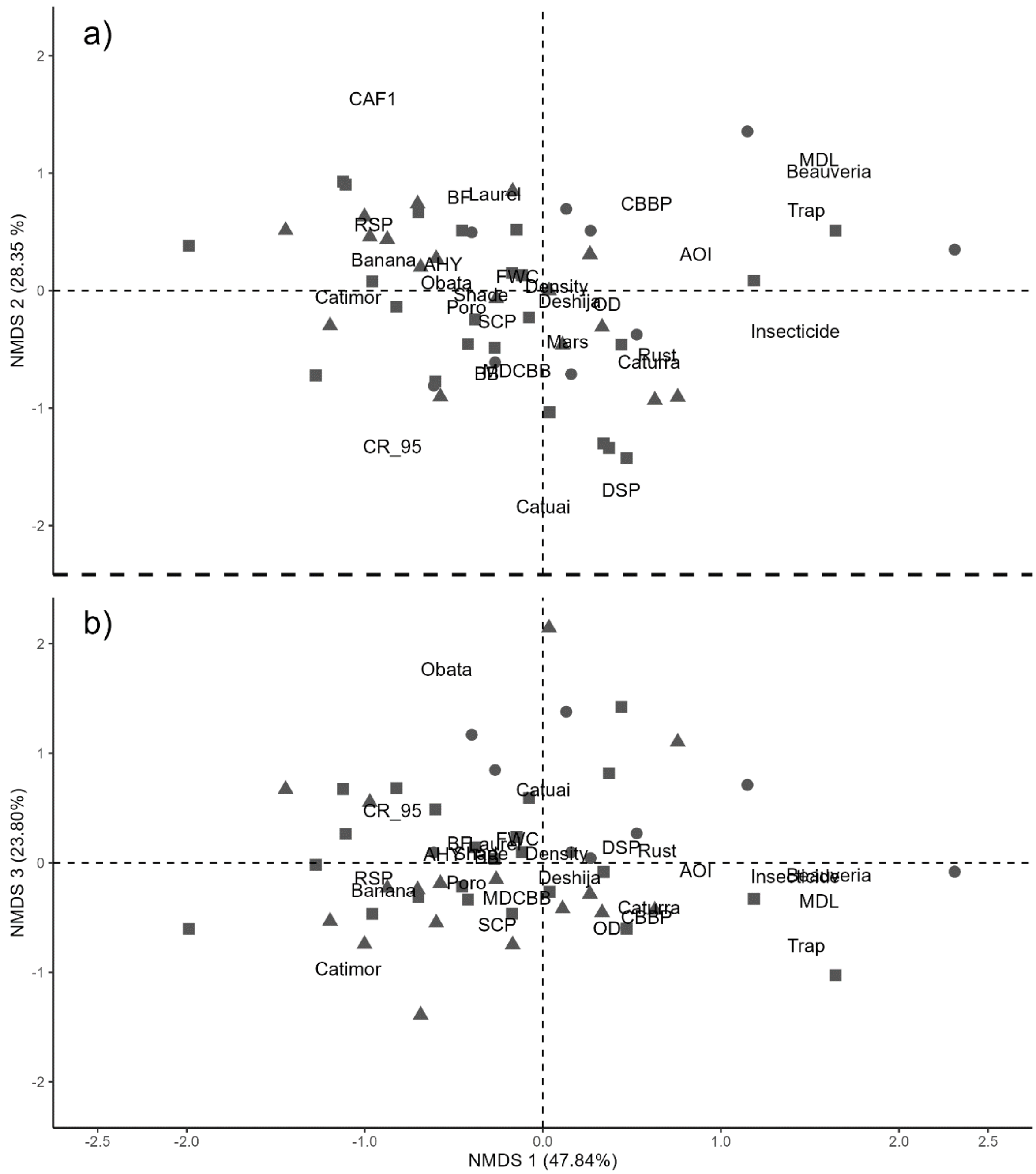


Figure 15. Ordination of plots according to characteristics of coffee plots and management.The point shape indicates the type of landscape where the plot is located: square = forest; circle = coffee; heterogeneous triangle = mixed.

3. 4 ACP on connectivity metrics

In the principal component analysis, the first two ordination axis explained 66% of the variability of all table. In the PC1, there was a gradient of plots from low connectivity (negative values) to high connectivity. All functional connectivity metrics based on graph theory showed high redundancy. The number of components (NC) (negative values on PC1) varied according to the dispersion distance threshold used, showing a group of the NC for threshold of CBB maximum dispersion distances around 40m and 60m and another one for threshold between 100m and 200m. The CCP, AWF and ECS metrics were opposed to NC on PC1. They showed high level of correlation with the plots that are in coffee landscapes. The PC2 is related to the edge and iji structural metrics with a positive correlation with the number of estimated components with dispersion thresholds between 40 and 60m and the metrics AWF computed using threshold of CBB maximum dispersion around 40, 60 and 100m. The contagion was negatively related to the edge and iji and positively (poor relationship) with the connectivity metrics estimated with circuits. In the space of the first two principal components, circuit-based metrics are of least importance (**¡Error! No se encuentra el origen de la referencia.**).

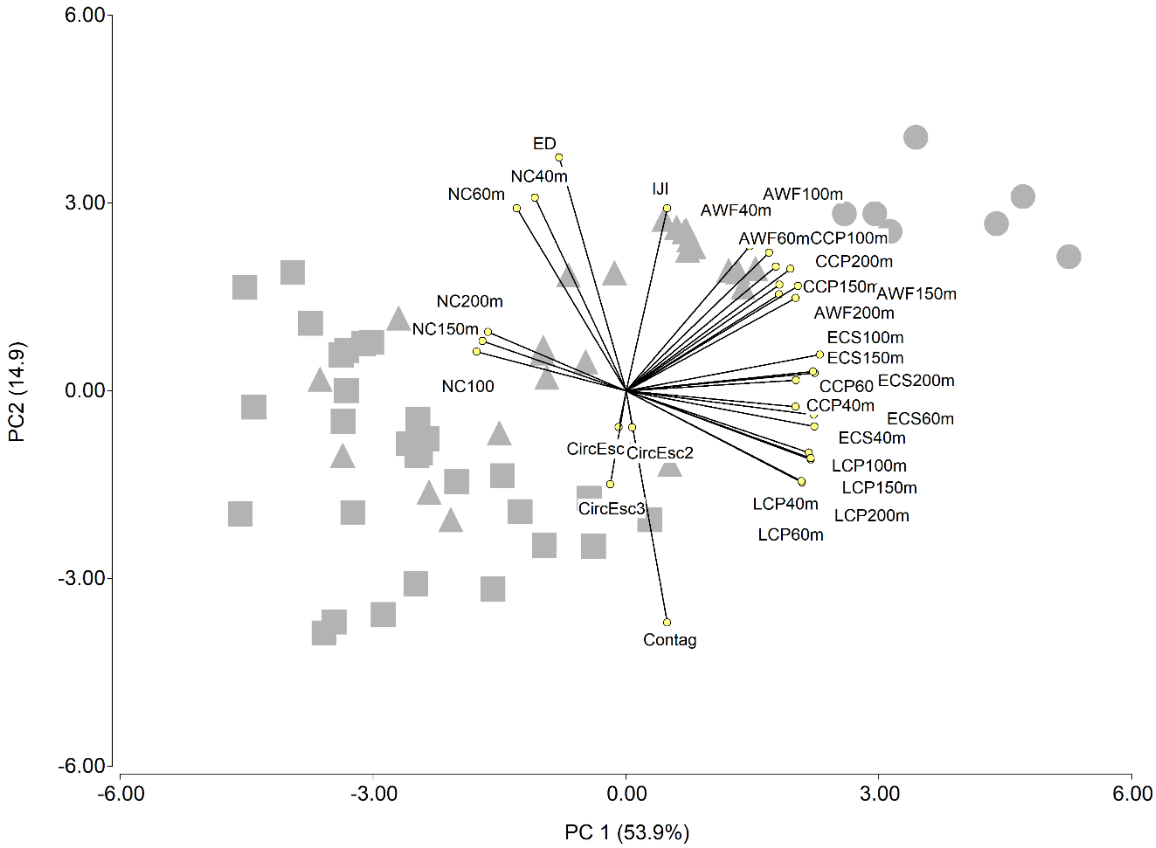


Figure 16. Ordering of the sampling plots through the different connectivity metrics and their relationships. ED is the Edge density, IJI is the Intercalation and Juxtaposition Index, contag is the contagion index, CircEsc1, 2 and 3 correspond to the different connectivity indices based on the circuit scenarios. NC is the number of components, CCP is the class matching probability, LCP is the landscape coincidence, ECS is the expected component size and AWF is the area-weight flux. The numbers 40, 60, 100, 150 and 200m correspond to the maximum dispersion distances used as threshold to estimate the connectivity metrics based on graph theory. The point shape indicates the type of landscape where the plot is located: square = forest; circle = coffee; heterogeneous triangle = mixed.

3. 5 Relationships between landscape connectivity metrics, plot management and the percentages of bored berries

Of all the possible models adjusted, the 10 models that best fit to explain the incidence of boring berries, the explanatory variables that stood out the most were the ordination axis 2, the number of components (NC) with dispersion distances of 100, 150 and 200 m (in three models) and class match probability (CCP) with dispersal distances of 60, 100 and 200 m (in three models), landscape match probability (LCP) with dispersal distances of 100 and 150 m (in two models), the circuit metric based on scenario three in two models, and the intercalation and juxtaposition index in one model (Table 7).

Table 7. The 10 models that best explained the incidence of bored berries and associated model selection statistics.

Management	Structural	Graph	Circuitscape	logLik	BIC	dLogLik	dBIC	df	weight
NMDS2	IJI	NC100m	Esc3	-277.35	588.23	7.703	2.545	8	0.0171
NMDS2	**-**	**NC100m**	**-**	-280.27	585.68	4.786	0.000	6	0.0613
NMDS2	**-**	**NC150m**	**-**	-280.78	586.70	4.279	1.013	6	0.0369
NMDS2	**-**	**NC200m**	**-**	-281.32	587.79	3.733	2.106	6	0.0214
NMDS2	**-**	**CCP60m**	**-**	-281.61	588.36	3.448	2.675	6	0.0160
NMDS2	**-**	**CCP100m**	**-**	-281.65	588.45	3.405	2.763	6	0.0154
NMDS2	**-**	**CCP200**	**-**	-281.32	587.78	3.740	2.093	6	0.0215
NMDS2	**-**	**LCP100m**	**-**	-281.59	588.32	3.467	2.638	6	0.0163
NMDS2	**-**	**LCP150m**	**-**	-281.62	588.38	3.436	2.700	6	0.0159
NMDS2	**-**	**-**	**Esc3**	-280.91	586.96	4.149	1.273	6	0.0324

Based on the evaluation of residual diagnostics using the DHARMa package (Hartig, 2022), the best model to explain bored berries percentage was ordination axis two (NDMS2), which mainly represents the management applied by farmers with a quadratic term, the NC with a dispersion threshold of 100m (NC100m), the interaction between the NDMS2 and the NC100m, and by the scenario of connectivity based on Circuitscape (Esc3) (Table 8). In this scenario of connectivity, the pastures and the sugar cane have intermediate resistance (50%) and the forests make it difficult to pass (20%).

Table 8. Marginal hypothesis of the predictor variables that explain the incidence of berries borer and associated statistics.

Predictor	Chisq	Df	Pr(>Chisq)
NMDS2	1.86	1	0.172
$NMDS2^2$	7.73	1	0.005
NC100m	8.64	1	0.003
NMDS2*NC100m	7.95	1	0.004
CircuitsEsc3	5.55	1	0.018

Plots where farmers mention that they have the presence of CBB, that they manage the CBB and that they carry out differentiated management of their lots (NMDS2 positive), have less bored berries when they are located in coffee patches that are less connected to each other at a maximum distance of 100m (greater number of component) in comparison with the same plots characteristics located in more connected coffee patches (Figure 17a). Conversely, plots where the farmers consider that other diseases cause more damage than CBB and so that are less managed for CBB, have less bored berries when they are in coffee patches more connected in comparison with the same plots characteristics located in less connected landscapes (Figure 17a).

Under the scenario that forest patches (20%) exert greater friction to CBB dispersion than pastures and sugarcane (50%), plots receiving fewer streams (fewer CBB arrival paths) have a lower incidence than those plots that receive a greater current (longer arrival path of CBB) (Figure 17b).

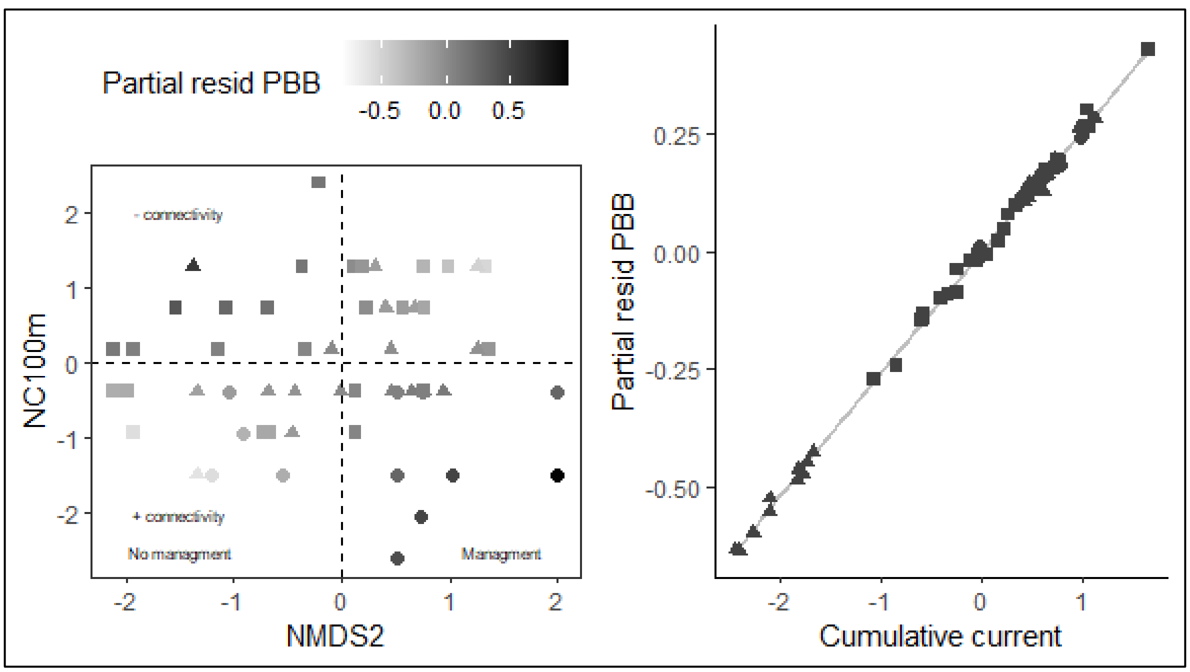


Figure 17. a) Interaction of NC100m and NMDS2 and b) landscape connectivity metric using circuitscape. The values on the Y axis correspond to the partial residuals of the proportion of berries borer (PBB). The point shape indicates the type of landscape where the plot is located: square = forest; circle = coffee; heterogeneous triangle.

4. Discussion

Our hypothesis that there is a synergy between management and connectivity is partially confirmed. Specifically, we found that coffee plots with both landscape connectivity and management have a higher incidence of bored berries than those plots that lack both connectivity and management. The response to connectivity supports the hypothesis of resource concentration at landscape scales (O'Rourke & Petersen, 2017). However, we were surprised to find that unconnected and unmanaged plots have a higher incidence of bored berries than connected but unmanaged plots. This unexpected result can be explained by the refuge hypothesis proposed by Tscharntke et al. (2016), which suggests that natural habitats surrounding crops do not necessarily improve biological control of pests.

4. 1 Bored berries incidence

We found a high incidence of bored green (average between 7 and 17%) and ripe berries (average between 18 and 22%) between August and November, with a maximum incidence of bored berries between 2 and 93%. We believe that it may be due to 1) little management that is carried out to control the CBB (less than 50% of the plots receive specific management for the CBB) (Ramirez-Valerio, D, 2021, personal communication), 2) the high proportion of abandoned coffee plantations that serve as sources of dispersal of the CBB to active coffee plantations; Out of the 3,900 ha of coffee accounted for in the study area, 901 ha are abandoned coffee plantations, representing 23% of the coffee area (Land uses Map, 2021). 3) The price off the production does not receive a penalty for the percentage of bored berries (Ramirez-Valerio, D, 2021, personal communication). These results are consistent with those reported by the farmers in the interviews; some farmers reported damage from the CBB around 17%.

4. 2 Characterization of the plot and perception of CBB damage and management

Non-metric multidimensional scaling (NMS) analysis ordered the plot with a mixture of coffee varieties between susceptible and resistant to rust attack (Catimor, CR_95 and Obata). Since the 2012 epidemic caused by coffee rust, many coffee plantations in Central America have been renewed with resistant varieties (Avelino and Rivas, 2014).

The presence of rust resistant coffee varieties (e.g. Obata, Marseillaise, Centroamericano1 (https://varieties.worldcoffeeresearch.org/es/varieties/), the few reports of CBB damage (13 farmers reported damage) and the few farms that specifically manage for CBB control suggest that farmers are more sensitive to other diseases (mainly rust) than to CBB. All varieties used by farmers are short and compact and good yields, facilitating the collection of berries at harvest time, however, in most of the farms evaluated we found high incidences of bored berries.

4. 3 Landscape connectivity

We observe three groups of connectivity metrics that add different information to the connectivity of the landscape. None of the metrics based on graph theory vary enough with increasing scattering distance except for the number of components (NC) that are separated. Possibly the sensitivity of these metrics at fine landscape scales are not a good indication of landscape connectivity for this study. On the one hand the structural metrics of edge, contagion, intercalation, and juxtaposition index can be useful for pest insect that use edges in their movement, which is not the case with the CBB. On the other hand, there is the group that corresponds to the index based on the accumulated current (circuits) as a measure of the flow of CBB that reaches a plot. The indices based on scenarios 1 and 2 show less variation than the index of the scenario 3 (Grass and reeds allow passage; 50% resistance value while the forest hinders: 20% resistance value). Scenarios 1 and 2 are unrealistic simulations given that different studies have shown borer dispersion in different land uses ((Declerck et al., 2013; Olivas et al., 2011; Vilchez-Mendoza et al., 2023, unpublished), while the values resistance of scenario 3 are in line with those reported by

Olivas et al. (2011), Avelino et al., (2012) and Vilchez-Mendoza et al. (2022) in the same landscape. Olivas et al. (2011) reported that CBB catches with traps are greater in grasslands and sugar cane than in forests. They found that the amount of CBB captured in forests was only 12% and 19% of the amount of CBB captured in sugarcane and pastures.

4. 4 Relationship between the bored berries incidence with connectivity landscape and management

Our results support the importance of the landscape context and the management of damage caused by pests (Bianchi et al., 2006; Karp et al., 2018; Paredes et al., 2021; Rusch et al., 2011; Soti et al., 2019; Zamberletti et al., 2021). Specifically, the incidence of bored berries recorded in the study plots is not only a consequence of the management and characteristics of the plots, but also of the degree of connectivity of the landscape and land uses that hinder or facilitate the dispersion of the CBB. We demonstrate the importance of forest patches near coffee plantations in hindering CBB movement with respect to pasture and sugarcane land uses. Also, forests provide habitat for natural enemies of CBB (e.g., birds (Martínez-Salinas et al., 2016)), decreasing the chance that CBB will be able to colonize new coffee plantations. A study carried out by Aristizábal & Metzger (2019), found a negative relationship between the abundance of CBB and greater forest cover.

Avelino et al. (2012) suggest that the ability of the CBB to disperse is controlled by the structure of the landscape, and that forest and pastures land uses limited coffee berry borer dispersion. Our results support their assertion of the role of the landscape and the importance of the forest in limiting CBB dispersion, but we believe that pastures and sugar canes can facilitate CBB dispersion, mainly by wind action (Avelino et al., 2012; Vilchez-Mendoza et al., 2022, unpublished). In our simulation scenario using circuitscape where pastures and sugar cane facilitate CBB dispersion (a permeability value of 50%) and the forest hinders it (permeability value of 20%), we found a positive relationship between the amount of current received by coffee plots (CBB flux) and the incidence of bored berries.

When there is high population of the CBB in coffee plots and few berries available (interseason), greater dispersion occurs in adjacent land uses (Olivas et al., 2011, Vilchez-

Mendoza et al. unpublished). But CBB is constantly emerging from berries, and continues to be found in adjacent land uses, possibly brought by the volatile compounds of berries in good condition and high quality (Dwyer et al., 2016) to nearby coffee patches. This attraction would be greater if the interface between coffee patches is pasture or sugarcane. If the interface ie a forest patch this would hinder movement, increase the probability of being predated and prevent the dispersal of volatile compounds from coffee berries.

Our hypothesis is supported by the results we found; management is not a sufficient security for pest control if the landscape context is not considered. Our results show that plots that have CBB management and are surrounded by coffee patches (NC100m) have a higher incidence of bored berries than plots that are isolated and have CBB management. Possibly coffee plots are connected to abandoned coffee plantations or poorly managed coffee plantations. Abandoned coffee plantations are common in the landscape and represent 23% of the total coffee area. They can be reservoirs of CBB and sources of dispersal in the landscape (Johnson and Manoukis, 2020). Management practices such as sanitary harvest and frequent harvests (Benavides et al., 2012; Cure et al., 2020; Pardey, 2006) can contribute to maintaining relatively low CBB populations on farms connected to poorly managed (Johnson and Manoukis, 2020) or abandoned coffee farms. However, this component is not enough. If there is no land uses that makes movement between plots difficult, the CBB will be attracted to the quality of the berries in the managed plot (Dwyer et al., 2016).

In plots where there is no specific management of the CBB and that are connected, there is less incidence of bored berries than in plots where there is no specific management of the CBB, and plots of coffee are isolated. Four hypotheses can be formulated. that the first one is that isolated plots maintain high borer populations that remain in the plot itself, without the possibility of moving to neighboring plots; it may be due to the size of larger coffee patches with sufficient refuge and resources (refuge hypothesis; Tscharntke et al, (2016),). Although we did not evaluate the size of the patches, we believe that it can explain this mechanism.

We need to investigate the effect of the size of the coffee patches in this context. The second one is that the environment favors population growth. In these coffee plantations the farmers carry out drastic pruning of tree shade, allowing an increase in temperature and a shorter generation time of the CBB (Bustillo et al. 1996, Damon 2000, Jaramillo et al. 2009, Jaramillo 2010, Azrag et al., 2020). The third hypothesis is that in connected plots without specific management, the action of natural enemies might be facilitated. Finally, the fourth hypothesis is that connected plots facilitate the dispersal of the borer outside the plots and this is the "connectivity hypothesis" (Tscharntke et al, (2016). But we can think that the connected plots have a greater movement resistance (bosque) and the unconnected plots have a lower resistance and possibly the wind is moving CBB beyond the dispersion threshold used in the metrics (threshold of 100m between patches).

5. Conclusions

Our results support the importance of the landscape context in farm management plans. It is not enough to control CBB if there are sources of CBB dispersal in the surrounding landscape or land uses that facilitate movement. It is possible that CBB is attracted to well-managed plots because of the good appearance of the berries. One way to reduce the probability of movement of CBB between neighboring coffee plantations may be the incorporation of buffers of multi-layered trees (a multi-layered live fence is not enough) around the plots. However, this option may be expensive and expected long-term effect. In addition, this reduces the effective area of coffee plots. One could think of incentives for the implementation of multi-stratum tree buffer (e.g., payments for ecosystem services, carbon certificates), and keep coffee within the strips with low densities, favoring habitat for natural enemies (e.g., birds, ants) (Martin et al., 2015; Martínez-Salinas et al., 2016) and providing other income alternatives to farmers (e.g., fruits, wood, firewood). The other way, with immediate results, is to carry out cooperative management among the farmers who share the surrounding landscape through the synchronization of the practices that they usually apply (Schellhorn et al., 2015).

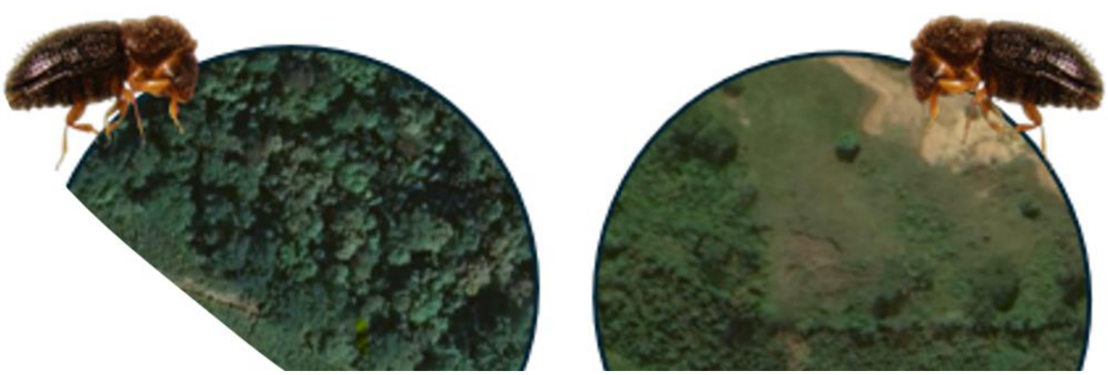
The use of connectivity metrics and graph-based circuit theory allowed us to understand the role of different land uses on CBB dispersion. This study adds to the recognition of landscape connectivity from the perspective of the role of different land uses on pest dispersion (Avelino et al., 2012; Moreno et al., 2022; Vilchez-Mendoza et al., 2022). The synergy between connectivity and management in coffee plots depends on multiple mechanisms (e.g., concentration of resources, microclimatic conditions, management, landscape configuration and connectivity). By understanding these mechanisms, farmers can improve the management of their coffee plots toward optimal productivity while promoting sustainability.

IV. Chapter III. Quantifying movement of the Coffee Berry Borer at the interface between coffee plantations and adjacent land uses

This chapter has been accepted in the special edition of the journal Frontiers in: Sustainable Food Systems-Crop Biology and Sustainability.

The chapter focuses on investigating the effect of land uses adjacent to the coffee plantation on the movement of the borer. Traps were placed on transects at the interface between active coffee plantations and adjacent land uses to quantify the CBB in active flight outside of coffee plantations.

We present a novel method to count CBB captured in traps using computer vision.



Quantifying movement of the Coffee Berry Borer at the interface between coffee plantations and adjacent land uses

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Keywords: *Hypothenemus hampei*, pest management, weather, edge effects, Costa Rica

Abstract

Insect pests cause important crop production losses worldwide. Their distribution and movement are affected by climate and land use change and agriculture intensification. Site colonization by insect pests is dependent on pest dispersal capability, the availability of resources, the presence of competitors or predators, the weather conditions and the characteristics of the surrounding landscape. Movement of pests between the plots might be considered in pest management strategies to counterbalance the traditional plot oriented strategies. In this study, our objective was to provide evidence of the movement of the coffee berry borer (CBB), the most important pest in coffee cultivation, from neighboring coffee plantations to adjacent land uses at different time periods of the coffee production cycle. For 10 months we captured the CBB with funnel traps in 13 coffee plots that had an interface with forests, pastures, and abandoned coffee plantations in Costa Rica. At each interface, we established three transects with a minimum distance of 50 m between them, in the direction of the wind. Within each transect, we placed four traps 20 m apart. We fitted generalized linear mixed models to evaluate the relationship between CBB captures and the type of interface, the position of the trap, wind velocity, rainfall, temperature and relative humidity, and their interactions. Our findings suggest that CBB moves into adjacent land uses when the coffee resource in the plot is limited. This effect varies according to the interface and the position of the trap. We also found an interaction between the interface and the position of the trap with the wind and relative humidity. Our findings suggest that movement of the CBB partly depends upon the adjacent land uses. The forest creates a barrier to CBB movement and may prevent the transport of the CBB considering the action of the wind speed. The pasture may facilitate movement of the CBB through the action of the wind speed and infest coffee plantations beyond its dispersal capacity. Our results

support the importance of considering the landscape context when developing CBB management strategies.

1. Introduction

The dispersion of insect pests results from an interaction between intrinsic biological characteristics of the species, biotic (availability of resources) and abiotic conditions of their environment. Successful colonization of sites by agricultural insect pests depends on the dispersal distance capacity of the individuals, the surrounding landscape characteristics (hostility of the matrix and energy wear), the availability of resources, the presence of competitors, predators, and the climatic conditions (Tischendorf and Fahrig, 2000; Laska et al., 2022). Most insect pests locate their hosts through visual and olfactory cues. A disruption of these signals can therefore reduce the incidence of attack on adjacent crops (O'Rourke and Petersen, 2017). Understanding insect pest dispersal strategies and the role of the landscape environment may shed light on control intervention (Hernández-Andrade et al., 2019).

The coffee berry borer (Hypothenemus hampei) is the most destructive pest in coffee cultivation, causing significant damage to the fruit and resulting in economic losses for farmers (Castaño, Benavides and Baker, 2005). CBB is present in all coffee-producing regions (Baker et al., 1992; Damon, 2000; Dickson et al., 2019) across the world likely due to passive transport by wind, workers, vehicles, and commerce, or by harvest-time workers moving from plantation to plantation (Damon, 2000). Once established in the plantation, the CBB female is the only one that can disperse from the infested berries by flying or walking to colonize new fruits (Damon, 2000; Benavides, Gongora and Bustillo, 2012). The main peaks of the CBB dispersion by flight usually occur during the dry season, after a rainfall and before the harvest period, induced by increased humidity and high temperatures (Baker et al., 1992; Mathieu, Marchillaud and Frcrot, 1997) and by olfactory stimuli mainly volatiles like alcohols, emitted by fruits during the ripening process (Mathieu et al., 2001). Around 10% of the fruits remain on the plant and on the ground after fruits harvest (Chamorro Trejos, Cárdenas Murillo and Herrera Herrera, 1995). The CBB individuals can survive within these residual fruits, waiting for optimal conditions to emerge. They will partly constitute the new population that will colonize the new fruits of the following season of production.

This pest is known to have a limited flying capacity but only few studies have set up specific experiments to evaluate it. Studies assessing CBB movement within coffee plantations report up to 348m under controlled conditions (Leefmans, 1923) and up to 30 m after coffee pruning in field conditions (Castaño et al., 2005). Using molecular markers, Gil et al., (2015) report that adults managed to fly up to 65m. However, in the literature there is little information about the movement of CBB in land uses adjacent to coffee plantations, and how these land uses can facilitate or prevent the movement of the pest. On this matter, Johnson and Manoukis (2020), report a greater flight activity of the CBB in poorly managed coffee plantations than in abandoned coffee plantations and forest, while Olivas et al. (2011) demonstrate that CBB can move up to 140m into adjacent land used from coffee plantations, being forests the land use showing the greatest friction to CBB movement. Moreover, other studies focus on the incidence of bored fruits rather than CBB movement, assessing the effect of landscape composition and configuration on the level of pest damage, and hypothesizing a barrier effect or the action of natural enemies in adjacent land uses (Avelino et al., 2012; Aristizábal and Metzger, 2019; Mosomtai et al., 2021; Vilchez-Mendoza et al., 2022).

In this study we aimed to provide evidence on the movement of the CBB from coffee plantations to adjacent land uses and vice-versa, throughout a coffee production cycle (from harvest to the appearance of the new fruits suitable for colonization). We hypothesize a spillover effect when coffee plantations do not have berries available ("hypothesis of absence of resources") due to harvest and during the flowering period. In this case, the CBB tends to disperse into adjacent land uses to search for new resources outside the coffee plantation that would result in an increase in captures in traps far from the edge of the plantation. The dispersion can be prevented or facilitated by different land use surrounding the coffee plot. Specifically, 1) the forest adjacent to coffee plots may act as a barrier for the dispersion of the CBB and may increase CBB predation, given its vegetation complexity and the presence of the CBB natural predators; 2) the pasture adjacent to coffee plots may facilitate the dispersion of the CBB, with few vegetative barriers and higher winds assisting in flight of the CBB; and 3) the abandoned coffee plots adjacent to coffee plots may contribute to an increase in CBB population, given that no management interventions are conducted in these plots.

2. Methods

2. 1 Study area

The study was conducted from August 2020 to June 2021, considering the periods of greatest coffee berry borer dispersion (April-June) when the rainy season begins and the first cohorts of fruits begin to be suitable for colonization, and after the harvest period (December-January). The study was set up in the Central Biological Volcanic Corridor of Talamanca (CBVCT), situated in southeastern of Costa Rica on the Caribbean slopes of Central cordillera (Figure 18). This area offers climatic conditions that favor the CBB development, with an annual rainfall of 2700mm and 22°C of temperature in average. Wind direction is oriented east/northeast all year with an annual average speed of 2.77 m/s (National Meteorology Institute, SA).

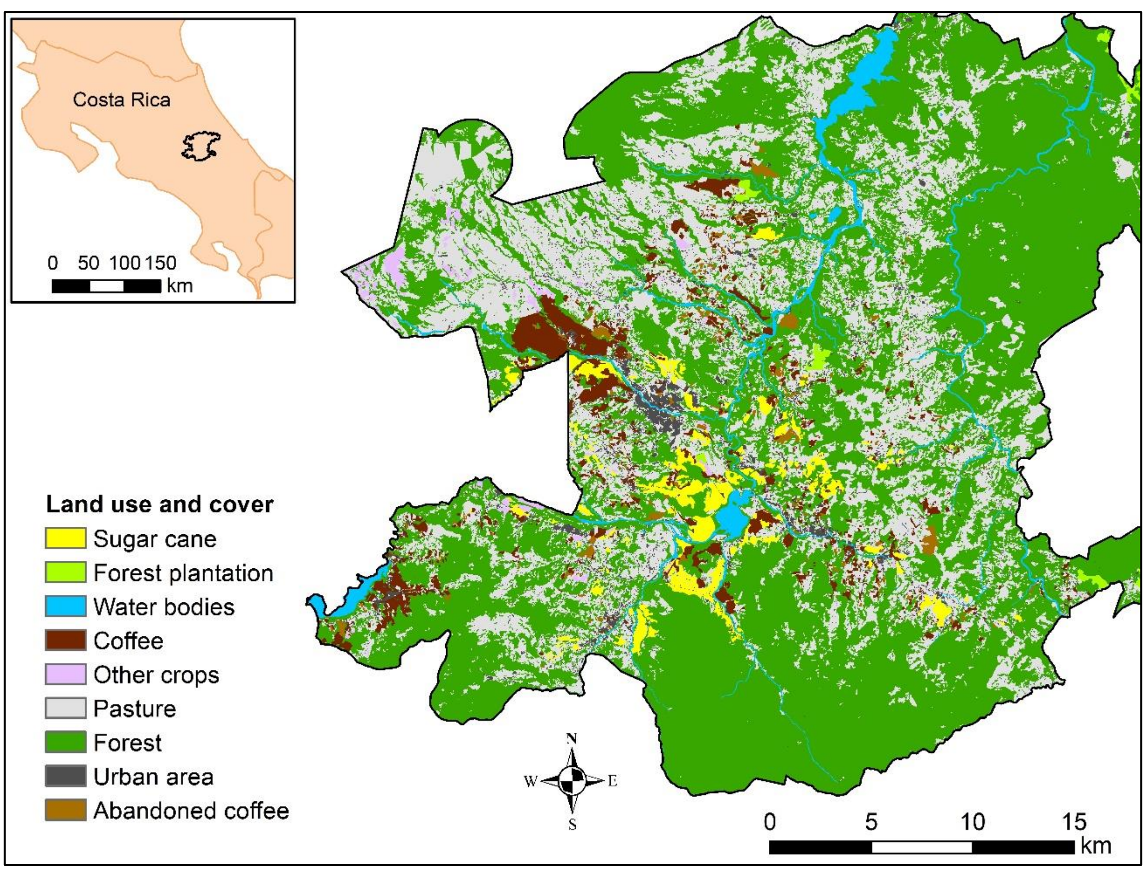


Figure 18. Location of the studio area.

2. 2 Site selection

Thirteen coffee plots characterized by an interface with either secondary degraded forest (n=6), pasture (n=5) or abandoned coffee (n=3) were selected. These land uses correspond to the dominant land uses in our study landscape. These plots were selected using an updated land use map for the study region (Amante 2020), through verification on the field and based on farmers allowance to work in their lots. The selected abandoned coffee plantations have been abandoned for at least 2 years. Information about structure and composition of the vegetation in these adjacent land uses was not available.

At each interface, three transects were located with a minimum distance of 50 m between each other (the largest was 60m). Four coffee berry borer traps (Brocap® + commercial attractants which is a mixture of methanol-ethanol 3:1 volume) separated by 20 m between each other were placed along each transect to avoid interference between the traps. The traps were located at a height of 1.20 meters from the ground. The first trap was located within the coffee plot, the second one at the border between the coffee plot and the adjacent land use, and the following two traps were located within the adjacent land use at 40 and 60 m from the first trap (considered as the source of CBB) (Figure 19). The transects were arranged in the direction of the prevailing wind (north-northeast or south, south-west). We also made sure that transects were not located in areas with slope higher than 30 degrees.

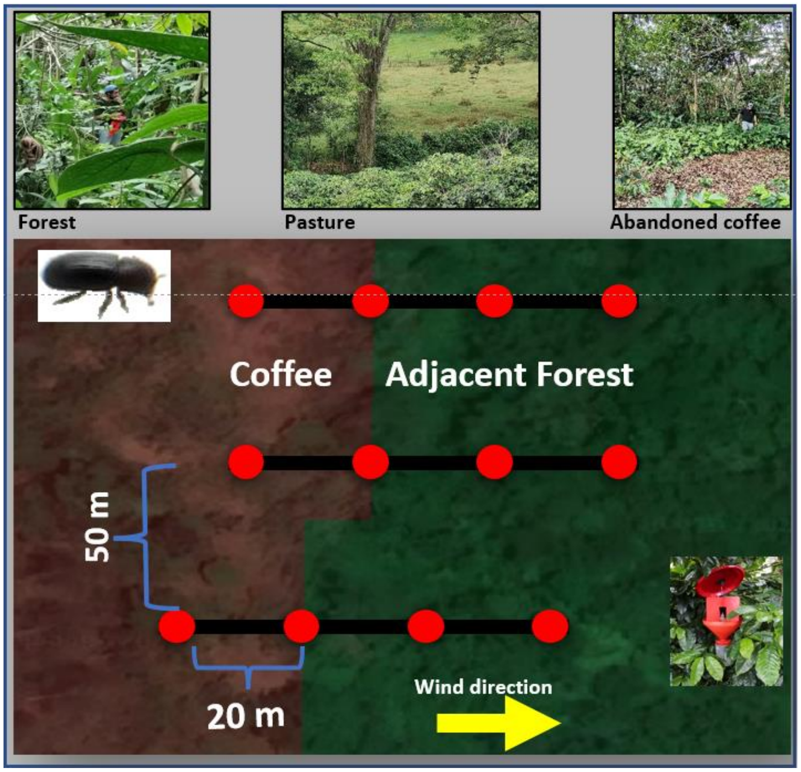


Figure 19. Design of coffee berry borer traps (in red) in coffee lands and adjacent land uses.

2. 3 Data collection and processing.

Traps were checked every 12 to 15 days and brought back to the laboratory for processing. Since counting CBB is a tedious and time-consuming task, we considered the use of artificial intelligence through signal detection algorithms to identify and count coffee berry borer specimens collected in traps. To do so we trained Yolov5 (Jocher *et al.*, 2021) core based on Corigan pipeline, an image analysis pipeline developed for small object detection using high resolution images (Tresson *et al.*, 2019). For training and validation, we used high-resolution photographs of CBB, taken under laboratory conditions. The pipeline was trained using photographs only containing CBB specimens, photographs in which CBB was combined with other species of Scolytinae, and photographs also including litter. This allowed to replicate the conditions in which CBB samples are usually collected in the field. Photographs were taken using a Panasonic DMC-G2 camera with a light aperture of 3.5, exposure time of 1/125s, an ISO of 100 and a focal length of 14 mm and at a resolution of 4000 x 2672 pixels of 180 dpi and 24bit depth. We used 318 photographs (with 4818 CBB) for training and 30 photographs (with 1430 CBB) to validate (see the algorithm in https://github.com/SVMendoza/Detection-and-count-CBB). Photographs were split into small segments to facilitate the training of the pipeline (Figure 20).

We took three photographs of each sample collected in the field. When the amount of CBB in a sample was substantial, the sample was divided into three parts to photograph each of them, and then add up the number of individuals detected. Throughout the study, this procedure was carried out only for two samples with high number of collected individuals. For the analysis, we decided to work with the maximum number of CBB detected by the pipeline in any of the three photographs. A total of 9404 photos were processed with the pipeline.

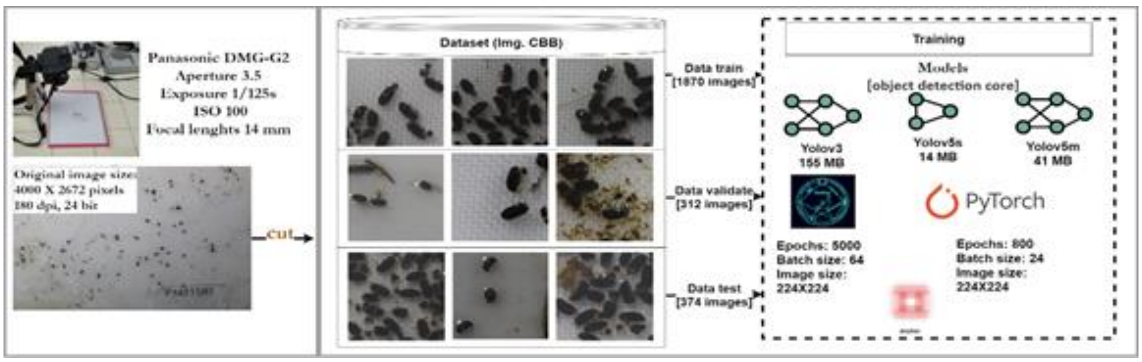


Figure 20. Representation of the steps training for pipeline.

2. 4 Climate variables

Climatic variables were obtained from the databases The Prediction of Worldwide Energy Resources (POWER) (https://power.larc.nasa.gov/docs/referencing/). The selected variables for this study were wind (speed (m/s) and direction (degrees)), relative humidity (%), daily precipitation (mm), and temperature (^{0}C). Since the traps were checked in a time interval between 12 and 15 days, we estimated the means of the temperature, of the relative humidity, and of the wind (speed and direction) and the accumulated precipitation for each time interval.

2. 5 Data analysis

To reduce the effect of transects within each site, we estimated the average CBB capture by site, trap position (coffee, edge, 20m and 40m), and date of capture (10 month of samples). All our analyzes were performed with this reduced data set.

Subsequently, to test differences between type of adjacent land use (forest, pasture, or abandoned coffee), trap position, and its interaction on the CBB captures, we fitted a generalized linear mixed model (glmm) using library lme4 (Bates et al., 2015) in R (R Core Team, 2023). We used a negative binomial distribution (function glmer.nb) and as a random effect we included the site (farm) and position of the trap since the traps were operated for 10 months (approximately 20 evaluations). Following a significant interaction between land use and trap position, we used Tukey's multiple comparison tests, using the emmeans (Lenth, 2023) and multcomp (Hothorn, Bretz and Westfall, 2008) libraries in R (R Core Team, 2023).

To add the effect of CBB capture time and its interaction with adjacent land use and trap position, we fitted a generalized additive mixed model (gamm) with negative binomial distribution. This model is similar to the generalized linear model with the difference that the evaluation time consists of a cubic smoothing base function, the random effects are the site (farm) and the position of the trap to consider variation between the samples. In addition, we added to the model an autoregressive order-1 (AR1) on the residuals to consider repeated measures across time. This model was built using the mgcv library (Wood, 2004).

Finally, to test the relationship between climatic variables and CBB catches, we fitted a generalized linear mixed models separately for each climatic variable. The structure of the model looks like the previously mentioned model, including the climatic variable as a fixed effect and the possible interaction with the adjacent land use and the position of the trap are added as a random effect. The fit of the models was evaluated through diagnostic graphs of the residuals and predicts. For the glmm models we use the DHARMa (Hartig, 2022) library, and for the gamm the gam.check function the mgcv library (Wood, 2004).

3. **Results**

3. 1 Capture

In the 10 months that the traps operated at the different sites, we capture 148,913 individual coffee berry borers. Thirty-nine percent of the captures occurred in the traps that are within the coffee plantation at 20m of the edge, 26% in the traps located at the edge, 18% and 17% in the trap located within the adjacent land uses at 20m and 40m of the edge respectively. Thirty-six percent of the CBB was captured in the traps located on the transects at the interface between coffee and forest, 29% in the traps located at the interface between coffee and abandoned coffee, and 35% was captured in the traps located at the interface between coffee and pasture. On average in the coffee-forest transect 36.77 CBB were captured per trap per sampling session (approximately 12 days), in the coffee-abandoned coffee transect 59.51 CBB were captured per trap, and in the coffee-pasture transect 71.58 CBB were captured per trap per sampling session.

The maximum abundance of CBB captured per land use was recorded at the end of the dry season and after the first rains where there is an increase in relative humidity and temperature (Figure 21a, and Figure 21b). During the peak in CBB capture, pasture recorded the highest abundance of CBB in the traps (Figure 21d). The period where the lowest number of CBB was obtained was at the end of the harvest.

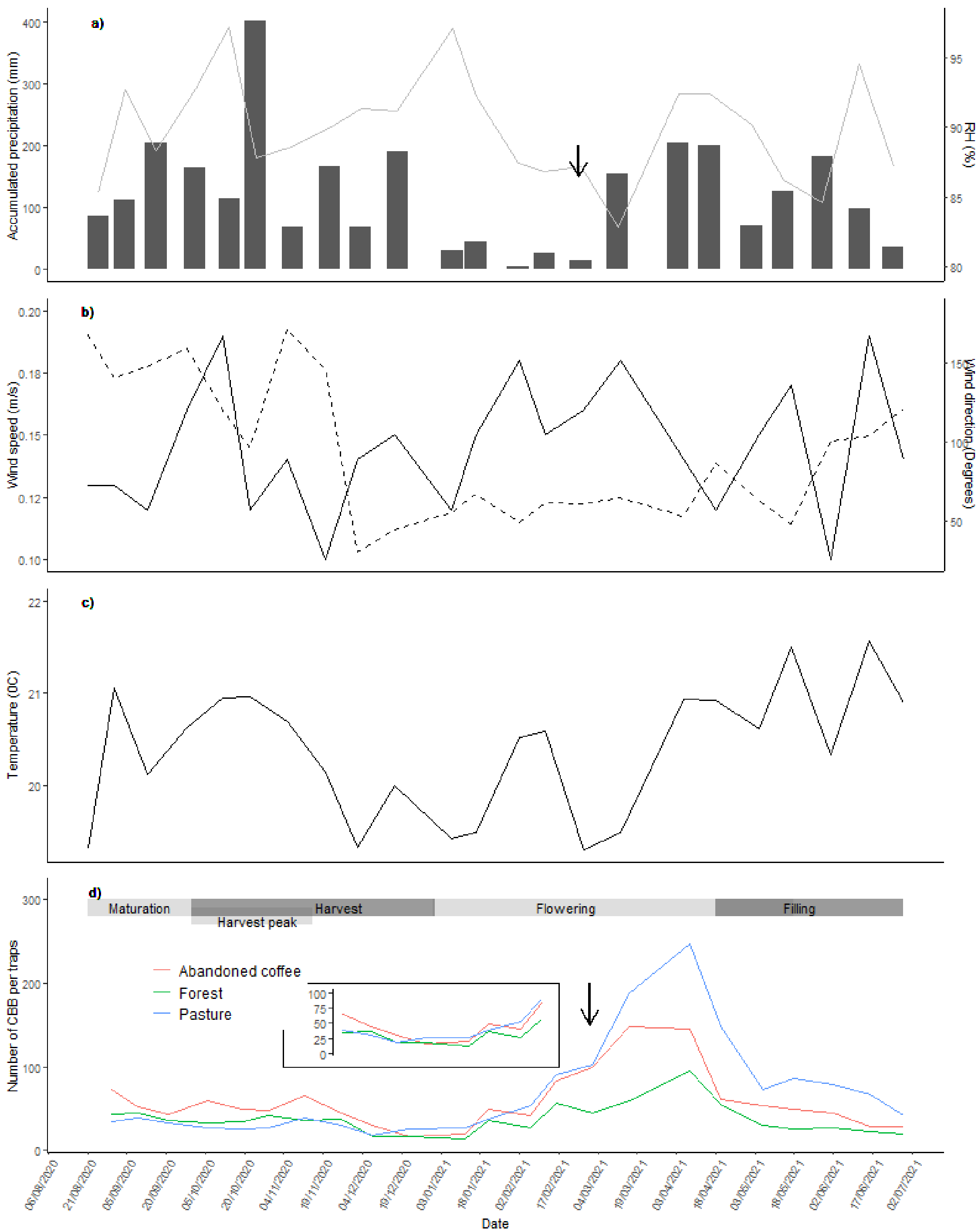


Figure 21. Capture of CBB throughout the sampling period and climatic variables: a) accumulated precipitation (bars), and relative humidity (line), b) wind speed and direction (dotted line), c) temperature, and d) average abundance of CBBs per land uses.

3. 2 Effect of land use and trap position

We found a significant interaction between adjacent land use and trap position ($\chi^2_6 = 53.11$, $p<0.0001$; Supplementary 1) on the number of captured CBB. The highest abundance of CBB was captured in the traps located inside the coffee plantation on the transect between coffee and pasture. The traps located on the edges did not show different abundance of CBB regardless of the adjacent land uses (Table 1). The traps located at 20 and 40m within the abandoned coffee plantations showed higher abundance of CBB in comparison with those located in other land use at 20m (Table 9).

Table 9. Marginals means and confidence intervals (95%) of the number of CBBs captured in each adjacent land use and trap position. Different letters, from Tukey comparisons (alpha=0.05), indicate significant differences both between trap position and between land uses.

LU	Coffee	Edge	20m	40m
Forest	36.23 [27.11, 48.91] ab	45.6 [33.12, 62.8] b	19.89 [13.6, 28.79] ab	26.05 [18.54, 36.97] ab
Abandoned coffee	37.71 [25.53, 56.26] ab	41.26 [24.29, 70.11] ab	56.83 [33.78, 95.58] a	43.38 [28.22, 66.02] ab
Pasture	247.15 [149.9, 407.48] c	43.38 [27.66, 68.72] b	9.3 [4.35, 19.89] b	28.22 [13.46, 58.56] ab

3. 3 Effect of land use, trap position and time

We also find a significant interaction between adjacent land use, trap position and time on the number of captured CBB. Effects of land use and trap position were more evident at certain times of the year (Supplementary 2) mainly at the end of the dry season and after the first rain from April to June (in red) and at the end of the harvest (in grey) (Figure 21). Traps placed within the active coffee plantations and near the pastures captured a greater number of CBB compared to those placed in coffee plantations bordering forests or abandoned coffee fields. In contrast, in the traps located on the edges there were no differences between the uses of land adjacent to the coffee plantation. On the other hand, in the traps located within the abandoned coffee plantations at 20 and 40 meters from the edge of the active coffee, a greater abundance of CBB were found than in the trap in the other land uses in the same positions. Even higher abundance of CBB was found in these traps than in the adjacent active coffee plantations. In addition, during the harvest period, the traps inside the forest (20 and 40m) had a higher number of CBBs than the traps located in pastures (grey region).

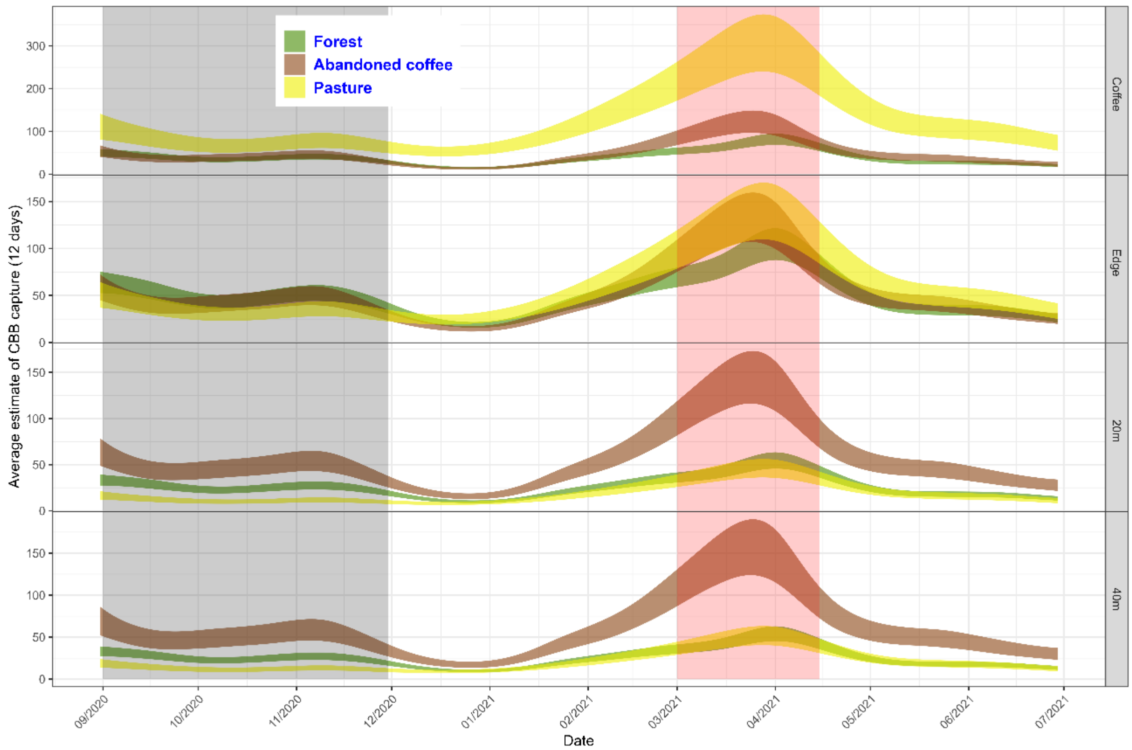


Table 10. Estimated number of CBBs over time based on adjacent land use and trap position. The colored area in orange corresponds to the period of berry development and the peak of greatest CBB emergence from the residual berries of the previous harvest.

3. 4 Relationship of meteorological conditions with abundance of capture CBB

We found an interaction (χ^2_{11} = 24.53, p = 0.0046; Supplementary 1) between the adjacent land uses, the position of the trap and the wind speed (Figure 22a). Specifically in the traps located inside the coffee plantation at the interface with pasture, the abundance of CBB was positively affected with wind speed. On the other hand, in the trap located at 40m from the edge within the pasture, the effect between the abundance of CBB and wind speed was negative (Figure 22a). For all the other traps position and adjacent land use (forest and abandoned coffee) there was no effect between the number of CBB collected and the wind speed.

The precipitation showed a non-linear effect (χ^2_1 = 12.84, p = 0.0013; Supplementary 1) with the abundance of CBB, but the effect was the same in all land uses whatever the traps position (Figure 22b). There was an interaction between relative humidity and adjacent land use and trap position (χ^2_{11} = 29.99, p = 0.0015; Supplementary 1). Relative humidity had a negative effect on the abundance of CBBs captured in traps located within the coffee plantation at the interface with pasture and at 40m within this land use (Figure 22c). Temperature did not show any effect with the captures of CBB (χ^2_1 = 0.84, p=0.35; Supplementary 1).

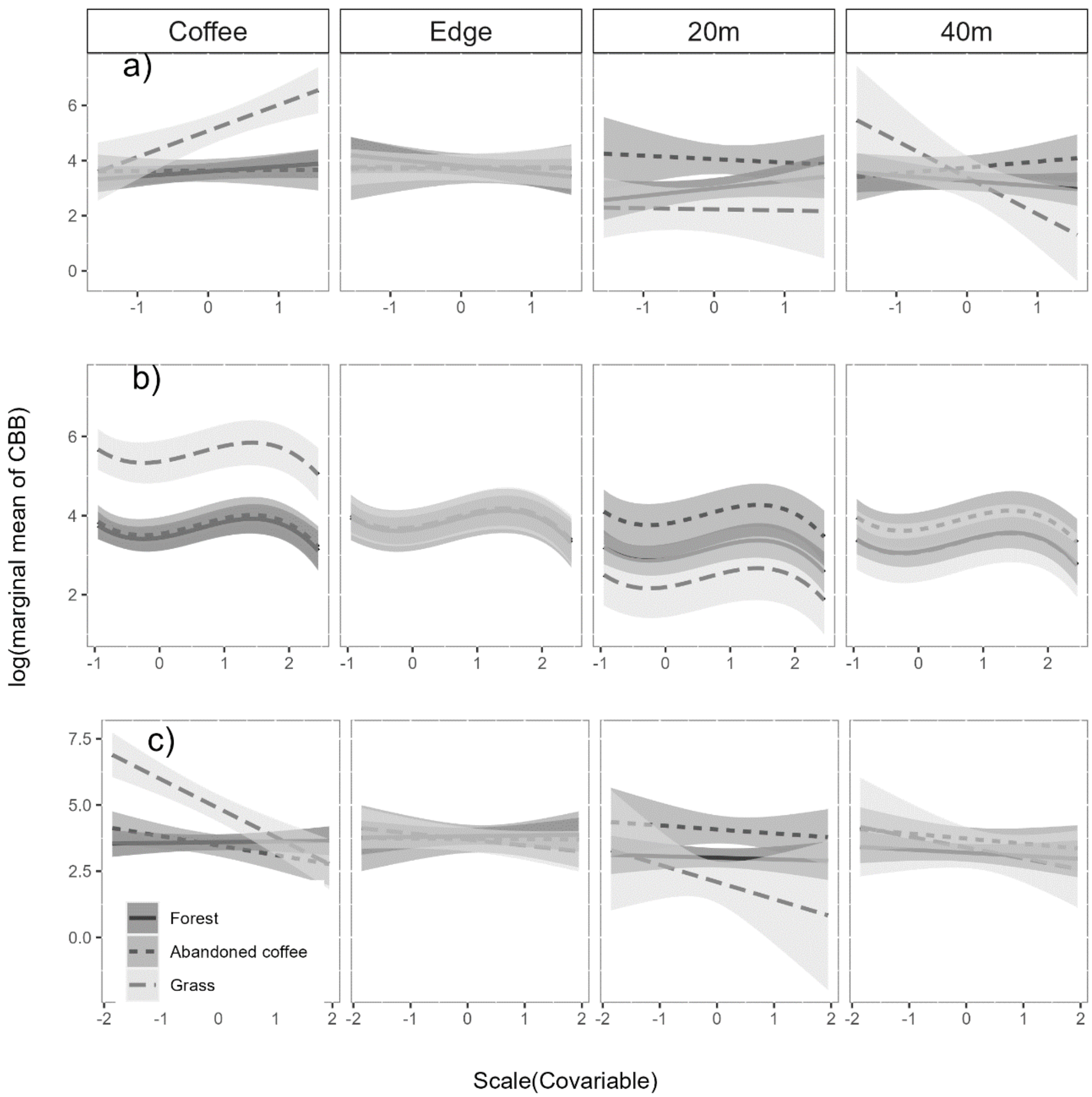


Figure 22. Relationship of the number of CBB, adjacent the land use, the spatial arrangement of the traps and scaled agroclimatic variables (a) Wind speed, b) rainfall and c) relative humidity. The Y axis is logarithm of scale.

4. **Discussion**

Our study demonstrated that female CBB can fly out of coffee patches and move to adjacent land uses in search of resources. We found that the CBB population outside coffee plantations accounts for approximately 26% of the total population, in contrast to the 4% reported by Olivas *et al.*, (2011) in the same landscape. This differences in the number of CBB outside coffee between these two studies may be due to differences in the study design and considered land uses, as Olivas et al. (2011) set 100 m transects from forest to sugar cane and pastures only.

We captured CBB throughout the sampling period, as reported by Aristizábal et al., (2017) in a study carried out on coffee farms in Hawaii. We did not find evidence to support our hypothesis (due to lack of resources) in periods of resource shortages. However, our experimental design provides some information about spillover effects at the edge and between the different land uses. We expected higher catches in the traps that are farthest from the edges of the coffee plantations during the period of scarcity of the suitable resources (at the end of the harvest and during the flowering season) that is more favorable for CBB movement. Nevertheless, in the forest and pasture, the tendency was to decrease as the traps were farther from the edge and regardless of the time of year. This pattern supports of the low capacity of movement of CBB (Gil et al. 2015). In the case of abandoned coffee, the abundance of trapped CBB was similar regardless of the position of the traps, reinforcing the hypothesis of a local population of CBB.

Higher populations of CBB females were captured at the end of the dry season and at the beginning of the rainy season (April-May) due to the appearance of the first suitable fruits. In fact, during this period, the main cohort of berries is older than 120 days. At this stage coffee berries start to be suitable for CBB females attacks (Montoya & Cardenas-Murillo, 1994; Benavides et al., 2012) due to the maximum moisture content and the average dry weight around 0.14g (Salazar *et al.*, 1994). This phenological stage might stimulate emergence of flying females from residual berries in the soil or on plants from the previous harvest (Dufour et al., 1997; Pereira et al., 2012). This reminds us of the importance of the sanitary harvest to control the CBB populations to prevent colonization of the new generations of berries (Pereira et al., 2012; Benavides et al., 2012; Johnson & Manoukis, 2020; Vilchez-Mendoza et al., 2022; Mathieu et al., 1997).

After this peak of captures, there are more berries suitable and less CBB captured in the traps, maybe due to the competition between the volatiles emitted by the berries and the attractants of the traps. During this period, the CBB are still captured outside the adjacent land uses. The largest captures are recorded in abandoned coffee plantations. We assumed that in this land use, there are still some coffee plants that produce some fruits that could be infested by CBB. The population collected may be an on-site population that is not related to the movements of individuals from nearby active coffee plantations. Gil et al., (2015) shows that less than 10% of dispersing population of CBB are able to disperse at distance > to 65m in coffee plantations.

During the harvest period, two small peaks of CBB captures are observed. We consider that it is an effect not only of the removal of berries by harvest action that favors emergence of females but also an effect of environmental conditions. The peak of rain and daylight that occurred during this period might stimulate CBB females emergence (Mathieu, Brun and Frérot, 1997).

The correlation of the accumulated rainfall of each sampling session with the CBB capture indicates that the increase in rainfall increases the CBB captured up to a point where the rain might become detrimental and reduce the number of CBB captured (Figure 22b). The coffee plantations adjacent to pastures registered a greater abundance of captured CBB females than the coffee plantations adjacent to the forest and to the abandoned coffee. We believe that the adjacency to the forest provides natural enemies which may remove CBB that are flying close to the edges. There is evidence of the effect of proximity to the forest on the reduction of bored berries (Avelino *et al.*, 2012; Karp *et al.*, 2013; Aristizábal and Metzger, 2019; Vilchez-Mendoza *et al.*, 2022).

Finally, in the present study our data suggests that movement of CBB might be governed by wind action. The interaction between the speed of the wind and the positions of the traps in the coffee plantations adjacent to pastures corroborates the action of the wind in facilitating the movement of the CBB (Baker, 1984). In the trap located inside the coffee plantation, there is greater capture when the wind speed increased, possibly because of the CBB movement inside the coffee plantation. In the trap located at 40m from the edge in the pasture, there is a negative relationship between the wind and the amount of CBB captured. One hypothesis could be that CBB that enters the pasture is transported by the wind beyond the location of the traps (more than 40m). According to (Alonzo, 1984), the flight of coffee berry borer adult females is reduced to a few meters unless they take advantage of air currents. A dispersion at large distances might depend on speed conditions and wind direction (Benavides, 2010). In contrast, the non-interaction of the wind with the position of the traps in coffee plantations adjacent to forests and abandoned coffee may be due to the resistance generated by these land uses to the wind. Johnson and Manoukis (2021) also suggest that vegetation surrounding coffee farms may act as physical barrier, and recommend the use of physical barriers or border crops densely planted to inhibit the migration of CBB. Future studies should consider variables related to vegetation structure to better understand potential mechanisms related to the resistance offered by adjacent land uses.

5. Conclusions

Our study highlights the significance of adjacent land uses in the dispersal of CBB. Specifically, our results suggest that open agricultural systems such as pastures can facilitate the movement of CBB by wind, possibly beyond CBB dispersal ability. Other dominant open systems in Ventral American landscapes include sugar cane and diverse annual crops that could have similar effect on CBB populations as pastures in our study.

Abandoned coffee areas in our landscape are a source of CBB for adjacent coffee plantations, hosting CBB populations even up to 2- years after abandonment. In our study area the gradual abandonment of coffee cultivation due to low productivity and changes in market prices, makes the management of theses abandoned areas a priority.

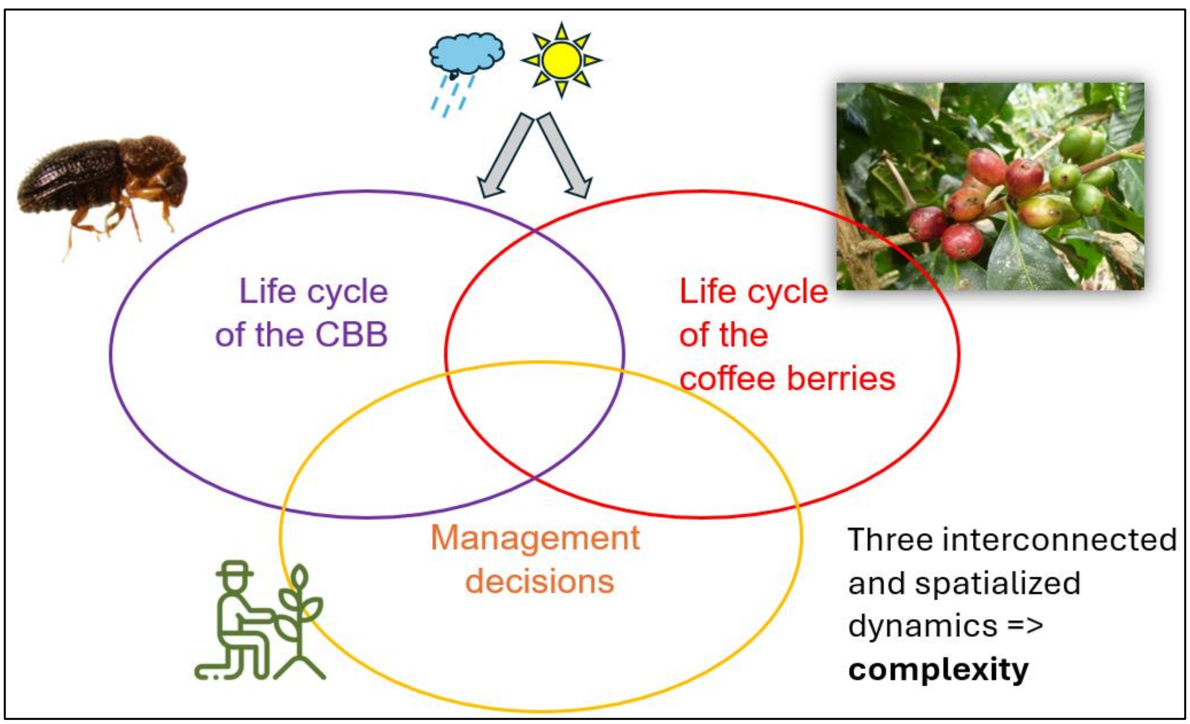
Our results suggest that forests can be considered as natural barriers to the movement of CBB, which is probably related to their greater vegetation complexity that modifies the direction and speed of wind and prevents CBB transport.

Considering the importance of landscape configuration and composition on CBB incidence in coffee plantations, we suggest that the management that abandoned coffee areas should be considered in which remanent coffee plants are removed or shade management is done to promote the growth of secondary vegetation. Also, the use of vegetation barriers and the consideration of buffer areas between coffee cultivation and adjacent land uses should be considered.

Finally, the information generated in our study on CBB incidence in coffee plantations and adjacent land uses can be used to assign permeability values in studies of CBB movement using tools such as graph or circuit theory, an alternative to more expensive dispersion studies in the field.

V. Chapter IV. Coffee berry borer dynamics: A multi-agent simulation approach to explore cooperative management at the landscape scale

This chapter serves as the focal point of this thesis, as it presents a proposal for the development of a multi-agent model that explores various CBB cooperative management scenarios at different spatial scales. The model proposal is informed by a comprehensive literature review, specifically on the biology of the CBB and the environmental factors that influence its life cycle, while also incorporating empirical knowledge from the three previously described chapters. In describing the model, we utilize the Unified Modeling Language (UML) to depict the model from a static perspective using class diagrams, as well as to illustrate the behavior of each of the agents involved in the model through dynamic diagrams.



Coffee berry borer dynamics: A multi-agent simulation approach to explore cooperative management at the landscape scale

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1. Introduction

Alternatives to traditional management approaches for the control of pests and diseases has aroused interest in integrated management that considers multiple spatial scales. The coffee berry borer (CBB) is a significant pest in all coffee-producing regions, causing losses by directly damaging the berries and impacting the quantity and quality of the coffee harvest. Its complex life cycle, which develops inside the berries (Vega et al., 2009), makes it a challenging pest to control.

Historically, CBB management strategies have been primarily applied at the plot level, overlooking other spatial scales. Recent studies have highlighted the significance of landscape configuration in influencing CBB incidence (Avelino et al., 2012, Aristizábal et al., 2019, Mosomtai et al., 2021, Vilchez-Mendoza et al. 2022). There is increasing evidence of the landscape's role in conservation natural enemies of pests (Bianchi et al., 2006). However, while the importance of landscape context requires further assessment, it is essential to study its integration with on-farm pest management strategies and the local characteristics of production systems (Martin et al., 2019, Thies & Tscharntke, 1999, Thies and Tscharntke 2003, Tscharntke et al., 2005). Furthermore, understanding how one farmer's management decisions may impact neighboring farmers' pest control in the shared the landscape would be valuable.

Evaluating the dynamics of the CBB, plot characteristics, surrounding landscape, bioclimatic conditions and the management decisions influenced by economic benefits or neighbors' decisions is challenging due to the myriad interactions involved. One approach to exploring these interactions is through the development of simulation models, enabling the evaluation of various management scenarios across multiple spatial scales and diverse coffee landscape configurations.

Currently, there have been proposals for simulation models of CBB dynamics to explore certain CBB control practices (Gutierrez et al., 1998; Rendón et al., 2008; Cure et al., 2020). However, these models do not consider landscape scales, surrounding environment of the plot, or the socio-economic characteristics of farmers.

Agent-based models (ABM) are useful tools to explore CBB dynamics under various management strategies and at multiple spatial scales considering external factors that influence management decisions (e.g., the volatility of coffee prices). The ABM paradigm allows the modeler to concretize the entities he perceives (the agents), to organize them by describing their relationships, and to implement the whole on a computer platform. An ABM can then be used to study the evolution of these agents and of their organization under various scenarios. Such ABM makes it possible to determine what effect on the system may be produced by different farmer's strategies (Ghazi et al. 2011) or to evaluate the response of the interactions between the agents at different spatially scales.

In contrast to conventional modeling based on differential equation systems, agent-based modeling proposes a bottom-up paradigm that connects two levels: the level of the agents and the entities, and the level of the whole system (Ferber, 1999). The articulation between the individual and the collective levels addresses changes in scale, which seems essential for understanding specific phenomena (Bommel, 2020). As such, ABMs have proven to be powerful tools for simulating complex processes or mechanisms involving many interactions.

As Epstein and Axtell pointed out in their famous book "Growing Artificial Societies" in 1996, *"Artificial society modeling allows us to "grow" social structures in silico demonstrating that certain sets of microspecifications are sufficient to generate the* *macrophenomena of interest. Indeed, it holds out the prospect of a new, generative, kind of social science"* (Epstein and Axtell, 1996).

From this perspective, we designed an ABM of CBB dynamics that considers climatic conditions, landscape context, plot characteristics and management strategies considered by the farmers involved in CBB control. This modeling approach can contribute to explore different management strategies for CBB control considering the surrounding landscape and even explore cooperative management approaches among farmers sharing a common landscape and evaluate the response or adaptation of farmers' management to changes in international coffee prices.

2. Agent based modeling-Coffee Berry Borer (ABM-CBB)

2. 1 Overview

We present a conceptual model of ABM-CBB using the unified modeling language (UML, Bommel & Müller, 2007). Indeed, we believe it is useful to illustrate a description by adding diagrams that synthesize the textual descriptions. Thus, we present a class diagram showing the structure of the model and its components (Desing concepts and details how: classes, attributes, methods, and associations), and dynamic diagrams showing the states and transitions of the different agents (coffee plantation, CBB and farmer) and the different actions and their connections over the year.

2. 2 Purpose

The **purpose** of this model will to collectively explore various management strategies with coffee farmers in the Turrialba region, Costa Rica, following the ComMod approach (Companion Modelling, ComMod 2005, Étienne, 2011), This participatory work aims to accompany the enhance the collective decision-making process by designing a share model that integrates various viewpoints on the coffee-CBB interactions. Workshops with farmers will organize to explain the current state of the model and to collectively explore some simulations, followed by debriefing phases to revise the conceptual model and discuss possible solutions. The ComMod approach serves as a social learning method that gradually enhances knowledge by sharing and comparing different simulations and exploring their consequences in the long term (Le Page & Perroton 2017)

2. 3 Entities, state variables and scale

The entities that considering in the model involves agents (coffee berries, CBB, and farmers), general environment, known as the landscape, and climatic conditions (see the UML class diagram, Figure 23).

The main state variables that describe the entities are presented in table 11.

Table 11. Main state variables on model entities

Entities	Variable of state	Unit	Variable type
CBB	Stage	Egg, larvae, pupa, adult	Categorical
	Sex	Female, Male	Boolean
	Female dispersal	Yes, No	Boolean
	Age	Degrees days (Thermal time)	Real
Berry	Stage	pin, green, mature, overripe, dry	Categorical
	Berry plant?	Yes, No	Boolean
	Age	Days	Date
	Weight	Grams	Real
Farmer	Management-CBB?	Yes, No	Categorical
	Shade pruning	Yes, No	Boolean
	Harvest	Yes, No	Boolean
Cell	Cover	Coffee, forest, open area, other	Categorical
Coffee cell	Shade?	Yes, No	Boolean
	Management?	Yes, No	Boolean
Weather	cell shade?	Yes, No	Boolean

The spatial extent is 1 km^2 (100 ha), representing the landscape scale, which may be dominated by coffee plantations or composed of different land uses, such as forest patches, pastures, or other crops. The landscape is divided into plots, which are the management units of the farmers. A coffee plot has a minimum size of 2,400 m^2 (0.24 ha), serving as the minimum area of an agricultural management unit that a small farmer in Central America can own. Each plot is comprised of 20X20m^2 cells (a subarea of 400 square meters), which represents the minimum spatial unit of the model.

The cell size was selected considering the most likely displacement of CBB as it merges toward the berries: when searching for berries to colonize, an adult female can fly in laboratory conditions for 20 and 100 min (Baker 1984). The extent of the cell also depends on the influence of the canopy of a shade tree in coffee plantations who influences microclimatic conditions. The cell is the minimum spatial scale for this model: this is the scale where the rules governing coffee berries, the CBB and some management decisions occur (Figure 23).

In one cell (minimum spatial scale) until 90000 to 200000 berries can develop depending on the density of the coffee plantation, and between 60000 and 80000 CBB can be present depending on the level of infestation. So, Millions of berry borers and hundreds of berries can occur in a small coffee plantation. For this reason, coffee berries and CBB in the model are grouped into cohorts. Indeed, it is not computationally feasible to consider each berry and insect as an agent, because this would make the simulations too slow and impractical to interact with farmers.

The time scale of the model is one year with time steps of one day. It begins approximately 20 days before the first flowering of the coffee tree and ends after the last coffee harvest.

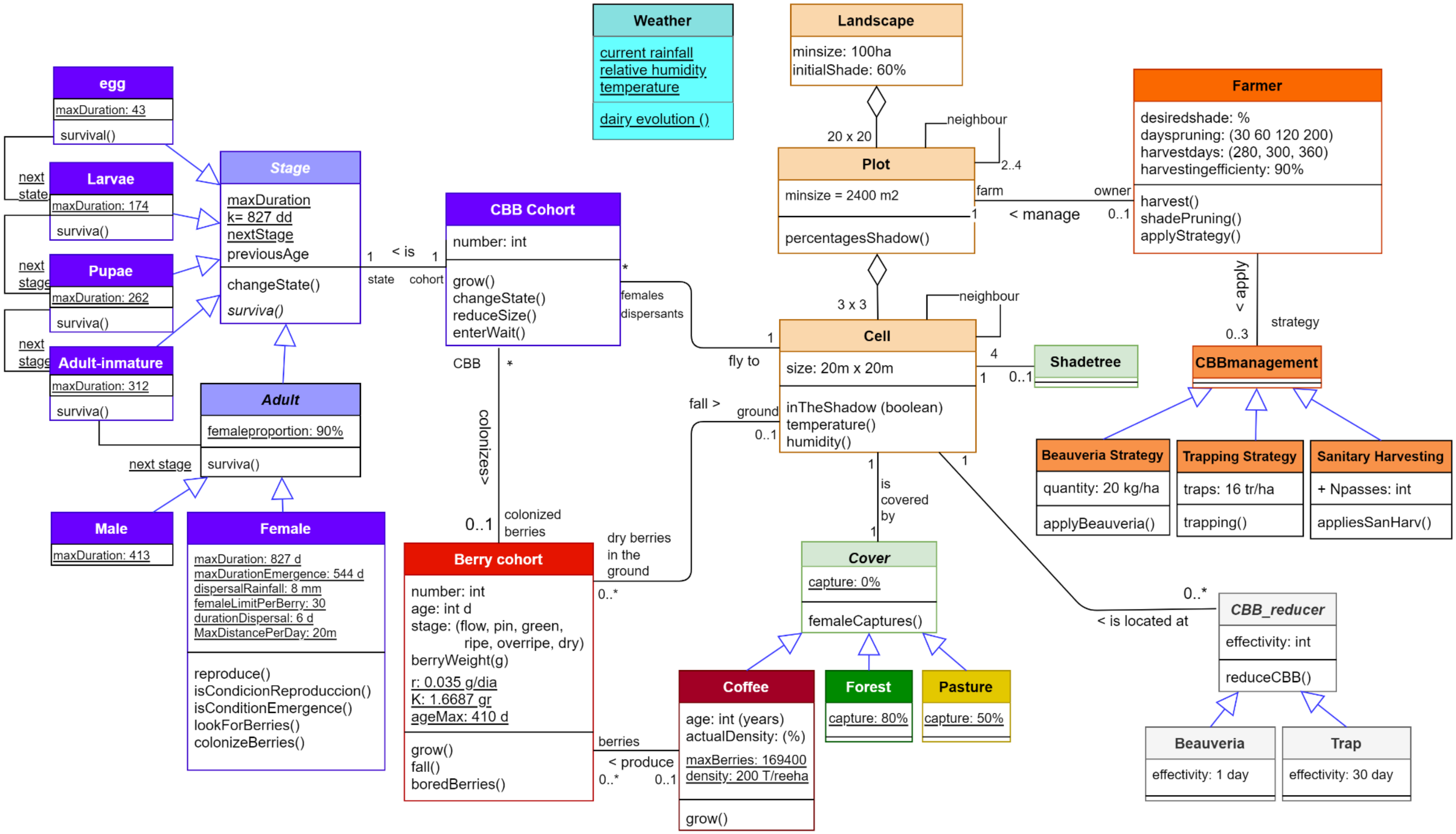

Figure 23. Class diagram representing the entities, state variables and scale of the ABM-CBB (Class, attributes and methods). This diagram was used to present and discuss the conceptual model with coffee farmers and technical researchers from the different coffee institutes in Central America, its original description is in Spanish.

2. 4 States and transitions of the different agents

This section describes the behavior and rules that define the state and transition of each of the agents in the model.

2. 4. 1. The coffee berries

Coffee trees is not individually represented in the model. Therefore, each coffee cell contains cohorts of berries. The development of coffee berries is determined by a logistic function based on their fresh weight. Typically, at plantations around 1200m elevation with average temperature of 22°C, the development of the berries from flowering to harvest lasts approximately 210 days. In contrast, at an elevation of approximately 1800 m with average temperature of 19°C, the development period extends to about 270 days (Velez et al. 2000, Jaramillo and Guzman 1984). In the ABM-CBB, the growth of the berries from flowering to reaching the ripening state is parameterized to occur in 210 days, in line with forecasts used by Central American coffee institutes. However, it is also possible to switch to thermal times, where the development period is influenced by temperature.

The development of coffee berries begins with flowering, which is triggered by a rainfall event of approximately 10 mm occurring between days 20 and 160 at the start of the cycle (De Alvin, 1960; Rees, 2016). During this period, up to four flowering events can take place, with a minimum interval of 20 days between each event. The percentage of initial flowering in each event is randomly selected from a vector containing values of 20, 27, 24, and 29%, representing the total number of berries developing in a cell. The overall number of berries expected to develop is influenced by the plantation's density.

The growth of coffee berries begins immediately after initiation, with the initial weight of a berry being 0.01g for the first 82 days. It then progresses to the button stage, where the weight increases to 0.015g over a period of 28 days, before transitioning to the green berry stage (as shown in Figure 24). During the green stage, the berry undergoes rapid growth, reaching a water content of 85% of its total weight, until it eventually enters the ripening stage, weighing 73g (Salazar et al., 1994). The berries become susceptible to CBB attack at 120 days of age, specifically during the green phase (Montoya & Cárdenas-Murillo, 1994; Benavides et al., 2012). In the ABM-CBB model, the berries vulnerable to CBB colonization are those in the physiological ripening stage, at approximately 136 days after flowering, marking the beginning of CBB reproduction (Montoya & Cardenas-Murillo, 1994).

Around 182 to 260 days after flowering, the berry is ready for harvest (Salazar et al., 1994). If not harvested, the berry begins an over-ripening process approximately 240 days after flowering. During the overripe phase, lasting 20 days, the berry undergoes weight loss and drying. Subsequently, in the dry phase, the berry may remain on the plant or fall to the ground. If fallen, the berry persists for 150 days before disappearing (as depicted in Figure 24). Although there is no specific information on the duration of a dry berry's suitability for sustaining borer populations, based on the experience of Ing. Angel Trejos (personal communication, researcher at the Instituto del Cafe de Honduras), it is assumed that the berry remains suitable for up to 150 days after harvest.

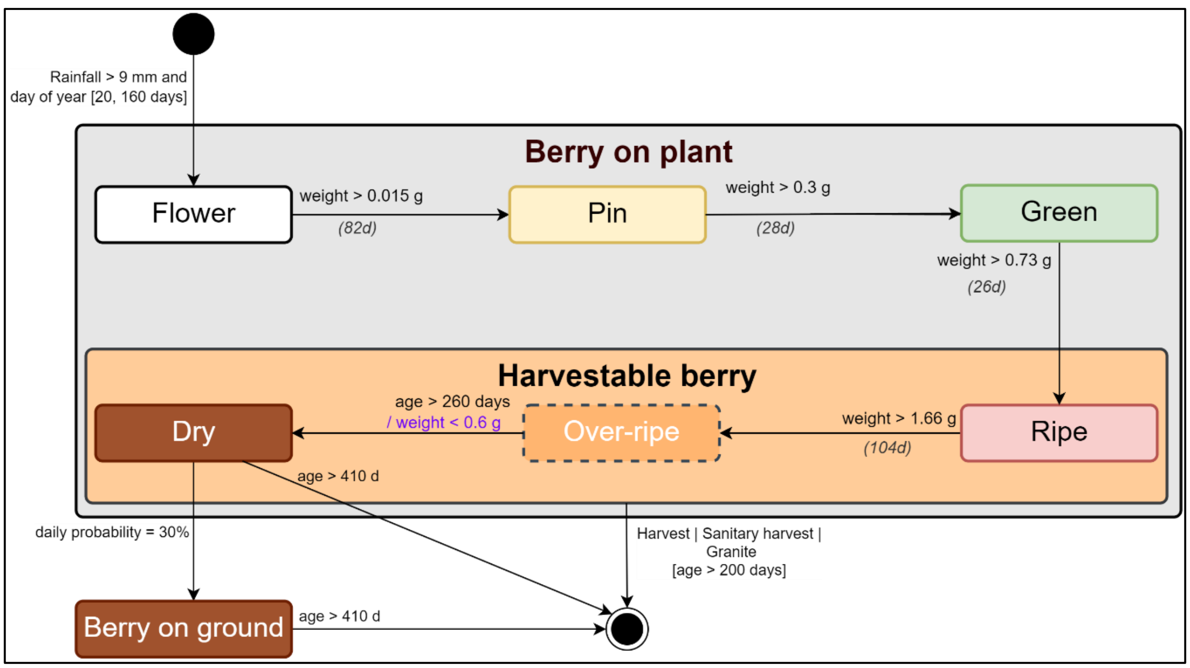

Figure 24. UML state-transition diagram of the development of a coffee berry. The time lapse of the in the model is days. We include in the diagram the degree days (thermal time) for future changes in the development of the berries.

2. 4. 2. The CBB

The development of the Coffee Berry Borer (CBB) is described using thermal time (degree days, DD), as estimated by Jaramillo et al. (2009) from the egg stage to the maximum lifespan of an adult (see Figure 25). Temperature strongly influences the CBB's development, with a thermal tolerance between 16°C and 32°C and an optimum of 24°C (Azrag et al., 2020; Jaramillo et al., 2009a). The development time of the CBB is temperature-dependent, with reports suggesting a 3-day reduction in the cycle for each 1°C increase in temperature (Vargas, 2006; Montoya, 1993; Romero, 2003; Beker et al., 1992; Bergamin, 1943, Bustillo et al., 1996, Jaramillo et al., 2009). Higher temperatures can lead to an increased number of CBB generations.

The CBB's development begins at the egg stage with a base temperature of 15°C, accumulating up to 32 DD. It then progresses to the larva stage for 174 DD before reaching the pupa stage, which lasts 262 DD. The immature adult stage lasts 312 DD, after which males and females are separated into two cohorts at a 1:9 ratio. Adult males remain in the berry until a maximum age of 413 DD, while females are fecundated and emerge from the berries to disperse and colonize others if they are less than 544 DD. The emergence is influenced by the number of females in the berry, the age of the berry since flowering, and rainfall events over eight mm (Montoya & Cardenas-Murillo, 1994; Benavides et al., 2012). If a female does not emerge and reaches the maximum emergence age (544 DD), it immediately begins oviposition. Each female lays its eggs in the berry it occupies, creating a new cohort of eggs (of N individuals) in the same cohort of berries. Fecundity is based on the data reported by Jaramillo et al. (2009).

When a dispersing female CBB finds a healthy berry, it colonizes it and begins oviposition. If the berry is already occupied by other CBB, the female continues to fly in search of a healthy, unoccupied berry. The female's movement from one berry to another is random, and if it flies in a linear path, it can travel up to 140m, as reported by Olivas et al. (2009). However, the probability of linear movement is low, and the expected movement is no more than 40m (Gil et al., 2015), equivalent to 2 cells in the model.

A dispersing female CBB can fly around for up to six days in search of suitable berries before dying. Mathieu et al. (1997) reported that a female CBB can survive without food for up to 11 days after leaving a dried berry under controlled conditions. However, in natural conditions, CBBs are exposed to predators and weather conditions, which can also lead to their mortality. The dispersing female may also die before finding a suitable berry if it is captured by a trap or comes into contact with Beauveria (see farmer strategies in the next section). The cycle for a female CBB ends at 827 thermal time (DD).

Additionally, all stages of the CBB experience intrinsic mortality, as well as mortality due to rain. The intrinsic mortality function was derived from Romero & Cortina (2007), and the rain mortality was taken from Rodríguez et al. (2013). In this model, the mortality functions are adapted according to the current state of the cohort, leading to a reduction in the number of individuals in a cohort that is affected by rain. When the number of individuals in a cohort reaches zero, the cohort is removed from the model.

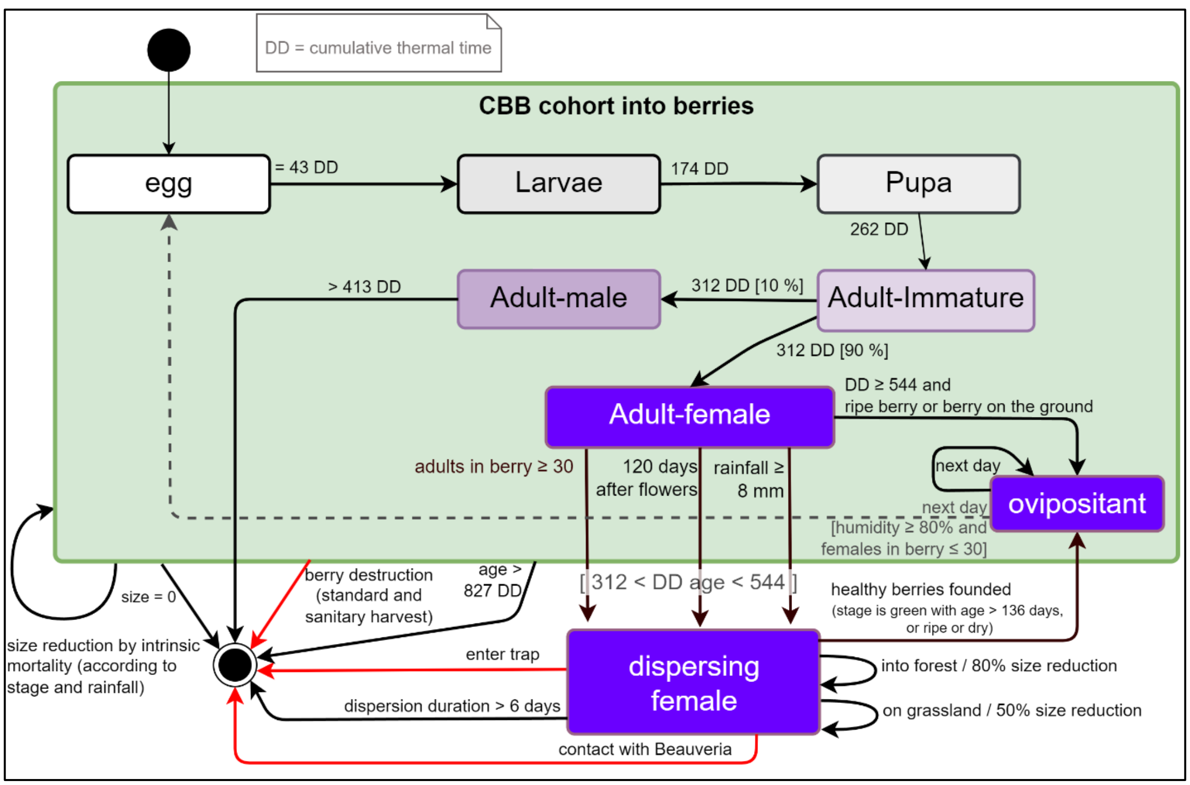

Figure 25. The UML State-Transition diagram presents the different stages of a cohort of CBB eliminations by intentional actions of the farmer. The gray dashed pseudo-transition

indicates that a cohort creates a new cohort of eggs, each day when the relative humidity is above 80%. But the reproduction stops if more than 30 females are present within the bay.

The landscape context influences the movement of the CBB: a flying female CBB may enter a land use adjacent to the coffee plantation. These land uses can be forest, pasture (open land use) or abandoned coffee. The rules that govern the movement of the CBB are the same as in an active coffee plantation. However, if a cohort of CBB enters the forest, 80% of its population dies and this mortality rate is repeated every day it is in the forest. Instead, if the CBB cohort enters a pasture 50% of its population dies. In other words, if a CBB cohort made up of 1,000 individuals enters the forest, it disappears after four days. On the other hand, if it enters a grass, the population can move for six days and arrive with 1% of its initial population to colonize another coffee patch. If the CBB cohort enters an abandoned coffee plantation, its activity is equal to that of an active coffee plantation, i.e., there is no mortality. These rules are based on the results of the work of chapter II of the thesis.

2. 4. 3. The Farmer

The farmer plays an active role in managing his farm, which is composed of plots. At the beginning of the simulation, the farmer decides on the amount of shade trees to maintain on his farm based on the *initialProportionOfShade* parameter (see figure 23). The percentage of shade in a plot is determined by the number of cells containing shade trees versus those with no shade (full sun conditions).

The farmer also decides when to harvest the coffee trees and may choose to implement a control system for the Coffee Berry Borer (CBB). If the farmer decides to prune his trees to achieve a specific shade percentage, he randomly eliminates some shade trees to convert cells to full sun. As the shade trees regenerate, the cells that changed from shade to full sun return to their initial shade condition after four months. Therefore, the farmer may decide to perform more than one pruning per year to maintain his desired shade level, with pruning days at 30, 60, 120, and 200.

Each farmer harvests his farm at specific times, which are set at the 260th, 280th, 300th, and 310th days of the year in the current version. During the harvest, both healthy and infected berries are collected, leading to a reduction in the population of Coffee Berry Borers (CBBs). However, the harvest efficiency is not optimal, and 10% of the ripe and dry berries remain on the trees, meaning that the size of each cohort of mature berries is reduced by 90%.

The farmer can also conduct berry sampling to estimate the incidence of bored berries. Based on this sampling, the farmer can decide to implement CBB management. The current version of the model offers four types of management strategies, although other strategies are also possible.

2. 4. 3. 1. The Traps' strategy

The farmer can place traps to control the CBB. He decides the number of traps (10 by default) and their location (regular repartition on the coffee cells). Each trap can capture a proportion of dispersing CBBs that are emerging from the cell or arriving from neighboring cells. Gil et al (2007) report that the capture effectiveness of the trap in capturing CBB is a is a function of distance ($\mu traps_t = 0.17719 - 0.0405 \log(distance)$), ie., CBB that emerges near the trap is more likely to be captured.

The traps lose their effectiveness by 50% if the farmer does not inspect them within 30 days. If not checked within 60 days, the traps lose completely their effectiveness. Indeed, traps that have not been checked for a prolonged duration tend to fill up with dead leaves that affect the action of the diffuser or the capture.

In the model, the daily capture effectiveness of a trap located in a cell is a uniform function between 25 and 46% if the cell is in shaded condition or vary between 15 and 36% in full sun condition. These values were estimated by bootstrapping capture rates at different distances between 1 to 10 m using the Gil et al (2007) equation. The greater effectiveness of captures in shade conditions with respect to full sun is assumed by the prolonged effect of the diffuser of the trap in shaded conditions: as the attractant in the traps is a mixture of methanol and ethanol in a 3:1 ratio, it evaporates more slowly under the shade.

2. 4. 3. 2. The Beauveria strategy

The farmer can opt for a management strategy using *Beauveria bassiana*, fungus pathogen used for biological control. The effectiveness of *Beauveria bassiana* in controlling CBB can fluctuate from very low values, close to 4%, to high levels of 80% (Benavides et al., 2012). This fluctuation of the effectiveness can result from the quality of the management, or the climatic conditions, or from the quality and concentration of the fungi used on the farm. To include the effect of this strategy in our model, we used the reports in the literature on the effectiveness of *Beauveria bassiana* for the control of CBB, with the resampling method that estimates a range of percentage of attack $\sim N(38.61, 14.62)$. When the farmer sprays the *Beauveria bassiana* on his plot, the effectiveness is uniform for all the cells of the plot. It only kills the flying CBBs at the moment of application, since the colonization mechanism of Beauveria after application is not known (Duffort B. 2021, com. pers).

The *Beauveria bassiana* may have a greater effect in shaded conditions (due to higher relative humidity) than in full sun. This effect is considered in the model: in shade conditions, the control effectiveness by Beauveria on the CBB is randomly set between 41% and 99% (only on the application day), while in full sun, it is between 18% and 64%. The model randomly selects a value from a normal distribution depending on whether the cell is shade or sun, for an application of 20 kg/ha of Beauveria with a lifespan of 1 day.

2. 4. 3. 3. The Sanitary harvest strategy

The farmer can decide the moment of the harvest, and even not carry it out if the market conditions are not favorable. Not harvesting may be a reasonable decision when market prices for coffee are low and the return between sales and profits is negative. The farmer can perform until four harvests per year. Usually, the effectivity of the harvest is 90% of the ripe berries. After a harvest, 10% of the berries remain on the plant (Chamorro et al. 1995). The percentage of remaining berries can be higher if the farmer does not make a timely harvest, because the overripe berries tend to fall.

Thus, a farmer may decide to make a sanitary harvest. It is the most efficient practice for CBB control since it removes berries that provide habitat for CBB populations which will colonize the next season's berries. If the farmer decides to make a sanitary harvest, the percentage of remaining berries in the plot is set to 1%. The following activity diagram shows the organization of the farmer' activity in a year.

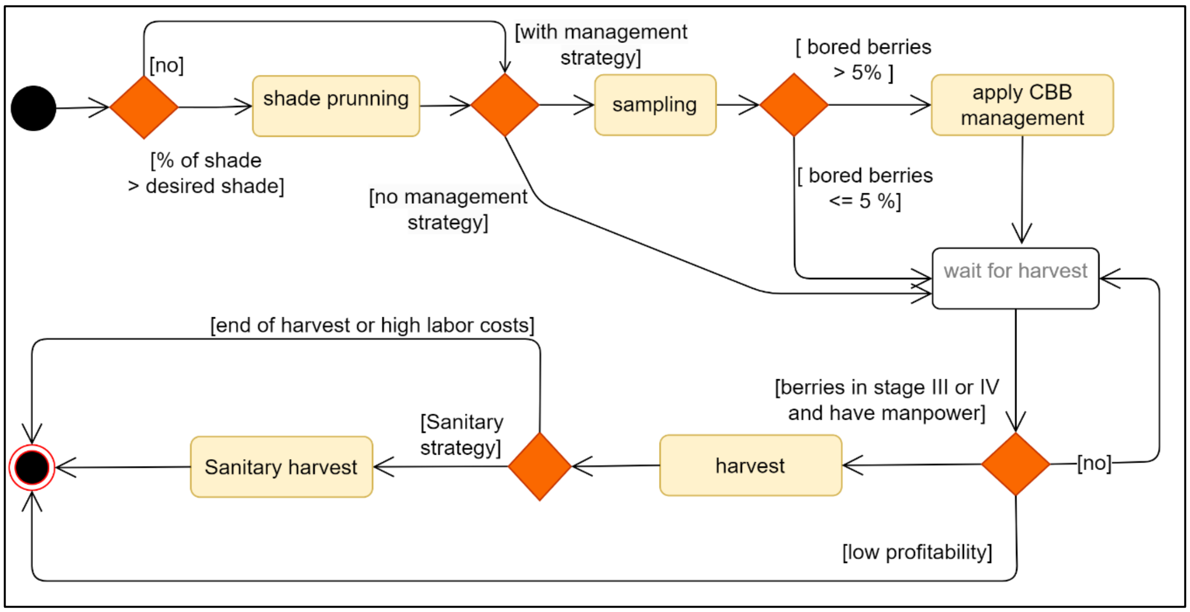

Figure 26. UML activity diagram representing the flow of action of the farmer in a year.

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2. 1 Design concepts

2. 1. 1. Stochasticity

The model is a stochastic system since several parameters are estimated or selected randomly. For example, the effectiveness of control strategies may vary randomly (see more detail the Farmer and management strategies), as well as the spatial movement of the CBB.

2. 1. 2. Observation

The ABM-CBB can collect a lot of information such that the total number of berries for each stage or the number of berries attacked by the CBB (bored berries), the weight of berries and the weight of borer berries. About CBB, information is collected on the number of CBBs for each stage of development, the number of moving CBB, the quantity of dead insects per trap or by *Beauveria* or in forests and pastures land. These observations can be done at plant, cell, or global level. They are updated at each time step.

Regarding the farmer, information is collected on the total harvest, on expenses related to each management practice or control strategy (tree shade pruning, use of traps, application of *Beauveria*, standard and sanitary harvest). Units of measure are translated into US dollars according to the selected scenario and the costs for each activity or inputs.

2. 2 Initialization

The model can be initialized from a wide range of spatial configurations called spatial scenarios. Each scenario is composed of at least four land use classes: coffee and abandoned coffee, forest, and pasture (open areas). From each initial state, the conditions for coffee plots are determined.

When initializing the ABM-CBB, a constant plant density per hectare and expected values of berry development are assumed. Initially, all coffee cells retain 1% residual berries from the previous harvest, in a green to dry state. In these residual berries, the simulation begins with cohorts of female borers with ages between 540 and 550 DD, grouped into 4 cohorts of 20 to 60 individuals. These female borers are randomly distributed within the coffee plots. Additionally, the coffee plots start with a percentage of shade trees (which modify the local climatic conditions). In the model it is possible to create between 1 and 5 farmers who own the plots and who share the same landscape scenario. They start with independent management strategies.

2. 3 Input

ABM-CBB includes environmental conditions; daily temperature, relative humidity, and precipitation, through time series of a consecutive year (Figure 27). At each step (day), the scheduler updates the climate (rainfall, relative humidity, and average temperature). This climate data (known as forcing variables) is repeated every year. The climatic conditions on a given day are identical across the landscape but are adapted to each cell depending on the presence or absence of shade trees.

Following this update, the scheduler activates the cells. Each one adapts the global climatic data to its current state: if the rainfall value is the same for all the cells, the relative humidity and the temperature are modified when shade trees are presents. In that case, a random fluctuation between -3 to -6°C (Jaramillo-Robledo, 2005; Vaast et al., 2006) is calculated on the daily temperature (provided by the forcing variable), and the relative humidity is increased by 5 to 15% (Olivas et al 2023, Mariño et al. 2016).

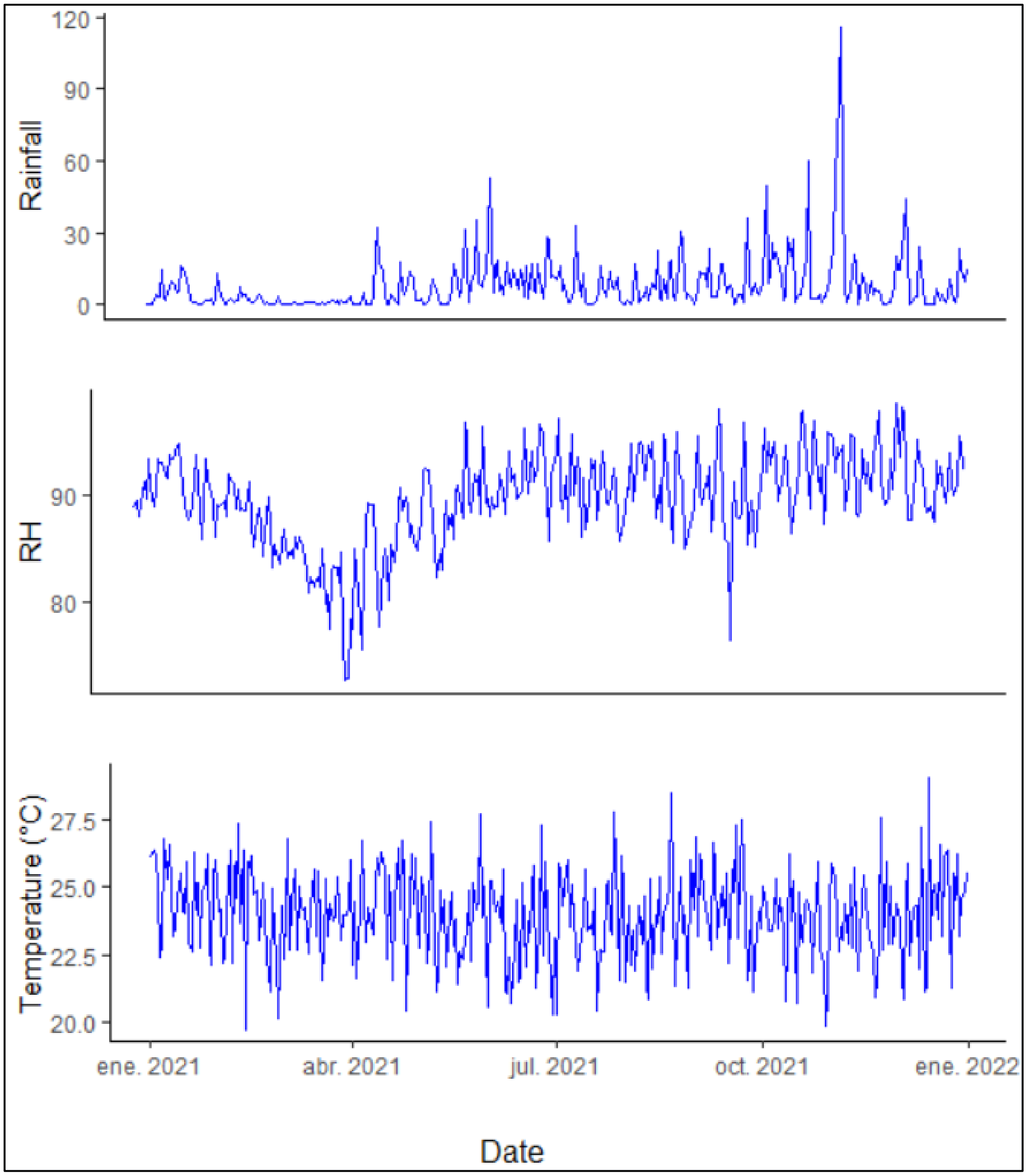

Figure 27. The model's environmental forcing, based on the timeseries from CATIE meteorological station.

3. Assumptions and limitation of the model

The model's conceptualization and parameterization are considered appropriate for its intended purpose, to seeking a balance between realism and simplicity.

- The ABM-CBB not include a physiological component for the coffee tree, only considers the development of berries and the dynamic of the CBB infestation at the cell level.

- All coffee plantations are assumed to be productive.
- The appearance of flowers is synchronized across the entire landscape.
- All cells within a plot have an equal berry load, without differentiation between full sun and shade.
- All coffee plantations have the same age and planting density.
- All berries within a cohort can be infested by CBB at the same time.
- Each CBB only colonizes one berry.
- The model does not consider a berry preference function for the CBB.

It is important to note that the objective of the model is not to make production forecasts, but rather to focus on berry development and the impact of CBB infestation. This allows you to create a simplified representation of the coffee system, focusing on the key aspects of interest and avoiding excessive complexity.

4. Next steps

The next step in this project is to finalize the programming and its respective description using the OOD (Overview, Design concepts, Details) protocol (Grimm et al., 2010), which will facilitate a detailed understanding of the ABM-CBB. By programming and detailing the model, we aim to apply it to scenarios using ComMod approach (Companion Modelling, ComMod 2005, Étienne, 2011). This will help us understand and contribute to the importance of including the landscape scale for better control of the borer and even clarify the dilemma of the shadow effect in the incidence of the CBB.

Furthermore, to guarantee the validity and applicability of the model, it is essential to have feedback from coffee growers, who are the main actors in pest management. Their experience and knowledge will be key to improving and adjusting the model, ensuring that it reasonably reflects the reality of the system. Collaboration with farmers will also help to identify possible improvements in the implementation of management practices

To facilitate access and use of the model, I hope in the future to host it on a server and develop a mobile application. This would allow coffee specialist technicians, researchers and farmers to access the model through their mobile phones, providing them with a practical and easy-to-use tool for making informed decisions in the management of CBB.

The mobile application could provide specific management recommendations for each farm and the possibility of sharing data and experiences with other users.

Regarding future improvements to the model, I hope to continue incorporating new variables and considering other relevant aspects that may influence the dynamics of CBB and its management (i.e., coffee pruning). This includes the possibility of incorporating real-time climate data, as well as new control and management strategies emerging from future research. The final objective is to continue improving the performance of the model without losing the balance between simplicity and realism with the objective of providing farmers and agricultural technicians with a reliable tool in CBB management that they can adapt to the environmental conditions of their system and support management decisions. Also, it is a tool that can support research and can clarify the interactions between agents and their environment (e.g., the interactions that occur between management and the surrounding landscape). In summary, this work has laid the foundations for the development of a multi-agent model in CBB management, seeking a way to understand the landscape context in pest management with the objective of cooperative management among farmers, contributing to their well-being and the environment.

5. Performance of model

In addition to searching scientific literature to develop the proposal for this model, the great difficulty of this already complicated simulator will be to thoroughly verify the correct functioning of the underlying mechanisms. Switching from simple agents (a berry, an insect) to cohorts (a set of berries or insects) required adjustments both to verify the correct evolution of each type of entity, but also to avoid the number of cohorts becoming too large. Indeed, a CBB cohort groups together individuals born at the same time and within the same berry (or berries cohort). During its evolution, this CBB cohort changes its stage and is often led to split. For example, when turning mature, one part becomes adult males and the other adult females. Another example: when it encounters colonizable berries, a dispersing female must also split if the number of unoccupied berries is less than the size of the cohort of these females. All these mechanisms can quickly lead to coding errors, but also to too many agents, which slows down the simulations excessively and prevents their analyses. This is why several methods of the model only consist in checking the consistency of the whole. Moreover, at the end of each step, a procedure is executed in order to aggregate cohorts of CBBs positioned on the same berries and sharing the same stage. Although it slightly degrades the individual-centered dimension of the model, this mechanism reduces the number of agents and allowed us to conduct sensitivity analyses. However, we analyzed that, compared to a simulation without aggregation, keeping at most 4 CBB cohorts with the same stage (and within the same berry cohort) had very little effect on the results.

In any case, moving from an individual-centered model to a cohort model is not equivalent: for example, when a cohort of 1000 females disperses, not all the 1000 females move to the same cell (and to the same berries). At individual level, one would expect a more homogeneous distribution in space of the CBBs. By working with cohorts, we are thus at the limit of the agent (or individual-centered) paradigm. But this is surely the price to pay when we consider millions of individuals.

IV. General discussion

1. The contribution of the work

The main aim of the work was to understand and model the processes structuring the dynamics of CBB populations and associated damage at different spatial scales. This work provides evidence of the importance of the surrounding landscape on the incidence of bored berries, the movement of CBB and joins a series of works that highlight the role of the landscape in pest management (Bianchi et al., 2006). An agent-based model (ABM-CBB) is proposed that articulates the knowledge of the biology of the CBB, the characteristics of the plots, the frequent management applied to it and the landscape context to achieve and value strategies of management that consider multiple spatial scales, to explore cooperative management between farmers who share the surrounding landscape and where the farmer is a central and active agent of the system.

2. Hierarchizing spatial effects on CBB dynamics

Through a variance partitioning approach (chapter 1) we show that maximum bored berries in coffee plantations are explained by factors operating at multiple spatial scales and that the joint effects of these factors are more important than the separate effects (individual effects). The resource concentration hypothesis proposed by Root (1973) and extended to the landscape scale by O'Rourke & Petersen, (2017) is supported by the relationships found in this study. On the one hand, the relationship of maximum bored berries with the number of nodes with berries, distance between plants and density of coffee trees support the hypothesis at the plot scale. On the other hand, positive relationships with the percentage of coffee cover and the berries index and negative partial relationships with the percentages of forest cover, and the Shannon evenness index support the extension of the hypothesis to the landscape scale, recognizing that both scales are important for CBB management and that continuing with a management approach at the plantation level will be less effective than considering the surrounding landscape.

3. Improving knowledge on CBB dispersion

Our results join the evidence demonstrated by Olivas et al. (2009) in the same landscape of CBB movement in land uses adjacent to coffee plantations. CBB can utilize adjacent land uses in search of resources, constantly emerging CBB from berries within coffee plantations and moving into adjacent land uses. We found that the highest rates of CBB capture in adjacent land uses coincides with the time when the new generation of berries are fit to be bored (Montoya & Cardenas-Murillo, 1994; Benavides et al., 2012) and not what we assumed to be after berry harvest when resources (berries) are limited in the plantation so we expected it to stimulate CBB movement across the landscape to search for new resources. The results are to be expected given that females leaving the berry are strongly attracted to the volatile compound of ripe berries (Frederic Mathieu et al., 2001). The findings of this study demonstrate the importance of land uses in facilitating the movement of CBB and how these adjacent land uses can influence coffee plantation conditions. For example, we found that pastures adjacent to coffee plantations facilitate the movement of CBB supported by wind action, and that coffee plantations captured more CBB (twice as much) than coffee plantations adjacent to forest or abandoned coffee, suggesting firstly that the microclimate in coffee plantations can be influenced by the adjacent land use conditions, and secondly the provision of natural enemies provided by the adjacent land use (e.g., forest).

4. Landscape connectivity: a good tool to better plan CBB management strategies at plot scale

Our results confirm once again the importance of the landscape through metrics of functional connectivity (landscape configuration and composition). It is not possible to continue with a plantation-level management approach given the importance of the surrounding landscape, and to explore strategies that can contribute to multi-scale CBB management. For example, different land uses adjacent to the coffee plantation can facilitate CBB movement, poor or no CBB management in some plots or abandoned plots can negatively impact surrounding plots with efficient CBB management. It is supported by the synergy between management and connectivity, i.e., when coffee plots have high connectivity and apply management for CBB control they may have a higher incidence of bored berries than when these plots are isolated in the landscape. Plots with no CBB management and connected plots have a lower incidence of bored berries than those that are not connected. This is unexpected in the study, but we believe that there are bottom-up and top-down mechanisms at work that explain this finding; we assume that unconnected plots with higher incidence of bored berries are favored by microclimate (top-down), resource concentration (bottom-up) and plot size. On the other hand, connected plots allow the movement of CBB populations, favoring the action of natural enemies. Understanding landscape connectivity and CBB movement is crucial for the design of management strategies considering multiple spatial scales, as the current management approach is not sufficient security for pest control if the landscape context is not considered. Pests and natural enemies use the landscape to move around in search of resources (Merriam 1984). The ease with which they can move through the landscape depends on the degree of complexity of the landscape, the availability of resources and their ability to disperse (Kindlmann & Burel, 2008, Goodwin & Fahrig, 2002). Therefore, methodologies that assess the functional connectivity of the landscape (based on circuits or networks) for pests and natural enemies are crucial for management decisions at landscape scales (Moreno et al. 2023).

5. ABM: a good tool to integrate knowledge and simulate CBB management strategy scenario

Furthermore, to evaluate cooperative management strategies that consider the modularity between management, plot characteristics and the surrounding landscape or to evaluate plot designs (structure) considering the landscape configuration, we developed a game that involves scenarios with different landscape conditions, market conditions (external factors) and the costs associated with the management of the system and where farmers are an active agent who decide on the management of the CBB.

6. Review of choices made in this thesis

The combination of the approach of this thesis through observation studies (chapters 1 to 3) and a simulation part (chapter 4) allowed the work to be approached holistically. The field work provided a more complete understanding of the role of the landscape and helped to clarify the importance of multiple scales and their interactions with management, something not studied in the case of the CBB, allowing the incorporation of the knowledge generated within the ABM-CBB the multiple spatial scales in the spatiotemporal dynamics of the CBB as a tool to explore cooperative management strategies with coffee farmers. This would not have been possible in an observational or experimental study due to the complexity of the interaction. This provides a more complete understanding of the system and the interactions at different levels of organization.

It is important to note that the chosen approach may present limitations and challenges. A limitation of the observational studies was the time scale to evaluate the effects of CBB on coffee berry production (chapters 1 and 2). During the field phase (chapter two) after generating detailed spatial information of the selected landscapes (field evaluation) and the design, it was not possible to carry out evaluations in some coffee farms because permission was not obtained from the owners. On the other hand, in the ABM-CBB, at the beginning of the conceptual model approach, it was decided not to incorporate more detailed information on some system processes (e.g., the physiology of coffee trees and management practices such as coffee pruning) always given that the balance between simplicity and complexity of the simulator had to be evaluated. Another limitation in this study is the lack of active participation of farmers, validation, and calibration in a participatory process, given that during the development process of the conceptual model the covid-19 pandemic occurred. However, provisions were made, and care was taken to ensure that both parts of the thesis were rigorously addressed, and valid conclusions were obtained.

Studies in agricultural landscapes in Central America such as the one in this thesis are a challenge given that they are made up of mosaics of heterogeneous and very dynamic land uses.

7. Limits and validity of the approaches

The variance partitioning is a good approach to understand the response of pests or natural enemies to their environment at different spatial scales (e.g., management and landscape configuration and composition). On the other hand, the use of connectivity metrics or scenarios based on graphs or circuits are an alternative to understand how pests or natural enemies perceive the landscape for their dispersal from the perspective of the role of different land uses in pest dispersal (Avelino et al., 2012; Moreno et al., 2022; Vilchez-Mendoza et al., 2022). The synergy between connectivity and pest management depends on multiple mechanisms (e.g., resource concentration, microclimatic conditions, management, landscape configuration). Understanding these mechanisms allows us to think of management alternatives to improve productivity and promote the sustainability of the system, producers, and the environment. Trapping methods along environmental gradients offer a cost-effective and informative approach to studying pest movement and dispersal across landscapes, particularly when more expensive methods are not feasible (e.g., molecular markers). The methodological approaches used in this research can be applied in other coffee landscapes where CBB has negative impacts or be useful in studies with other pests.

An important limitation of this study is the restricted time frame during which the research was conducted in the field. To enhance the validity of the findings, it is crucial to extend the study duration to cover two or three coffee cycles, spanning at least two consecutive years. This extended timeframe is necessary considering the significant impact of climatic variations on pest dynamics.

Alternatively, it would be valuable to replicate the study in diverse landscapes within the region. These landscapes should encompass varying tree shade conditions and landscape configurations, including different land uses. Such variations could introduce additional or different effects on the Coffee Berry Borer (CBB). Replicating the study in this manner would strengthen the robustness of the conclusions and implications drawn from the results. It would also help determine whether the responses of CBB to management practices, modulated by the landscape, are generalizable or if they depend on specific landscape conditions. By addressing these aspects, the study's findings would be more comprehensive and provide a broader understanding of the dynamics and management of CBB in different landscapes.

8. Why an ABM model?

Multi-agent models are an excellent tool to interact and study together with farmers the role of the landscape in pest control, with supporting management strategies that help reduce the economic impact, management cost and environmental sustainability, allowing an articulation between individuals and collective levels with scale changes that allow the simulation of complex processes or mechanisms essential in the modeling of pests (Bommel, 2020) and complex socio-ecological systems. The use of simulation tools that incorporate empirical knowledge, farmers' management experience and pest biology is essential to explore management strategies (Petit et al., 2020) at multiple spatial scales (e.g., ABM-CBB). However, it is important not to lose sight of the purpose of the tool, in our case it is a simulator that aims to support management decisions and explore cooperative management between farmers without aiming at forecasting. It is also important to have a balance between simplicity and complexity of the system to be modelled.

In the proposed multi-agent model, we aim to address cohort-based modeling, which necessitates a comprehensive evaluation of all model mechanisms to mitigate the impact of the paradigm shift

9. Perspectives of the work

5. 1 To test, validate and improve the simulation model with users

To run the ABM-CBB and interact with farmers through role plays, it is necessary that farmers can socialize with the model, understand how it works and perform the necessary calibrations. With simulations as a powerful tool for complex systems such as ABM-CBB, it is possible to explore different management strategies, their effectiveness in controlling CBB and in assessing the economic impacts that the strategies would entail and therefore have a better understanding of the different spatial scales of CBB management, without losing perspective that farmers are managing a complex system that is not solely focused on CBB management (Gurr et al., 2017).

With the knowledge acquired in this work, the adoption of strategies at the plot scale (e.g., timely harvest, sanitary harvest, application of traps and Beauveria) is proposed considering the surrounding landscape (e.g., coordinated management between farmers) that imply a change towards social. This work helps to construct shared interests for long-term benefits (Salliou et al., 2021) and public policies through incentive programs as a compensation method that promotes sustainable management of the productive system and the landscape.

The next step of this work is to conduct workshops with coffee farmers in Central America to calibrate and test the model. That would also help to to evaluate the importance of the landscape in the incidence of the CBB and cooperative management strategies to reduce the damage caused by the borer and the economic costs associated with its management. We hope to develop an ABM-CBB mobile application so that technicians and producers can have access to this tool. The adoption of the ABM-CBB by the different coffee institutes, cooperatives or producer associations in Central America will allow the study and evaluation of cooperative management strategies to make informed decisions.

5. 2 Management implications

With the knowledge gained, timely harvesting of coffee berries and cooperative management among farmers sharing the surrounding landscape are important, possibly by synchronizing the practices they usually apply (Schellhorn et al., 2015). On the other hand, plot characteristics such as spacing of coffee plants, tree shade and the surrounding landscape (configuration, composition; connectivity) need to be considered in any management plan.

We believe it is important to include barriers through forest conservation and restoration or the inclusion of multi-layered live fences, or tree shade in the system (PES) with diverse species that provide multiple functions to hinder the movement of CBB and to harness a variety of ecosystem services (e.g., provisioning service). Adoption should be accompanied by incentives (e.g., payments for ecosystem services, carbon certificates, coffee plantation certification). Tree shading and planting spacing of coffee trees can be assessed in different arrangements to optimize the areas of small plots in coffee production.

An example of design at plot level (Figure 28) considering our results is that in the center of the plot high densities of coffee plants and low tree cover (shade trees) can be managed and as the edges of the plot, the tree density can be increased and the spacing of the coffee plants decreased (lower densities). This can have a positive impact on the reduction of bored berries and a decrease in the productivity of the plot, compensated by the payment received for some compensation mechanism and for the provisioning service that the producer receives from the tree cover (e.g., fruits, wood, or firewood).

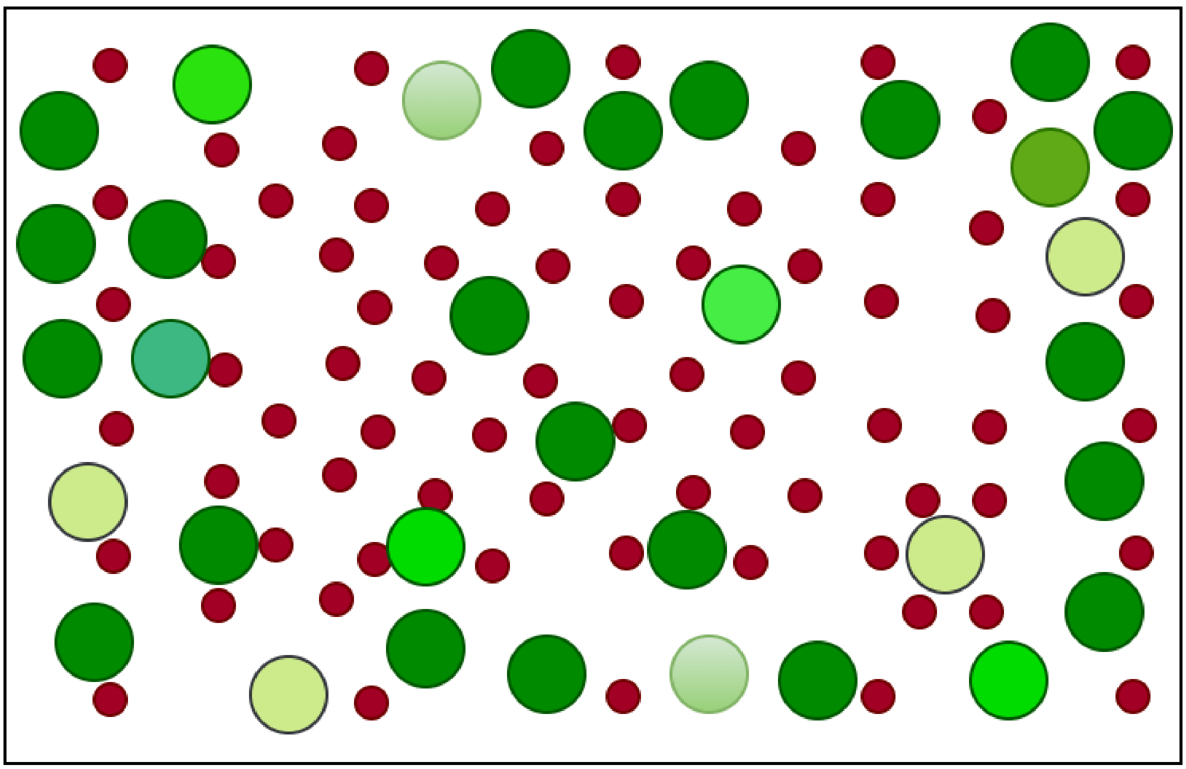

Figure 28. Hypothetical design of the structure of a coffee agroforestry system with low densities of coffee trees and high densities of shade trees.

10. **Messages**

This study puts on the table the importance of considering the landscape in the management of the CBB, however, we need to clarify some mechanisms that operate at different scales to have a more detailed understanding of the dynamics of the CBB, the multiple spatial scales and the environmental conditions. That would help to fill gaps regarding one of the most studied pests such as CBB. In this way, management strategies can be proposed that can range from the application of control practices and the opportune moment of their application, to redesign of agroforestry systems or the surrounding landscape. Management practice decisions have economic, social, and political implications, which is why it is necessary to develop participatory simulation tools that incorporate empirical knowledge and the experience of coffee producers and technicians to make informed decisions in favor of improve farmers' livelihoods and the environment.

Coffee agroforestry systems in Latin America are of great economic and social importance for many small producers, being in most cases the main livelihood, but they face significant challenges in terms of pest and disease management in a changing world. Through my research, I seek to collaborate in the management of CBB from an ecological perspective and to collaborate with the adoption of computational tools for evidence-based decisions. I hope that this work, especially the ABM-CBB, helps promote the adoption of sustainable management practices for the control of CBB and contributes to improving coffee growing in Latin America.

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Annex. Dynamique spatio-temporelle du scolyte des baies du caféier (Hypothenemus hampei): proposition d'un outil de simulation pour la planification de stratégies de gestion et de contrôle à plusieurs échelles spatiales

1. Introduction

Le scolyte des baies du caféier (CBB) est le ravageur le plus important de la culture du café partout dans le monde, causant des dommages considérables à la fois à la production et à la qualité des fruits, menaçant ainsi la sécurité alimentaire des petits agriculteurs. Son contrôle reste difficile, bien que différentes stratégies de contrôle aient été développées (pratiques culturales, contrôle mécanique, utilisation de pièges, ennemis naturels) (Aristizábal et al., 2016; Benavides et al., 2012; Damon, 2000; Dufour & Frérot, 2008). L'importance de la conservation de la biodiversité et des services écosystémiques associés pour la lutte contre les ravageurs n'est pas très bien reconnue. La plupart des travaux mettent surtout en avant le rôle des ennemis naturels présents dans les agro écosystèmes écologiquement intensifs dans la régulation des ravageurs. Cependant, peu de choses sont connues sur l’effet du paysage environnant et quasiment rien n'est connu sur les interactions possibles de gestion se déroulant à différentes échelles spatiales (Martínez-Salinas et al., 2016, 2022; Perfecto & Vandermeer, 2006; Smith et al., 2022). Ce constat est vrai pour le CBB. En effet, les études concernant la gestion du CBB se sont concentrées sur l'échelle de la parcelle (Aristizábal et al., 2016; Benavides et al., 2012; Damon, 2000; Dufour & Frérot, 2008) et ne prennent pas en compte les facteurs à l'échelle du paysage.

Cette thèse démontre l'importance du paysage environnant dans l'incidence des fruits infestés par le CBB. Elle montre qu’il n'est pas possible de séparer les effets des facteurs qui agissent au sein du système ou dans son environnement (voir chapitre I). Nous avons aussi montré que la connectivité du paysage est une caractéristique importante à prendre en compte lors de l'élaboration des stratégies de contrôle (voir chapitre II). Nous avons aussi mis en évidence que les femelles CBB émergent constamment à la recherche de nouveaux fruits et qu'elles peuvent circuler au sein de zones adjacentes à la plantation de café. Dans les zones dépourvues de couverture arborée, elles sont capables de se déplacer au-delà de la lisière sous l'action du vent (voir chapitre III). Cette thèse s'inscrit dans une série de travaux qui mettent en évidence le rôle du paysage dans la lutte contre les ravageurs (Bianchi et al., 2006; Chaplin-Kramer et al., 2011; Rusch et al., 2016). En fin de compte, nous proposons un modèle de simulation basé sur des agents (CBB-ABM) qui articule la connaissance sur la biologie du CBB, les caractéristiques des parcelles, la gestion fréquemment appliquée par les producteurs et le contexte paysager. Le but de ce modèle est de rechercher et d’évaluer des stratégies de gestion qui prennent en compte des échelles spatiales multiples et explorent la possibilité d'une gestion coopérative entre les agriculteurs qui partagent un même paysage environnant. Dans ce modèle de simulation, l'agriculteur est un agent central et actif dans le système.

2. Chapitre I. Évaluation des effets conjoints du paysage, des caractéristiques de l'exploitation et des pratiques de gestion des cultures sur les dégâts causés par les scolytes des baies (CBB) dans les plantations de café

Ce chapitre de la thèse s'attache à comprendre comment différents facteurs liés à la gestion du CBB à l'échelle de la parcelle et du paysage expliquent l'incidence des fruits scolytés dans un paysage constitué de plantation de caféiers au Costa Rica. Plus précisément, nous nous sommes demandés s'il existait des facteurs à une échelle spécifique qui pouvaient expliquer les dégâts causés ou s'il s'agissait d'un effet conjoint entre plusieurs facteurs à différentes échelles.

2. 1 Méthodologie

Pour réaliser ce travail, des parcelles ont été sélectionnées sur un gradient altitudinal compris entre 613 et 1259 m d'altitude. La méthodologie utilisée dans l'étude a consisté à sélectionner cinquante plantations de café situées dans différentes zones caractérisées par des niveaux de complexités variables. Différentes altitudes et structures de paysage ainsi que des pratiques de gestion agricole ont été prises en compte. Les plantations ont été sélectionnées en fonction de la volonté des agriculteurs de collaborer et d'autoriser l'accès à leurs exploitations durant une année.

Nous nous sommes basés sur des photographies aériennes, pour cartographier l'usage des terres et caractériser le paysage autour des plantations de café. Des mesures du paysage, telles que l'indice de régularité de Shannon et l'indice d'agrégation, ont été calculées pour évaluer la composition et la distribution spatiale du paysage. Des informations ont également été recueillies sur les pratiques de gestion agricole des agriculteurs, y compris la lutte contre le scolyte (utilisation de pièges, d'insecticides chimiques et d'autres techniques de gestion).

Le nombre de baies infestées par le scolyte a été échantillonné quatre fois entre mai et novembre 2009. Étant donné que la phénologie des différentes variétés de café et les pics de récolte diffèrent d'une exploitation à l'autre, il a été décidé d'utiliser le nombre maximal de baies infestées par parcelle comme variable de réponse pour l'analyse statistique au cours des quatre périodes d'échantillonnage.

Les variables ont été regroupées en fonction de la gestion, des caractéristiques du site et des variables décrivant le paysage environnant (composition et configuration). En utilisant des régressions partielles par le biais de l'approche de partitionnement de la variance et à l'aide d'arbres de régression, nous avons évalué l'importance relative de chaque ensemble de variables et leur contribution à l'explication de la quantité maximale de fruits endommagés (Figure 1).

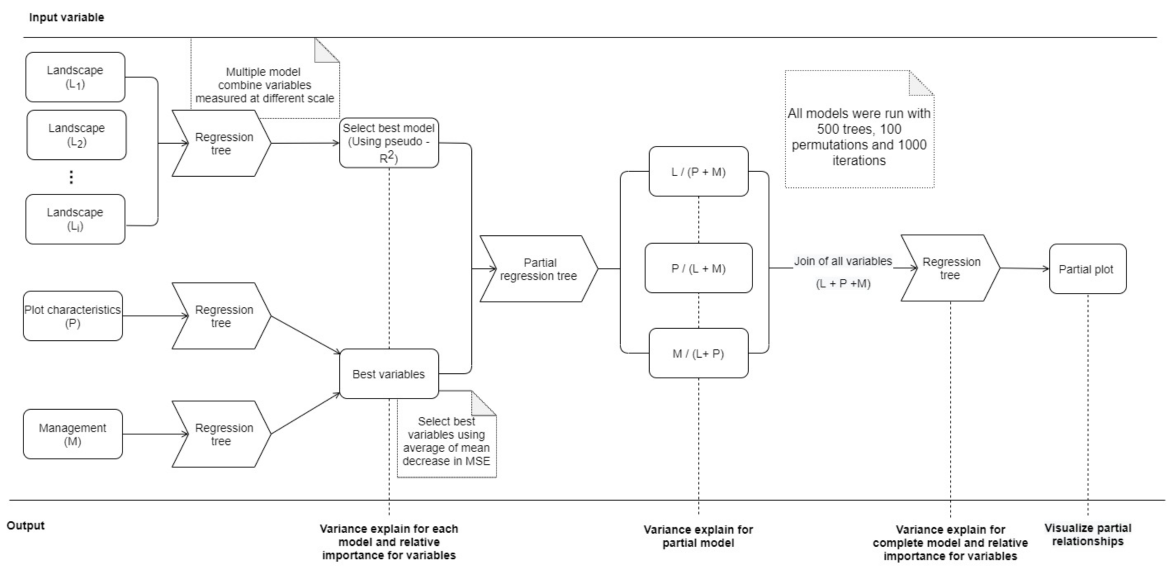

Figure 1. Processus d'analyse pour évaluer la contribution relative de toutes les variables.

2. 2 Principales conclusions

Les facteurs opérant au niveau du paysage sont aussi importants que ceux opérant uniquement à l'échelle de la parcelle. Nous avons constaté que la part de la variance du nombre maximal de baies infestées expliquée par les effets conjoints de chaque groupe de variables (gestion, contexte paysager et caractéristiques de la parcelle) est plus importante que la part de la variance expliquée par les caractéristiques de chaque groupe (effets uniques). En d'autres termes, la quantité maximale de fruits scolytés est expliquée par les effets conjoints des variables et il est difficile de séparer ces effets. L'effet individuel n'est pas suffisant pour expliquer les dégâts causés par le scolyte, ce qui montre qu'il ne faut pas ignorer le paysage environnant lorsque l'on propose des pratiques de lutte contre le scolyte, et qu'il faut regarder au-delà de la parcelle.

Les mécanismes que proposent (O'Rourke & Petersen, 2017) pour étendre la théorie de la concentration des ressources à l'échelle du paysage est démontrée dans cette étude.

A l'échelle de la parcelle, les variables importantes corrélées avec le nombre maximum de baies infestées sont le nombre de nœuds fructifères, la distance entre les plantes et la densité de plants de café, ce qui soutient l'hypothèse de la concentration des ressources à l'échelle de la parcelle (Root, 1973). A l'échelle du paysage, des relations positives sont observées avec le pourcentage de surface de café présent et l'indice de grain le plus élevé, et des relations négatives avec les pourcentages de forêt, de pâturage et de canne à sucre dans le paysage, et l'indice d'homogénéité de Shannon.

2. 3 **Messages**

Les facteurs contribuant à la réduction du nombre de fruits scolytés dans notre région d'étude ont été identifiés. Nous avons montré que des paysages plus hétérogènes, avec plus de forêts et moins de caféiers agrégés, combinés à une plus faible densité de caféiers au sein de la parcelle, une fréquence d'élagage plus faible et de bonnes pratiques sanitaires de récolte (qui réduisent le nombre de grains de café résiduels après la récolte) entraînent une diminution du nombre de grains infestés. Sur la base de nos résultats, nous pensons qu'un plan de gestion intégré du scolyte à l'échelle d'une zone doit prendre en compte les influences d'échelles spatiales multiples, ainsi qu'une action coordonnée entre les agriculteurs partageant le même paysage. Ces stratégies de gestion devraient soutenues et accompagnées par politiques incitatives encourageant les agriculteurs à les adopter. (Brévault y Clouvel, 2019).

3. Chapitre II. Interactions entre la connectivité du paysage et la lutte contre les ravageurs

Dans ce chapitre, nous abordons les implications du paysage et de la gestion directement du point de vue de la connectivité. La connectivité des paysages a des implications au niveau des ennemis naturels et des ravageurs (Guo et al., 2022; Mitchell et al., 2013; Moreno et al., 2022) et constitue donc un élément clé à prendre en compte dans la lutte contre les ravageurs.

Dans le cadre de cette recherche, nous avons émis l'hypothèse que les parcelles de café connectées et peu résistantes au mouvement du CBB, que n'appliquent pas de gestion contre le CBB, auront une incidence plus élevée de fruits scolytés que les parcelles qui ne sont pas connectées et qui appliquent une lutte contre le CBB, c'est-à-dire que nous nous attendons à une action synergique entre la connectivité et la gestion sur l'incidence des fruits scolytes.

3. 1 Methodologie

Pour répondre à notre hypothèse, nous avons évalué la connectivité des paysages en utilisant différentes approches de mesure de la connectivité. D'une part, nous avons estimé la connectivité fonctionnelle, en utilisant la théorie des circuits et en simulant différents scénarios de dispersion du scolyte, et en utilisant aussi la théorie des graphes. D'autre part, nous avons estimé les paramètres de configuration du paysage comme un proxy de la connectivité structurelle du paysage (par exemple, la contagion).

Nous avons travaillé sur 14 paysages de 500 m de rayon qui ont été catégorisés selon leur niveau d'hétérogénéité (% de forêt, % de café, indice d'hétérogénéité et équitabilité des usages) et nous avons considéré deux niveaux d'élévation pour réduire l'effet de l'élévation sur l'incidence du CBB. Nous avons travaillé à partir d'une carte d'occupation des sols de la région (Amante, 2020), de polygones de plantations de café au format shape fourmi par l'Instititut du Café du Costa Rica (ICAFE). Il y a ensuite eu une étape de validation sur le terrain afin d'obtenir la carte d'occupation des sols la plus affinée et la plus fiable possible pour notre objectif (voir détails dans le chapitre II de cette thèse). Au sein de ces 14 micro-paysages, 66 parcelles ont été sélectionnées pour recueillir des informations sur la gestion agronomique, et en particulier sur la gestion du scolyte, par le biais d'entretiens avec les agriculteurs. D'autre part, quatre évaluations sur le terrain ont été effectuées dans ces parcelles pour estimer l'incidence des fruits scolytés. Il convient de mentionner que le nombre de caféiers évalués dans chaque paysage n'était pas égal, c'est-à-dire que la conception était déséquilibrée.

Les variables de gestion et les caractéristiques des parcelles ont été combinées dans une analyse d'échelle multidimensionnelle non métrique (NMDS). En utilisant l'approche de régression multiple, nous avons ajusté des modèles mixtes généralisés et pris en compte la structure de corrélation des parcelles (étage altitudinal et paysager) et la redondance des variables explicatives. La première étape a consisté à ajuster tous les modèles possibles basés sur la combinaison des mesures de connectivité structurelle et fonctionnelle (circuits et graphs) et des variables de gestion (détails de la méthodologie et de l'analyse dans le chapitre II de la thèse). Une fois les meilleurs modèles identifiés en utilisant l'AIC et le BIC comme critères de sélection, nous avons évalué les diagnostics et le manque d'ajustement pour identifier le modèle qui expliquait le mieux la structure des données.

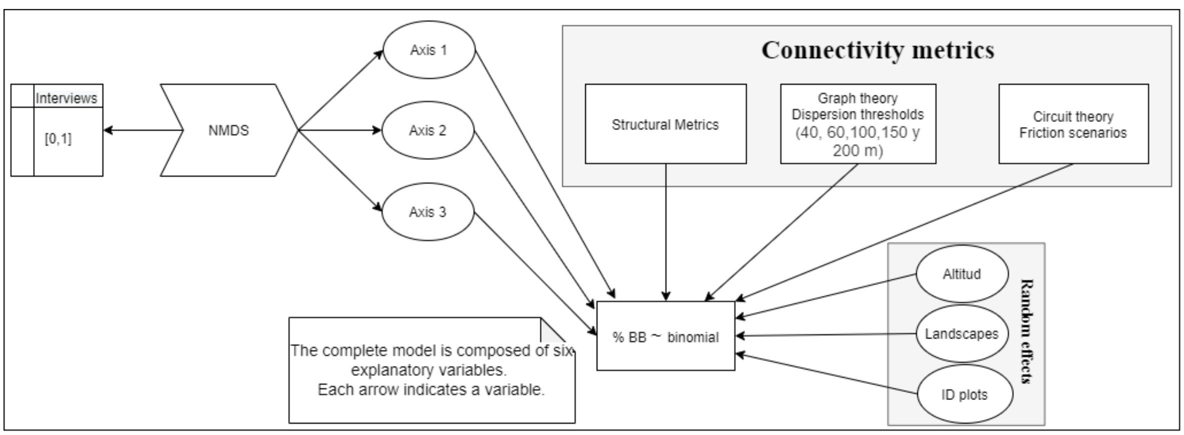

Figure 2. Graphique de représentation de l'analyse des données. Sélection des 15 modèles à l'aide des critères AIC et BIC. Une seule métrique de connectivité pour chaque boîte entre dans chaque modèle.

3. 2 Principales conclusions

Dans ce chapitre, nous démontrons une fois de plus l'importance du paysage, en suggérant que les agriculteurs partageant le même paysage devraient coordonner leurs stratégies de gestion pour un contrôle plus efficace du scolyte. Une bonne gestion ne suffit pas si les parcelles de café environnantes présentent des niveaux de populations élevées de scolytes (par exemple, à proximité de plantations de café abandonnées ou mal gérées). Néanmoins, notre hypothèse selon laquelle il existe une synergie entre la gestion et la connectivité est partiellement confirmée.

Plus précisément, nous avons constaté que les parcelles de café qui bénéficient d'une connectivité et d'une gestion plus importante ont une incidence plus élevée de fruits scolytés que les parcelles dépourvues de connectivité et de gestion. Nous avons été surpris de constater que l'incidence des fruits infestés était plus faible dans les parcelles connectées et non gérées que dans les parcelles connectées et gérées. Nous avons envisagé quatre hypothèses pour expliquer ce résultat qui sont présentées dans le chapitre 4. D'autre part, la métrique du circuit mesurant la quantité de courant atteignant la parcelle (courant = flux de CBB) où la forêt exerce une plus grande résistance que le pâturage avait une corrélation positive avec l'incidence des fruits scolytés, suggérant que plus la probabilité de connectivité est élevée et plus la résistance du paysage est faible, plus les dommages causés par le CBB sont importants.

3. 3 Messages

Une fois de plus, nous avons mis en évidence l'importance du paysage dans la gestion du CBB, en particulier la connectivité du paysage. Cela nous amène à penser que nous devons mieux comprendre les mécanismes opérant à différentes échelles et comment nous pouvons rendre l’effet de la gestion et de la connectivité plus synergique. Sur la base des principales conclusions, nous pouvons envisager de redessiner les paysages et les parcelles afin d'optimiser la lutte contre les ravageurs, la conservation de la biodiversité et d'améliorer les services écosystémiques fournis par la biodiversité dans ces paysages. Toutefois, il ne s'agit pas d'une tâche facile, elle n'a pas d'effet immédiat. Des politiques publiques, des incitations et des stratégies sont nécessaires pour que les agriculteurs puissent s'approprier le changement d’échelle dans la gestion du CBB.

4. Chapitre III. Quantification des déplacements du scolyte du caféier à l'interface entre les plantations de café et les usages de sols adjacents

Cette étude a porté sur les mouvements du scolyte dans les plantations de café avec différents usages des terres adjacentes (forêt, pâturage et plantations de café abandonnées). Nous avons émis l'hypothèse du manque de ressources, qui suppose qu'à la fin de la récolte et pendant la saison de floraison, lorsque les fruits sont rares, nous aurons des captures plus importantes dans les pièges éloignés de la plantation de café en raison de l'effet de débordement du scolyte. Cela induirait le mouvement vers l'intérieur des autres usages de sol adjacents, en raison de la rareté des ressources dans la parcelle, forçant le scolyte à se déplacer dans ces usages de sol pour chercher de nouveaux sites.

4. 1 Methodologie

Treize parcelles de café caractérisées par une interface avec une forêt secondaire dégradée (n=6), une zone de pâturage (n=5) ou une zone de café abandonné (n=3) ont été sélectionnées. A chaque interface, trois transects ont été placés à au moins 50 m de distance (le plus grand était de 60 m). Le long de chaque transect, quatre pièges à scolytes (Brocap® + attractifs commerciaux) ont été placés à 20 m les uns des autres pour éviter toute interférence entre les pièges (Figure 3). Le transect commençait à 20 m à l'intérieur de la plantation de café (piège 1) jusqu'à 40 m à l'intérieur de l'usage de sol adjacents (piège 4).

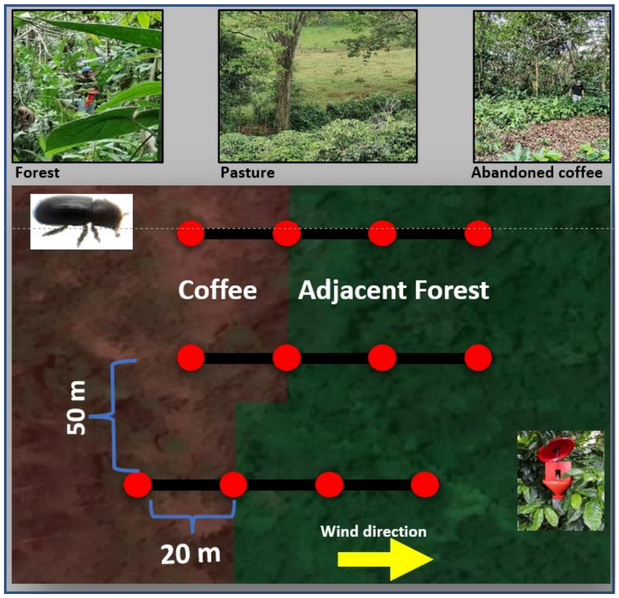

Figure 3. Déploiement des pièges à scolytes (en rouge) dans les plantations de caféiers et dans les usages de terres adjacents.

Les pièges ont été vérifiés entre 12 et 15 jours, et les échantillons collectés ont été apportés au laboratoire pour être pris en photos (trois photos par échantillon). Nous avons utilisé un algorithme de détection d'objets pour détecter et compter le nombre de CBB sur chaque photographie. Cet algorithme a été préalablement entraîné (voir détails au chapitre III). Les pièges sont restés installés d'août 2020 à juin 2021.

Nous avons utilisé des modèles mixtes linéaires généralisés pour évaluer l'interaction entre les usages de sols adjacents et la position des pièges. Nous avons également ajusté un modèle mixte additif généralisé pour évaluer la tendance des captures au cours de la période d'échantillonnage. Enfin, nous avons évalué la relation entre les variables climatiques et les captures de CBB.

4. 2 Messages

Notre hypothèse principale (manque de ressources) ne s'est pas vérifiée, dans les forêts et les pâturages, la tendance était à la baisse à mesure que les pièges s'éloignaient de la lisière et quelle que soit la période de l'année. Nous montrons l'importance de l'usage des sols adjacents dans la dispersion du scolyte, bien que cette population de scolytes ne représente qu'environ 4 % de la population se déplaçant dans les plantations de café (Olivas et al., 2009).

Les femelles du scolyte du caféier peuvent sortir de la plantation de café et se déplacer dans les terres adjacentes. Cependant, dans les forêts et les pâturages, la tendance était à la baisse au fur et à mesure que les pièges s'éloignaient de la lisière et quelle que soit la période de l'année. Les captures maximales de scolytes ont eu lieu à la fin de la saison sèche et au début de la saison des pluies (avril-mai), période à laquelle les cohortes de baies issues des premières fleurs (janvier-février) peuvent être âgée de plus de 120 jours et atteindre un taux d'humidité maximal ce qui est favorable à la colonisation des fruits par le scolyte (Salazar et al., 1994).

Pendant la récolte, deux petits pics de capture du scolyte sont observés, marqués notamment dans les parcelles de caféiers abandonnés, ce qui suggère que ce n'est pas un effet de l'enlèvement des baies par l'action de la récolte, mais plutôt un effet des conditions environnementales telles que la pluie ou la lumière du jour qui stimule l'émergence du scolyte (Mathieu et al., 1997).

Les plantations de café abandonnées sont une source de scolytes qui peuvent faciliter l'infestation des baies dans les plantations de café gérées. Les forêts créent une barrière au mouvement, fournissent des ennemis naturels pour la lutte contre le scolyte et empêchent même le transport du scolyte par le vent. D'autre part, les pâturages peuvent faciliter le déplacement du scolyte par le vent et infester les plantations de café gérées, peut-être au-delà de ce qui est documenté.

5. Chapitre 4. Dynamique du scolyte du caféier : Une approche de simulation multi-agents pour explorer la gestion coopérative à l'échelle du paysage

Dans ce chapitre, nous proposons un modèle basé sur des agents, appelé ABM-CBB, qui intègre des connaissances empiriques sur la dynamique du scolyte, le développement des fruits du caféier et les producteurs en tant qu'agents. Nous cherchons à aller au-delà des modèles analytiques proposés (Cure et al., 2020; Gutierrez et al., 1998; Rodríguez et al., 2013) en intégrant différentes échelles spatiales et l'agriculteur comme acteur principal du système à travers les décisions de gestion qu'il peut prendre au cours de la simulation.

Un modèle multi-agents est un ensemble d'entités appelées agents (dans le modèle, le CBB, les fruits et le producteur) qui interagissent entre eux et avec leur environnement (climat, paysage, parcelles, cellule), le produit de leurs interactions individuelles créant des changements dans le système. L'avantage des modèles basés sur les agents est leur flexibilité avec des interactions non linéaires. L'articulation entre les niveaux individuel et collectif abordant les changements d'échelle, qui semble essentielle pour comprendre des phénomènes spécifiques et l'autonomie des niveaux individuel et collectif, est un facteur clé dans le développement des modèles à base d'agents (Bommel, 2020). Les modèles basés sur les agents proposent un paradigme de simulation ascendant qui relie le niveau de l'agent et le niveau du système (Ferber, 1999).

Un des objectifs de l'ABM-CBB est d'explorer collectivement diverses stratégies de gestion avec les caféiculteurs de la région de Turrialba au Costa Rica. Suivant l'approche ComMod (Companion Modelling, ComMod 2005, Étienne, 2011), l'objectif de ce travail participatif est d'accompagner les agriculteurs pour améliorer le processus de décision collective plutôt que d'offrir des solutions "clés en main".

La présentation détaillée de ce modèle et les étapes nécessaires à sa construction sont présentées dans le Chapitre 4 de la thèse.

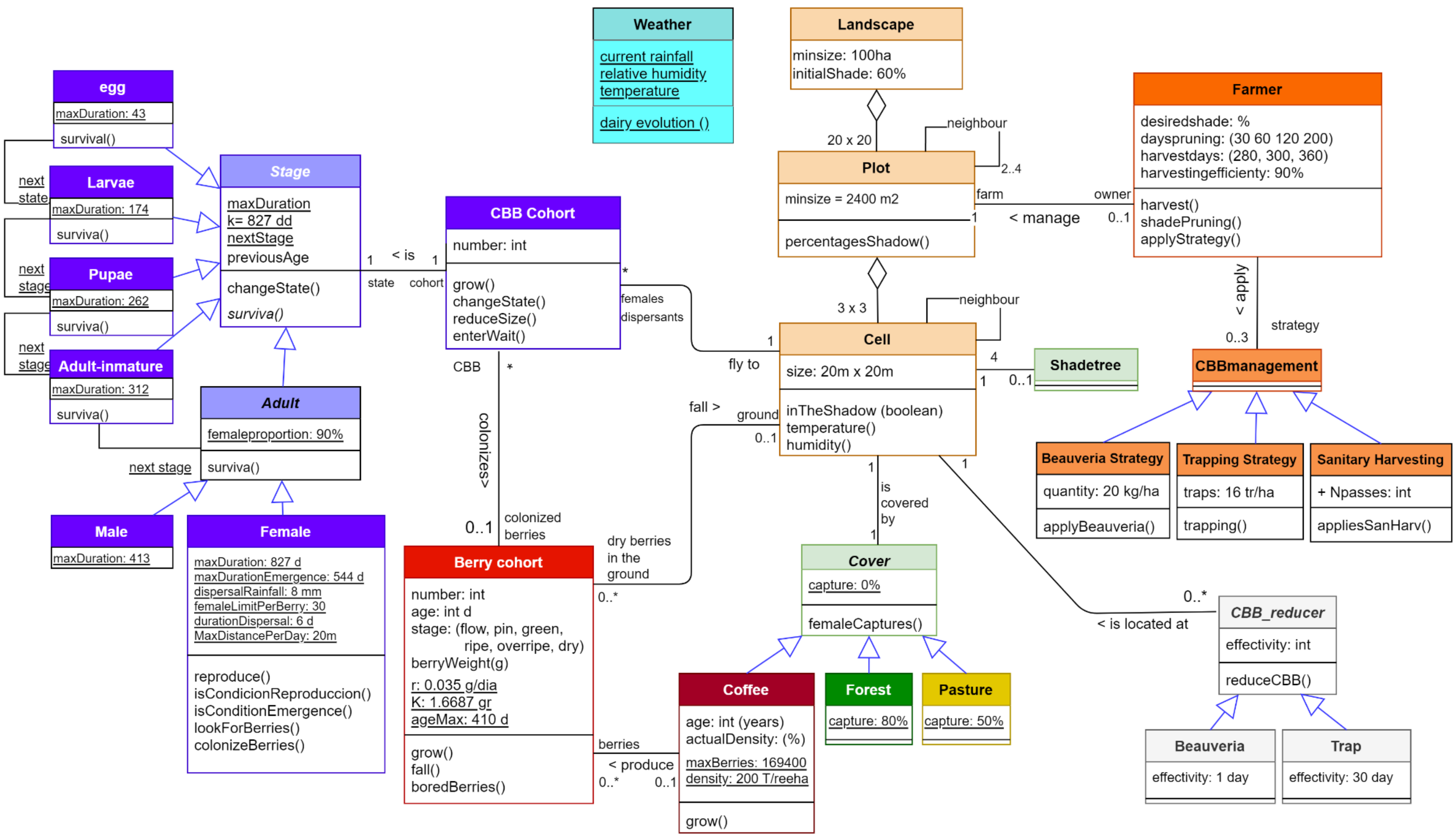

Figure 4. Diagramme de classes représentant les entités, les variables d'état et l'échelle de l'ABM-CBB (classe, attributs et méthodes). Ce diagramme a été utilisé pour présenter et discuter le modèle conceptuel avec les caféiculteurs et les chercheurs techniques des différents instituts du café en Amérique centrale, sa description originale est en espagnol.

6. Limitations

La conceptualisation et la paramétrisation du modèle sont considérées comme adaptées à l'objectif visé. Le modèle ABM-CBB ne comprend pas de composante physiologique pour les plants de café, il ne prend en compte que le développement des baies et la dynamique de l'infestation par le scolyte au niveau cellulaire. Toutes les plantations de café sont supposées être productives. L'émergence des fleurs est synchronisée à travers le paysage, entre autres. Cela permet de créer une représentation simplifiée du système caféier, en se concentrant sur les aspects clés d'intérêt et en évitant une complexité excessive. Une autre limitation est que nous n'avons pas été en mesure durant le temps de la thèse de réaliser les simulations et la socialisation du modèle avec les producteurs et les techniciens pour valider et recevoir un retour d'information.

7. Conclusions

Grâce aux connaissances acquises, il est important de récolter les baies de café de mnière rigoureuse au moment adéquat et de mettre en place une gestion coopérative entre les agriculteurs qui partagent le paysage environnant, en synchronisant éventuellement les pratiques qu'ils ont l'habitude d'appliquer (Schellhorn et al., 2015). Il est aussi important d'explorer les alternatives de gestion au niveau du paysage en tant qu'actions découlant de la refonte des systèmes agroforestiers du café et du paysage. Ces alternatives sont coûteuses en temps et en efforts, n'ont pas d'impact immédiat et nécessitent des politiques et des incitations pour être adoptées par les agriculteurs. Cependant, les stratégies de gestion utilisant la ABM-CBB peuvent être explorées avec la participation des agriculteurs, en cherchant à identifier la stratégie qui réduira les coûts associés à la gestion du scolyte ou les pertes dues aux dégâts.

D'un autre côté, il y a aussi un manque de recherche empirique pour aider à identifier ou clarifier les mécanismes qui peuvent être considérés pour la gestion du CBB en se concentrant sur différentes échelles.

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