

Article

Optimizing Pathogen Control through Mixed Cocoa–Plantain Agroecosystems in the Ecuadorian Coastal Region

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Abstract: Mixed production systems play a vital role in the economic sustainability and ecological balance of agroecosystems. Cocoa and plantain are key crops in Ecuador but face phytosanitary challenges, like witches' broom and black sigatoka diseases, especially when cultivated under monocropping systems. Combining habitat manipulation with adaptive pathogen management (APM) strategies can mitigate these challenges, but their efficacy in mixed cropping systems remains unclear. This study investigates disease and pest incidence in mixed cocoa–plantain systems during the establishment phase, focusing on the impact of spatial arrangements. Mixed agroecosystems showed a lower witches' broom incidence in cocoa than monocultures. Whereas, in plantain, there was a consistent black sigatoka incidence across spatial arrangements but a lower infection rate per leaf within mixed systems. We found varied nematode populations with monocultures hosting the highest root damage due to phytoparasitic nematodes. Weevil populations were also influenced by spatial arrangements with monocultures among the highest. Overall, mixed agroecosystems influence disease and pest incidence, potentially hindering pathogen spread. Plantain–cocoa associations reduce disease incidence in cocoa but may not affect the overall incidence of black sigatoka in plantain, at least during the establishment phase. Continued monitoring is crucial for understanding the long-term impacts and microclimatic effects on pest populations that could offer sustainable pest management strategies, reducing the reliance on chemical pesticides.

Keywords: mixed cropping systems; *Theobroma cacao*; plantain; adaptive pathogen management; sustainable pest management



Citation: Vera-Velez, R.; Ramos-Veintimilla, R.; Grijalva-Olmedo, J. Optimizing Pathogen Control through Mixed Cocoa–Plantain Agroecosystems in the Ecuadorian Coastal Region. *Agronomy* **2024**, *14*, 1107. <https://doi.org/10.3390/agronomy14061107>

Academic Editor: Robert P. Larkin

Received: 16 April 2024

Revised: 15 May 2024

Accepted: 21 May 2024

Published: 23 May 2024



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1. Introduction

Mixed production systems, predominant throughout tropical and subtropical regions, comprise roughly 80% of agricultural land, highlighting their significance for economic sustainability and ecological balance [1]. These systems, often referred to as mixed cropping systems, integrate various combinations of crops and sometimes trees, promoting biodiversity and enhancing ecosystem services. These agrosystems frequently include cocoa (*Theobroma cacao* L.) and plantain (*Musa* spp.) as both monocultures and integrated crops, contributing substantially to the annual revenue of tropical countries [2,3]. Cocoa, required for chocolate production, is a key driver of economic activity in countries like Ivory Coast, Ghana, and Ecuador [4]. Its economic significance is evident from its contribution to the livelihoods of millions of smallholder farmers and its substantial impact on the global economy with the chocolate industry valued at over \$110 billion annually [5]. In contrast, plantains are a fundamental food in many tropical regions. They are especially crucial in parts of Africa, Latin America, and the Caribbean as a vital source of carbohydrates

and energy for millions of people [6]. The cultivation of plantains promotes food security and generates income for numerous small-scale farmers, thereby playing a critical role in enhancing economic stability and lessening poverty in these areas [1]. Together, cocoa and plantains have substantial value in tropical agriculture, influencing both global commerce and local subsistence.

Despite their economic importance, productivity in agroecosystems is often limited by phytosanitary challenges. Cocoa, for instance, is particularly vulnerable to witches' broom disease caused by the hemibiotrophic fungal pathogen *Moniliophthora perniciosa* (Stahel) [7], capable of damaging up to 80% of plant tissues including fruits [8]. *M. perniciosa* is a challenging fungal pathogen that significantly impacts cocoa plants, particularly in Latin America. It triggers a condition known as "witches' broom", characterized by excessive branching of the cocoa trees, leading to reduced pod production and considerable economic losses for cocoa farmers [9]. The fungus infects the plant, causing a series of morphological and physiological changes, including the formation of green brooms that eventually dry up and die [10]. This disease cycle drastically reduces the yield of cocoa plants with losses reaching up to 90% in severely affected areas [10]. The life cycle of *M. perniciosa* includes both biotrophic and saprotrophic phases. During the biotrophic phase, the fungus infects living host tissues and evades detection by the plant's immune system for several weeks [11]. In the saprotrophic phase, it kills the infected tissues and feeds on the decayed material, spreading rapidly and manifesting visible disease symptoms [11]. This complex lifecycle presents challenges in managing the disease effectively, requiring ongoing research and innovative strategies.

Similarly, plantains face threats from black sigatoka disease (*Mycosphaerella fijiensis* Morelet), which significantly reduces yields [12]. Black sigatoka is a leaf spot disease that severely affects banana and plantain crops globally [1]. This disease poses a critical threat to both commercial and subsistence banana and plantain farming. The fungus responsible for black sigatoka manifests as dark streaks on leaves, which eventually become black and necrotic, giving the disease its name [13]. By significantly declining the photosynthetic capacity of the leaves, the disease inhibits plant growth and drastically reduces fruit yield and quality by up to 50% in some cases [14], thus putting considerable risk to food security in regions where bananas and plantains are critical.

Moreover, pests, such as the black weevil (*Cosmopolites sordidus* Germar) and various phytoparasitic nematodes like *Meloidogyne incognita* [15], further worsen these phytosanitary challenges, often requiring hazardous pesticides for pest management. *C. sordidus* is a root borer pest that significantly affects banana and plantain plants worldwide [16]. This beetle is notorious for its larvae, which burrow into the corms and roots, causing severe damage and often leading to plant death [17]. Infestations by *C. sordidus* not only reduce the plant's nutrient uptake but also increase its susceptibility to falling, particularly under windy conditions or when loaded with heavy fruit bunches [17]. Managing this pest is particularly challenging because the larvae are concealed within the plant's structure, rendering chemical controls difficult and frequently ineffective [18]. Similarly, parasitic nematodes pose a major threat to plantain cultivation, drastically reducing crop yields and quality. Among the various nematode species affecting plantains, the most harmful are typically the root-knot nematodes (*Meloidogyne* spp.) and the burrowing nematode (*Radopholus similis*) [19]. These nematodes attack plantain roots, causing physical damage and creating entry points for secondary infections by fungi [19]. Root-knot nematodes induce lesions on the roots, disrupting normal root functions and impairing nutrient and water uptake [20]. Burrowing nematodes, on the other hand, degrade the root cortex, compromising the structural integrity of the roots and increasing the risk of plant falling under the weight of fruit bunches or in adverse weather conditions [13].

In response to these challenges, adaptive pathogen management (APM) practices tailored to cocoa and plantain aim to enhance productivity and mitigate pest impacts. Techniques such as fruit removal and pruning for cocoa and leaf surgery and weevil trapping for plantain have been developed to manage pests and diseases [21]. However, the

efficacy of APM in mixed cropping systems in managing pests and diseases, particularly the incidence between cocoa and plantain, remains unclear. The potential for mixed systems to enhance resistance against pests and diseases lies in crop diversity acting as a natural barrier [2], thereby mitigating the susceptibility of either crop to specific pathogens. Additionally, mixed agroecosystems can help mitigate the impact of plant-parasitic nematodes on plantain, highlighting the potential for agroecological approaches to alleviate nematode-induced damage in plantain cropping systems.

Mixed cropping systems provide stability by diversifying crops within the same field, reducing the risk of single-crop failure due to sudden environmental issues. This diversity also reduces intraspecific competition that exceeds interspecific competition, enhancing resource utilization and overall productivity compared to monocultures [22,23]. Monocultures are highly susceptible to diseases and pests, whereas mixed cropping disrupts these cycles, making it harder for pathogens and pests to establish [24]. Combining mixed agroecosystems with adaptive pathogen management practices offers a sustainable approach by enhancing natural defense mechanisms and minimizing the reliance on chemical pesticides [25]. Further, habitat manipulation within mixed cropping systems further supports pest control and biodiversity that, in combination with APM practices, may represent an ecologically, socially, and economically acceptable approach to enhance agricultural sustainability and resilience [26].

Understanding the dynamics of plant–pathogen relationships in mixed cropping systems is crucial, particularly when considering crops like cocoa and plantain, each with highly specific pathosystems [27,28]. The interaction between crops can vary significantly with one crop potentially acting as a barrier against pests for the other. This mutual obstruction may emphasize the importance of exploiting mixed production systems, as they can offer better resilience against pest infestations compared to monocultures, where crops are more susceptible to damage from these organisms [29]. This study aims to investigate the incidence and progression of diseases in mixed cocoa–plantain systems, focusing on how this combination affects disease and pest incidence during the establishment phase. Specifically, our objective is to assess the impact of spatial arrangements within mixed cocoa–plantain on the prevalence of witches’ broom in cocoa and black sigatoka in plantain. Additionally, we aim to evaluate how these spatial arrangements influence the populations of phytoparasitic nematodes and black weevils, further clarifying the complex interactions within the agroecosystem and contributing to the development of sustainable agricultural practices that optimize productivity while minimizing environmental risks.

2. Materials and Methods

2.1. Study Area

The trial took place at the Pichilingue Tropical Experimental Station of the National Institute of Farming Research in Los Ríos, Ecuador (latitude 01°05′ S, longitude 79°27′ West). The area is situated 120 m above sea level and belongs to a tropical humid forest climate characterized by an average annual temperature of 25 °C, an annual precipitation of 2442 mm/year, and a relative humidity of 85% [30].

We assessed the cocoa and plantain combinations under three distinct spatial arrangements or planting distances (Figure 1). These arrangements included the following: (a) cocoa–plantain in double rows: cocoa plants were organized in paired rows at 3.0 m (between plants) × 2.0 m (between rows) with 4.0 m between each double row. Plantain plants were planted 6.0 m apart between each double row and 3.0 m apart within the rows with 0.5 m spacing inside each double row. This arrangement resulted in population densities of 833 plants/ha of cocoa and 1111 plants/ha of plantain. (b) cocoa–plantain in simple rows: cocoa and plantain were spaced 3.5 m apart between rows and 3.0 m between plants, yielding a total population density of 1906 plants/ha, evenly distributed between the crops. (c) high-density triangular arrangement: cocoa and plantain were positioned at 3.5 m from each other with a plantain row arranged at intervals of 1.75 m × 3.5 m. This configuration produced a total population density of 2838 plants/ha with 943 plants/ha

of cocoa and 1895 plants/ha of plantain. (d) monocultures: both cocoa and plantain were spaced 3.0 m between rows and 3.0 m between plants, resulting in a population density of 1111 plants/ha for each crop. All spatial arrangements were distributed in blocks and randomly placed in the field following a randomized complete block design (RCBD) with four replications. The total area of the trial encompassed 29,717 m² with each block covering 4752 m² and each plot occupying 864 m² (24 m × 36 m). We utilized the cocoa clones and the ‘barraganete’ cultivar for plantain.

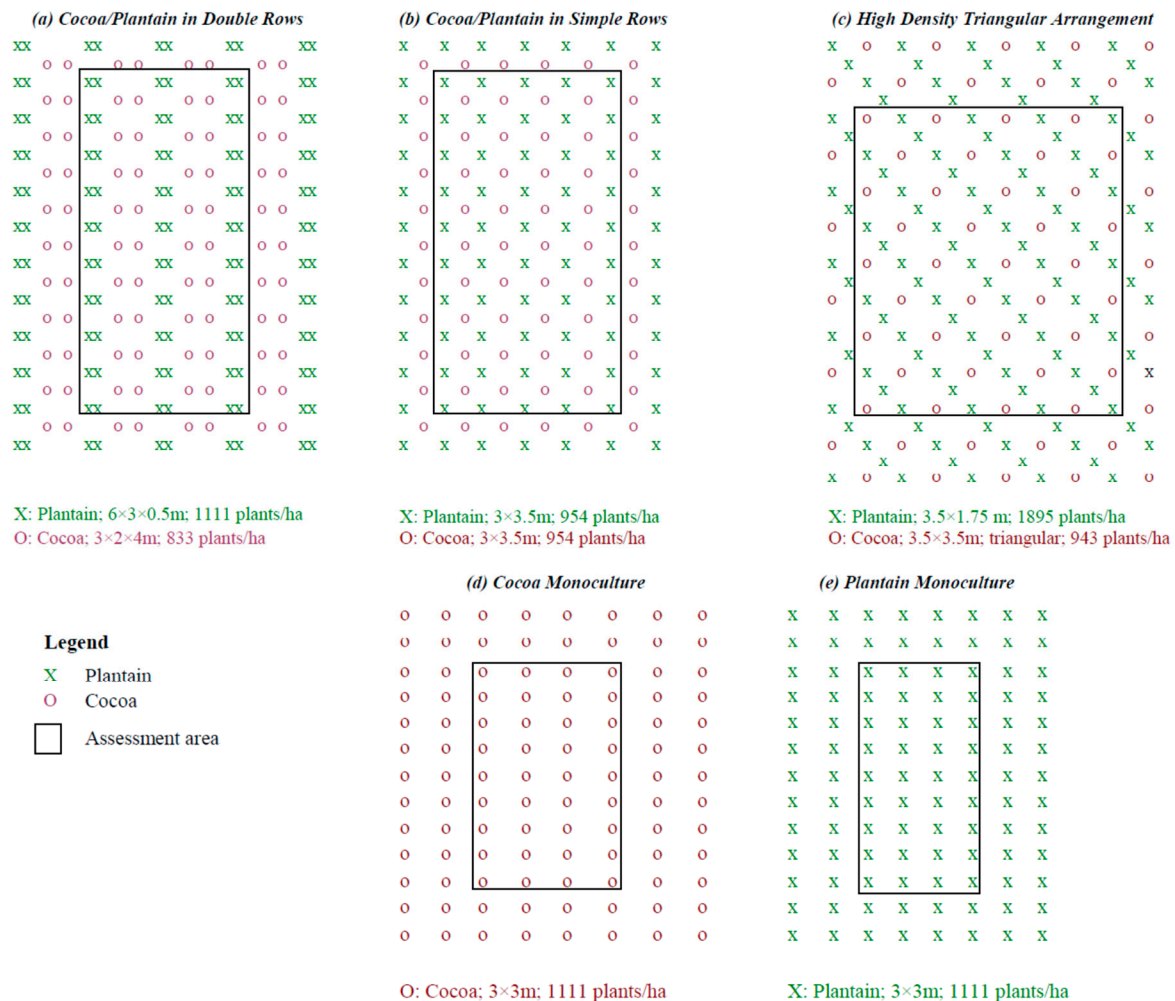


Figure 1. Visual representation illustrating the four spatial crop arrangements used to assess the incidence of pests and diseases in both mixed and monoculture systems of cocoa and plantain. The letters (a–c) denote the mixed agroecosystem arrangements, while (d,e) represent cocoa and plantain monocultures, respectively. Black squares describe the evaluation zones within each arrangement, mitigating edge effects.

2.2. Field Data Collection

The incidence and severity of pests and diseases in both cocoa and plantain were recorded throughout the study. For cocoa, observations included the total number of malformations associated with witches’ broom disease, including terminal, axillary, and stem shoots. The cocoa variables were documented for 36 plants within each spatial arrangement one year following trial establishment. In plantain, the number of sick leaves and infection rate per leaf of black sigatoka were monitored biweekly using the Stover and Dickson [31] scale, modified according to Gauhl [32] and Pasberg–Gauhl [33]. This grade scale is based on the percentage of leaf area with symptoms as follows: 0 = no symptoms, 1 = 1% and/or up to 10 spots with a dry center, 2 = 1% to 5%, 3 = 6% to 15%, 4 = 16% to 33%,

5 = 34% to 50%, and 6 = 51% to 100%. We considered sick leaves as those exhibiting grade 1 to 6 on the scale. The infection rate per leaf was also evaluated by using the same scale. These parameters in plantain were recorded in 20 plants randomly selected at each time of the evaluation from the age of four months until flowering for each spatial arrangement, which represents 6 months of biweekly evaluations with a total of twelve evaluations.

Furthermore, the population of black weevils and nematodes was quantified in each mixed arrangement system at one year of establishment. Phytoparasitic and beneficial nematodes present in the soil and roots were recorded using nematological analyses at one year of establishment. Twenty grams of compound soil samples (a mix of five subsamples per arrangement) was collected from each plot and analyzed using the Baerman technique modified according to Gowen and Edmuns [34]. Additionally, compound root samples (an aggregation of five subsamples) were collected, exclusively from plantain, and analyzed following Taylor and Loegering [35]. The incidence of black weevils was assessed by counting individuals, when found weevils were left on site to avoid any human influence on the experiment. We established “sandwich” traps installed within each plot, comprising portions of pseudo stems 80 cm in length with four transverse cuts of 10 to 15 cm width. Each sandwich trap contained pieces of pineapple as an attractant for adult black weevils. These traps were centrally positioned within each plot and covered with plantain leaves to prevent dehydration. All plant evaluations and insect monitoring were conducted within the ‘evaluation zone’ plot area to minimize edge effects and lack of spatial independence.

2.3. Data Analysis

The data underwent analysis tailored to the variables’ nature. Specifically, we employed a generalized linear mixed model to assess populations of nematodes and black weevils as well as the number of sick leaves in plantains and witches’ broom infections in cocoa. This approach allowed for us to address each block’s spatial lack of independence. In this model, the four spatial arrangements were considered fixed factors, while ‘block’ was treated as a random effect to capture block-level variability. In the case of the number of sick leaves, we also included a second ‘temporal’ random parameter to ensure the temporal independence of the variance of the nested bi-weekly measures. To accommodate the count nature of the dependent variable, we assumed a Poisson distribution with a ‘log’ link function. We performed subsequent post hoc analysis utilizing Fisher’s least significant difference test to explore significant model parameters.

Furthermore, the infection rate per leaf of black sigatoka was analyzed using a linear mixed model. Within this framework, the four spatial arrangements were treated as fixed factors, while ‘block’ was a random effect. To address the nested bi-weekly measures, a second ‘temporal’ random parameter was incorporated to ensure the temporal independence of the variance. The infection rate underwent arcsine–square root transformation to approximate a Gaussian distribution. Post hoc analysis for the infection rate variable also employed Fisher’s least significant difference test to discern significant model parameters.

Finally, all models’ residuals were tested to ensure they align with the assumptions of normality, homogeneity of variances, and linearity by visually inspecting the distribution of each model’s residuals. All statistical analyses were executed using R software version 4.3.2 [36].

3. Results

Implementing mixed agroecosystems greatly impacted the prevalence and intensity of pests and diseases in cocoa and plantain crops during their initial establishment phase (Table 1). Notably, in cocoa, the incidence of witches’ broom infection exhibited marked statistical differences among cultivation methods. Monoculture displayed an especially higher infection rate, averaging 11 infections per plant, surpassing the mixed systems, particularly the high-density triangular system (Table 1).

Table 1. The mean $\pm$ standard error (SE) of the number of individual pathogens assessed in both plantain and cocoa for each spatial arrangement within the mixed system arrangements, including double row, simple row, triangular HD, and monocultures (Mon. plantain and Mon. cocoa), is presented. In plantain, sigatoka infection rates per leaf are depicted within a range of 0 to 1. An asterisk (*) denotes the F value of the outcome model from temporal bi-weekly evaluations. numDF and denDF represent the degrees of freedom for each model's numerator and denominator, respectively. In this context, the numerator captures the variability within mixed cropping arrangements, and the denominator accounts for the degrees of freedom associated with each model's bias. The resulted p value of each variable's analysis is also presented in the table. Different lower-case letters in the table represent significant statistical differences.

Crop	Organism	Double Row	Simple Row	Triangular HD	Mon. Plantain	Mon. Cocoa	numDF/denDF	F Value	p Value
Plantain	Nematodes in soil	<i>M. incognita</i>	2899 $\pm$ 191 b	3134 $\pm$ 207 a	1300 $\pm$ 86 d	1883 $\pm$ 124 c	3/44	8850.39	<0.0001
		<i>R. similis</i>	177 $\pm$ 71 b	401 $\pm$ 160 a	19 $\pm$ 7 c	177 $\pm$ 71 b	3/44	1379.72	<0.0001
		<i>Rhabditis</i> spp.	838 $\pm$ 130 a	491 $\pm$ 76 c	742 $\pm$ 115 b	491 $\pm$ 76 c	3/44	657.68	<0.0001
		<i>Dorylaimus</i> spp.	446 $\pm$ 28 b	273 $\pm$ 17 d	385 $\pm$ 24 c	508 $\pm$ 32 a	3/44	724.28	<0.0001
		<i>Mononchus</i> spp.	325 $\pm$ 116 c	223 $\pm$ 80 d	1551 $\pm$ 554 a	380 $\pm$ 136 b	3/44	10,485.17	<0.0001
	Nematodes in roots	<i>M. incognita</i>	3263 $\pm$ 717 b	2656 $\pm$ 584 c	3301 $\pm$ 726 b	5434 $\pm$ 1195 a	3/44	5167.9	<0.0001
		<i>Helycotilenchus</i> spp.	180 $\pm$ 62 d	762 $\pm$ 262 a	443 $\pm$ 152 b	305 $\pm$ 104 c	3/44	1931.98	<0.0001
		<i>R. similis</i>	686 $\pm$ 199 c	1023 $\pm$ 296 b	2844 $\pm$ 825 a	2858 $\pm$ 829 a	3/44	9102.76	<0.0001
		<i>Pratylenchus</i> spp.	105 $\pm$ 38 c	78 $\pm$ 29 d	209 $\pm$ 77 a	131 $\pm$ 48 b	3/44	354.77	<0.0001
		<i>C. sordidus</i>	30 $\pm$ 3.08 c	22 $\pm$ 2.31 d	57 $\pm$ 5.56 a	45 $\pm$ 4.46 b	3/60	99.32	<0.0001
Cocoa	<i>M. fijiensis</i> : Number of sick leaves		0.27 $\pm$ 0.06	0.28 $\pm$ 0.06	0.26 $\pm$ 0.06	0.36 $\pm$ 0.06	3/183 1/183	1.23 0.06 *	0.30170 0.87930
	<i>M. fijiensis</i> : infection rate per leaf		0.65 $\pm$ 0.04 b	0.69 $\pm$ 0.04 ab	0.64 $\pm$ 0.04 b	0.74 $\pm$ 0.04 a	3/137 1/43	8.48 0.24 *	<0.0001 0.81110
	<i>M. perniciosa</i>		5 $\pm$ 0.61 b	4 $\pm$ 0.54 b	1 $\pm$ 0.21 c	11 $\pm$ 1.44 a	3/458	314.86	<0.0001

Similarly, mixed agroecosystems demonstrated greater resilience against pests in plantain. Specifically, significant variations in the populations of nematodes in both soil and roots and black weevils were observed between mixed and monoculture systems (Table 1). Interestingly, although a higher abundance of phytoparasitic nematodes was found in the soil of mixed agroecosystems compared to monoculture (Table 1), the most substantial root damage inflicted by *Meloidogyne* and *Radopholus* genera was predominantly observed in monoculture setups (Table 1).

At ground level, all four spatial arrangements exhibited notable differences in weevil populations with monocultures and triangular high-density mixed plantain systems consistently maintaining significantly higher numbers compared to other mixed arrangements (Table 1). Finally, while no statistically significant differences were observed among the four spatial arrangements in terms of the number of sick leaves caused by black sigatoka, monocultures showed a higher infection rate per leaf compared to mixed systems (Table 1).

4. Discussion

Mixed agroecosystems, characterized by the cultivation of multiple crops in close proximity, play a critical role in shaping the incidence and severity of pests and diseases, particularly in highly specific pathosystems such as those found in cocoa and plantain cultivation. The inherent variability introduced by mixed agroecosystems suggests a potential impediment to the spread of phytopathogenic fungi and insects [37]. This phenomenon is evident in cocoa cultivation, where associated systems demonstrate lower infection rates compared to monoculture setups (Table 1).

The reduced dispersal of basidiospores produced by the *Moniliophthora perniciosa* fungus or specific biotypes of this pathogen in cocoa-associated systems likely contributes to this observed trend [38,39]. The spores of *M. perniciosa* are disseminated through wind, rain splash, and insect vectors, effectively establishing the disease that primarily infects young meristematic tissues [9]. This leads to the formation of characteristic symptoms, such as hypertrophic growth, shoot proliferation (witches' brooms), and necrotic lesions, on stems and fruits [40]. However, implementing additional crops like plantains in a mixed-cropping system could potentially mitigate the spread and survival of the fungus. Plantains, which grow quickly and to a larger size, represent an inadequate host for the development of the fungus's basidiocarps. This can contribute to reducing spore survival and dissemination within agroecosystems, primarily by reducing wind exposure that is crucial for spore dispersal as observed in agroforestry settings [40]. Moreover, plantains may help minimize spore spread by maintaining constant humidity levels, thereby altering the micro-environment needed for the fungal basidiocarps to develop, which require alternating periods of wet and dry conditions [41,42].

Associated crops within mixed agroecosystems may also contribute organic matter and additional nutrients that mutually support the development and resistance to specific pathogens, thereby enhancing the overall resilience of the agroecosystem [43]. In our work, a similar trend of disease suppression is noted in plantain cultivation within mixed systems, though to a lesser extent, highlighting the complex interaction of factors influencing pest and disease incidence in agroecosystems. Numerous studies indicate that mixed cropping systems provide a promising strategy for optimizing nutrient utilization in agricultural settings. For example, the diversity in root structures and depths among different plant species facilitates efficient nutrient extraction from various soil layers, thus minimizing competition and enhancing nutrient uptake efficiency [44]. Furthermore, the presence of plants with complementary nutrient requirements in co-cultivated crops ensures the effective utilization of available nutrients [45] and contributes to reduced nutrient losses, improved soil health, and optimized nutrient cycling [46]. Overall, by enhancing both nutrient availability and uptake through the incorporation of multiple plant species, mixed cropping systems can foster indirect synergistic interactions that may promote an approach to managing pests and diseases.

On the other hand, during the establishment phase of cocoa and plantain systems, the presence of cocoa plants does not seem to impede the spread of black sigatoka fungus to plantain, as evidenced by the consistent number of sick leaves across different spatial arrangements. However, the infection intensity within each leaf varies significantly between spatial arrangements (Table 1), particularly in high-density plantain systems. Analogous to cocoa, alterations in microclimatic factors likely facilitate greater physiological and nutritional development in mixed systems, thereby enhancing resistance against pathogenic fungi with less efficient germination and penetration compared to monocultures [43,47]. It is well established that specific microclimate conditions, such as temperature, humidity, light intensity, and air movement, play a crucial role in facilitating the development of black sigatoka in plantain crops [48]. However, optimizing these microclimatic conditions can also enhance plant growth, photosynthesis, and the activation of defense mechanisms against pathogens in plantain. For instance, moderate temperatures achieved through a more spacious arrangement, due to the inclusion of a complementary crop like cocoa, can reduce leaf wetness duration and improve air circulation, thus mitigating the severity of black sigatoka by potentially reducing the virulence and aggressiveness of the fungus [49]. Therefore, while cocoa cannot block the dispersal of black sigatoka ascospores, the favorable conditions provided by the mixed cropping system may reduce the severity of leaf infections in plantain.

The incidence of nematode populations further demonstrates the complex relationships within mixed agroecosystems. Both mixed and monoculture systems exhibit a diverse range of parasitic and beneficial nematodes with variations across spatial arrangements. Notably, *Meloidogyne incognita* and *Radopholus similis* emerge as predominant among parasitic nematodes, while *Rhabditis* spp. (bacteriophage), *Mononchus* spp. (predator), and *Dorylaimus* spp. (omnivore) represent beneficial nematodes [50,51]. Despite their abundant presence across spatial arrangements, *Meloidogyne* and *Radopholus* exhibit varying impacts on plantain health with monoculture systems experiencing the highest impact from *Meloidogyne* infestations, possibly due to reduced root diversity compared to mixed cocoa and plantain systems [43,50–52]. Diverse root systems in plantain cultivation not only directly reduce nematode infections but also indirectly affect microbial communities in the rhizosphere. The rhizosphere, the narrow region of soil surrounding plant roots, is home to a diverse array of microorganisms that are crucial for nutrient cycling, disease suppression, and overall plant health [53]. Intercropping or agroforestry systems that include a variety of plant species can enhance the increase in beneficial microbes, such as nematophagous fungi and bacteria, within the rhizosphere [54]. These beneficial organisms can prey on nematodes or produce compounds toxic to them, thus naturally suppressing nematode populations [55]. Furthermore, increasing microbial diversity in the rhizosphere by integrating multiple plant species strengthens the resilience of the soil ecosystem and enhances its ability to manage nematode populations effectively [56]. Promoting microbial diversity in plantain mixed agroecosystems might represent a strategic approach to improving nematode management to enhance overall plant health and productivity.

Potentially, there is also an influence of microclimatic variations on the nematode populations that further emphasizes the interactions within mixed agroecosystems [44,47]. Soil microclimatic variation significantly influences nematode pathogen activity in plantain cultivation, shaping the incidence of nematode populations and their interactions with plant roots [57]. Microclimatic factors, such as soil temperature, moisture content, and aeration, are crucial in governing nematode behavior, reproduction, and virulence [58]. Optimal soil temperatures promote nematode activity and reproduction with variations affecting their developmental rates and population number, potentially impacting their movement, survival, and ability to seek hosts and establish infections [58]. Additionally, soil aeration affects nematode distribution and activity with well-aerated soils reducing nematode mobility and feeding behavior [59]. Changes in soil moisture levels may alter plant root exudation patterns, modifying attractant cues for nematodes or inducing stress responses that impact plant–nematode interactions [60]. Thus, variations in soil

microclimate caused by mixed cocoa–plantain agroecosystems could possibly contribute to nematode management by disrupting their feeding and pathogenic behavior.

The population abundance of adult weevils is also influenced by spatial arrangements in cocoa–plantain systems during the establishment phase. Both high-density and monoculture systems display higher insect populations with the triangular high-density arrangement displaying the highest weevil number, possibly due to favorable humidity and light conditions conducive to their reproduction and development [21,61]. Humidity and light conditions significantly influence the behavior and population number of black weevils (*Cosmopolites sordidus*) in plantain cultivation [62]. Less humid and brighter conditions, such as those found in cocoa–plantain intercropping systems arranged in double and single rows, may lead to reduced activity levels among weevils as they seek refuge to avoid predation and desiccation [17]. Understanding these environmental factors is essential for developing targeted pest management strategies that effectively mitigate black weevil damage and minimize yield losses in plantain crops.

5. Conclusions

The associations between plantain and cocoa significantly influence the incidence and severity of pests and diseases during the establishment phase, thereby altering the behavior of pathogens such as *M. fijiensis*, causing black sigatoka in plantain, and *M. pernicioso*, causing witches' broom in cocoa. The cocoa–plantain association also demonstrates that, despite the prevalence of *Meloidogyne* spp. across all spatial arrangements, plantain monoculture systems consistently host the highest population in roots during the establishment phase. In regions susceptible to witches' broom in cocoa, integrating plantain cultivation would be recommended to mitigate disease incidence and enhance agroecosystem resilience. However, to fully comprehend the complex interactions shaping pest and disease dynamics within mixed agroecosystems, continued observations across production cycles are needed. Furthermore, comprehensive studies explaining the microclimatic effects on cocoa–plantain systems and their subsequent influence on insect populations are essential for informing sustainable agricultural practices and enhancing food security in agroecological landscapes.

Author Contributions: Conceptualization and methodology, R.V.-V.; formal analysis and data curation, R.V.-V., R.R.-V. and J.G.-O.; writing—original draft preparation, R.V.-V.; writing—review and editing, R.R.-V. and J.G.-O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: Special thanks to Carmen Suarez-Capello and Danilo Vera-Coello for their invaluable guidance and insightful advice throughout the course of this research.

Conflicts of Interest: The authors declare no conflicts of interest.

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