

Contrasting Effects of Shade Tree Species Diversity on Incidence and Damage of Pests and Diseases of Robusta Coffee

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Abstract
In Uganda, most farmers grow their Robusta coffee, *Coffea canephora* in association with a diversity of shade tree species. Shade tree species diversity and density influence abiotic variables particularly, temperature and relative humidity. In turn, these may negatively or positively influence the population dynamics and damage caused by pest and diseases. Understanding these relationships is therefore vital for informing selection of shade tree species for ecological management of pests and diseases. We thus conducted a study in Kaweri Coffee Plantation Limited located in central Uganda to determine the effect of shade tree species diversity on the incidence and damage caused by pests and diseases on Robusta coffee. One plot measuring 100 x 100 m was demarcated in each of the four sections of the plantation: Kitagweta, Kyamutuma, Luwunga and Nonve. All the shade trees/shrubs and saplings (≤3 m) in the plot were counted and identified to species level. Additionally, incidence and damage of pests and diseases were assessed on 20 Robusta coffee trees selected along two diagonals in the plots. We recorded a total of 299 trees comprising of 22 species, with *Solanum giganteum* being the most abundant shrub (19.8 shrubs/ha) whereas, the most abundant shade tree species were *Albizia chinensis* (9.3 trees/ha) and *Markhamia lutea* (6.0 tree/ha). Eight (8) insect pests and two (2) diseases were recorded on Robusta coffee. These included, *Xylosandrus compactus, Leucoptera coffeella, Leucoplema dohertyi, Epicampoptera andersoni, Prophantis smaragdina*, *Planococcus* spp., *Hypothenemus hampei*, leaf eating beetles, *Hemilleia vastatrix* and *Cercospora coffeicola*. Our results further showed contrasting effects of shade tree species diversity on the incidence and damage of pests and diseases of Robusta coffee. Damage caused by *X. compactus* and *E. andersoni* as well as the incidence of *H. vastatrix* and *C. coffeicola* decreased significantly ($p \leq 0.05$) with increasing shade tree species diversity. Contrary, damage caused by all the other insect pests increased with increasing shade tree species diversity but, only significant ($p \leq 0.05$) in case of *P. smaragdina*, and *Planococcus* spp. There is therefore a need to thoroughly understand these dynamics if agroforestry systems are to be utilized as a strategy for ecological management of pests and diseases of Robusta coffee.
Keywords: Agroforestry-systems, *Cercospora-coffeicola*, *Coffea-canephora*, ecological-management, *Epicampoptera-andersoni*, *Hemilleia-vastatrix*, pest-and-disease-dynamics, *Xylosandrus-compactus*
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1. Introduction

Coffee is the leading cash crop of Uganda, playing a major economic role in providing foreign exchange (NCP 2013). For example, coffee exports for 12 months (September 2022, August 2023) totalled to 6.08 million bags worth US 918. 76 million (UCDA 2023). The crop is grown on an estimated 353,907 hectares of land by about 1.7 million smallholder farmers (a quarter of them being female-headed) with 90% of them owning gardens ranging between 0.5 and 2.5 hectares in size (Hill 2005; NCP 2013; Mugoya 2018). More than 9 million people in Uganda are estimated to derive their livelihood from coffee-related activities along the value chain (NCP 2013). Coffee therefore has a very high employment potential, and poverty reduction effect on the smallholder farming households of Uganda (NPA 2020). Two types of coffee are commonly grown in the country, with Robusta coffee occupying 80% and Arabica coffee taking the remaining 20%. Robusta coffee is grown in the low altitude areas of central, south-eastern, northern, western and part of southwestern Uganda up to 1,200 meters above sea level (a.b.s.l) (UCDA 2019).

The smallholder Ugandan farmers usually integrate their Robusta coffee with trees to form the coffee agroforestry systems - with a diversity of tree species forming a canopy layer (Kiyingi & Gwali 2012; Kalanzi & Nansereko 2014; Nakibuule et al. 2017; Kagezi et al. 2018; Kobusinge et al. 2018). But also, research and extension have identified and are promoting the integration of shade trees as an entry point for re-establishing the productivity of coffee (Schroth et al. 2000). These traditional coffee agro-systems have been reported to be vital habitats for biological diversity conservation owing to their complex vegetational structure and high plant diversity (Staver et al. 2001; Perfecto et al., 2003; Pineda et al. 2005; Tylianakis et al. 2005; Lozada et al. 2007; Teodoro et al, 2008). Coffee agroforestry systems differ in the amount of shade, which is dependent on shade tree diversity and density (Moguel & Toledo 1999; Klein et al. 2002; Lozada et al. 2007). Tree species identity may influence interactions between understory plants and other organisms since shade tree species differ in their canopy characteristics (such as height, leaf area index, canopy architecture) and leaf traits (e.g., specific leaf area, leaf size and leaf angle), among others (Gagliardi et al. 2021; Avelino et al. 2023).

This vegetational diversity affects microclimatic conditions, particularly, temperature and relative humidity and these in turn may positively or negatively influence the dynamics, incidence and damage caused by pests and diseases in coffee agroforestry systems (Rao et al. 2000; Klein et al. 2002; Yarnes & Boecklen 2005; Barbar et al. 2006; Teodoro et al. 2008; Kucel et al. 2011; Kagezi et al. 2013b; Bukomeko et al. 2018; Gagliardi et al. 2021; Avelino et al. 2023). For example, coffee grown in abandoned coffee agroforestry systems with higher shade tree species diversity registered lower densities of the coffee berry borer (CBB), *Hypothenemus hampei* compared to simple-shade and complex shade agroforests with lower shade tree species diversity (Teodoro et al. 2009). Similarly, Bukomeko et al. (2018) recorded lower damage by the black coffee twig borer (BCTB), *Xylosandrus compactus* on Robusta coffee grown under higher density of tree species exuding copious sap if injured, such as *Ficus natalensis* and *Carica papaya*. Contrary, higher infestation levels of *X. compactus* were observed in Robusta coffee agroforestry systems dominated by *Albizia chinensis* (Kucel et al. 2011; Kagezi et al. 2013b; Bukomeko et al. 2018). Similarly, high levels of coffee leaf rust (CLR), *Hemileia vastatrix* were recorded underneath the canopy of shade tree species, *Acacia abyssinica* and *Croton macrostachyus* whereas, higher incidence of coffee berry disease, *Colletotrichum kahawae* was underneath canopy of *A, abyssinica* and *Polyscias fulva*. (Ayalew et al. 2022).

A thorough understanding of the effect of shade tree species diversity and identity on the population dynamics, incidence and damage of pests and diseases in coffee agroforests therefore, may inform the selection of shade tree species by coffee producers, thereby contributing to ecologically-informed pest and disease management (Altieri et al., 1987; Tscharntke et al. 2011; Guo et al. 2019; Durand-Bessart et al. 2020; Ayalew et al. 2022). Basing on this background, we therefore conducted a study in a commercial Robusta coffee plantation in Mubende district, central Uganda to determine: - i) the species composition and abundance of shade trees, ii) the effect of shade tree species diversity on the incidence and damage caused by pests and diseases on Robusta coffee.

2. Materials and Methods

2.1 Description of the Study Area

The study was conducted on Robusta coffee in Kaweri Coffee Plantation Limited, located in Naluwondwa parish, Madudu sub-county, Buwekula County, Mubende District, central Uganda (Fig. 1). The Plantation is located at 0°36'59"N 31°28'28" E and lies between 1,245 and 1,350 m above sea level. The area receives an average of 1,125 mm (875-1,250 mm) per annum of rain, with minimum and maximum temperatures of 15 °C and 25 °C respectively. Furthermore, the area is made up of Pre-Cambrian and Cainozoic rocks overlain by red ferralitic soils and sandy loams characterized by large amounts of iron oxides (Kaweri Coffee Plantation Ltd, 2001). The plantation and the surrounding areas are dominated by savanna vegetation (Obua et al., 2005) and located on an area of 2,512 hectares of which 1570 hectares are covered by Robusta coffee while, 100 hectares are occupied by woodlots (Gissat Techno Consult Ltd, 2001). It is divided into four sections, including, Kitagweta, Kyamutuma, Luwunga and Nonve for easy of management (Kaweri Coffee Plantation Ltd, 2001; Obua et al., 2005). This particular plantation was purposively selected for the study because it has a broad diversity of shade tree species growing together with Robusta coffee of over 20 years of age (Kaweri Coffee Plantation Ltd, 2001).

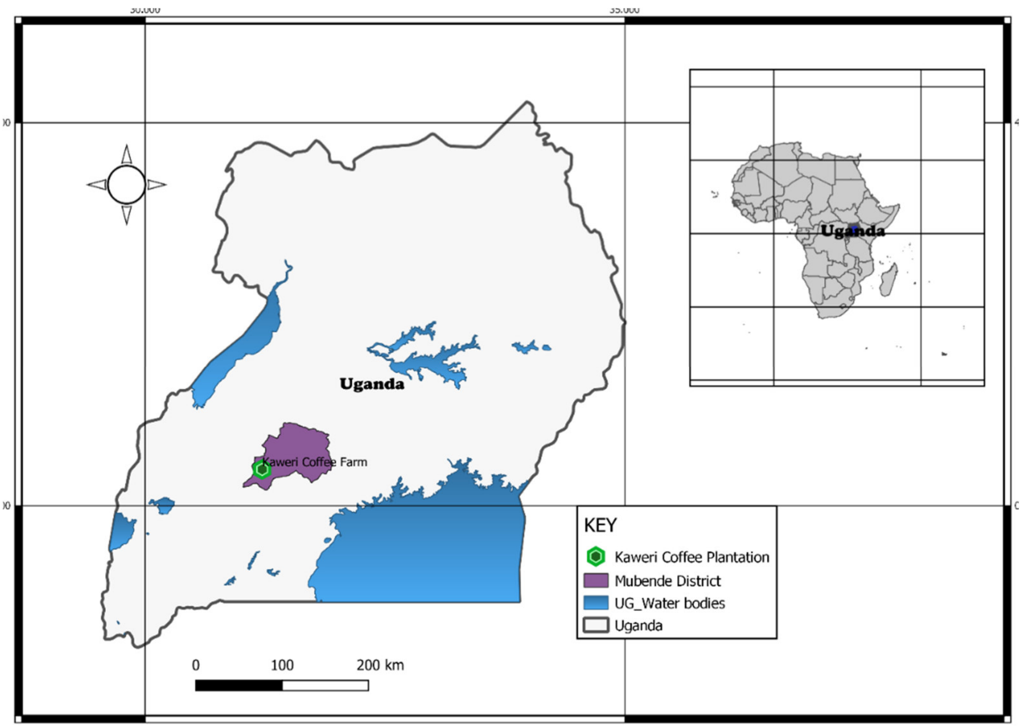

Figure 1: Location of Kaweri coffee plantation limited, Mubende district

2.2 Experimental set-up and Data Collection

A plot measuring 100m x 100 m (1 hectare) was demarcated in each of the four sections: Kitagweta, Kyamutuma, Luwunga and Nonve. In each section, data were collected on Robusta coffee plants along two cross diagonal transects running the full length of the demarcated plot (one running from left to right and the other one from right to left).

2.2.1 Shade Tree Diversity Assessment

All the individual trees including saplings measuring ≥3m tall (Isabirye 2009) in the plot were counted and then identified to species level using the tree identification guide of Katende et al. (1995). The counts of these shade tree species were then used to generate diversity indices (Isabirye 2009).

2.2.2 Assessment of Pests and Diseases on Robusta Coffee

Ten (10) Robusta coffee trees were systematically sampled along each diagonal, giving a total of 20 trees in each plot. The sampled trees were selected every after 14 m, derived from dividing the length of the diagonal (141 m) and the number of required trees (10). All the stems on each of the selected coffee trees were assessed for pest and disease incidence and damage. The canopy of each coffee stem was divided into three imaginary sections – upper, middle and lower (Kagezi et al. 2018; Sseremba et al. 2021). Each section was assessed separately but, the data were pooled together before analysis. The total number of primary branches (twigs) and those infested by the black coffee twig borer (BCTB), *Xylosandrus compactus* (Eichhoff) was established and used to estimate the percentage infestation. One primary branch was then randomly selected in each of the three canopy sections and assessed. The total number of leaves as well as those damaged by the coffee leaf miner (CLM), *Leucoptera coffeella* (Guérin-Mèneville & Perrottet), coffee leaf skeletonizer (CLS), *Leucoplema dohertyi* (Warren), tailed caterpillars, *Epicampoptera andersoni* (Tams), leaf eating beetles, coffee leaf rust caused by *Hemilleia vastatrix* (Berk. and Br.) and brown eye spot disease (BES) caused by *Cercospora coffeicola* (B. & CKE.) was established and used to estimate their percentage incidence and damage. Then, the number of berry clusters on each of the selected primary branch as well as those damaged by canopy mealy bugs (CMB), *Planococcus* spp., coffee berry moth (CBM), *Prophantis smaragdina* (Butler) and red blister disease (RBD) caused by *C. coffeicola* was established and used to calculate their percentage incidence and damage. One berry cluster was then randomly selected from the sampled berry clusters and the total number of berries as well as those damage by the coffee berry borer (CBB), *Hypothenemus hampei* (Ferrari) and RBD.

2.2.3 Data Analysis

Shade tree species diversity analysis was performed by computing Rènyi diversity profiles at 1000 permutations and determining the species richness (S), Shannon diversity index (H) and Simpson diversity index (D–1) from the Hα values using the 'Biodiversity R' package of R statistical software (R version 4.0.5). In addition, chi square analysis was performed to compare the average tree density (trees/ha), Species Richness and Shannon Diversity (H') across the sections. Regression analysis was also performed to determine the relationship between shade tree diversity (H') and the incidence of pests and diseases of Robusta coffee. These analyses were done using Statistical Analysis System (SAS) software (SAS Institute 2008).

3. Results and Discussion

3.1 Shade Tree Species Composition and Abundance

We recorded a total of 299 trees (height=≥3m), with an average density of 74.6 trees/shrubs per hectare (Table 1). This density varied significantly ($p<.0001$) across the sections, with the highest density (173 trees/ha) being recorded in Kyamutuma section and lowest (27 trees/ha) in Nonve section (Table 2). Our finding is in line with a density of 57.18 trees/ha observed in farmers' coffee gardens in four districts of central Uganda including Mubende, our study site (van Asten et al, 2012). However, the observed tree species density is generally higher than that reported in farmers' gardens (ranging between 29 and 39 trees/ha) in Greater Luwero area of central Uganda (Bukomeko, 2017) but lower than that observed in a commercial coffee estate near Mabira forest, central Uganda (140 trees/ha) (Gwali et al, 2015) and in farmers' gardens in Mt Elgon area (116 trees/ha) (Negawo & Beyene 2017). This could be in part due to the relatively high tree intensification in the commercial coffee farms (Rice 2008).

Shade tree species density is known to enhance the growth and yield of coffee (e.g. Nesper et al. 2017; Piato et al. 2020; Anhar et al, 2021) but, high shade tree density can also reduce coffee yield (Diriba, et al, 2021). Shade trees increase competition for nutrients, water and light as well as reducing carbon assimilation due to light interception (DaMatta et al. 2007; Nigussie et al. 2014). However, shade vegetation cover and structure are more important to coffee production than tree density and actual tree species employed (Soto-Pinto et al. 2000). A densely planted but well-pruned shade vegetation induces the same coffee yields as a sparsely planted but less pruned plantation (Peeters et al., 2003). There is therefore a need to establish optimal shade levels that avoid a lot of yield penalty on coffee (Moguel & Toledo 1999; Soto-Pinto et al. 2000; Cerda et al. 2020).

Furthermore, the trees/shrubs recorded in our study comprised of 22 species belonging to 15 families (Table 1). This result is in line with the 29 shade tree species recorded in low rainfall zone of the neighboring Greater Luwero area of central Uganda (Bukomeko et al. 2018) and Western Wellega, Ethiopia (Tazebew & Asfaw 2018). Species richness and Shannon Diversity Index (H') were not significantly ($p\geq0.05$) different across the sections. But, Kyamutuma section had the highest species richness of 16 species and Shannon Diversity Index of 2.38 whereas, Nonve had the lowest species richness of 10 species and H of 1.989 (Table 2). Variations in species richness and Shannon Diversity Index in different coffee plots on the same farm have also been reported elsewhere (Muleta et al. 2007; Denu 2019). This could in part be attributed to differences in the intensity of management practices that might vary from plot to plot or from farmer to farmer (Kitessa 2015; Denu 2019; Gamachu & Jegora 2019). Nevertheless, the Shannon Diversity Index recorded in our study falls within the range of other coffee agroforestry systems in Uganda (Negawo & Beyene 2017) and elsewhere (Tazebew & Asfaw 2018; Gamachu & Jegora 2019; Kewessa et al. 2019) though, higher values have been reported in other coffee agroforestry systems (e.g. Gwali et al. 2015). This could be in part due to the importance farmers attach to some of the shade trees species for additional services such as timber extraction, medicinal value, honey production, fodder for their cattle, fuel wood and organic matter production, among others (Ebisa & Abdela 2017). Coffee agroforestry systems are known to deliver ecosystem services at both local and landscape scales that are critical for rural livelihoods like additional food products (Vaast et al. 2016; Bukomeko et al. 2018). Therefore, increasing shade tree species diversity will increase ecosystem functioning and stability of ecosystem delivery (Gamfeldt et al. 2013; de Beenhouwer et al. 2013; Barnes et al. 2014; Caudill et al. 2014).

Our results further showed that Moraceae (33.3%) and Fabaceae (26.7%) were the most common families in Kaweri Coffee Plantation (Table 1), agreeing with observations in other coffee agroforestry systems of Uganda (Negawo & Beyene 2017) and elsewhere (Soto-Pinto et al. 2001; López-Gómez, et al. 2008; Zekwan et al. 2021). *Solanum giganteum* Jacq., locally known as 'setaaba' was the most abundant shrub (19.8 shrubs/ha) whereas, the most abundant shade tree species were *Albizia chinensis* Osb. Merr. (9.3 trees/ha) and *Markhamia lutea* (Benth.) K.Schum. (6.0 tree/ha). Gwali et al. (2015) also observed *A. chinensis* as the most abundant shade tree species in a commercial coffee estate in central Uganda. *A. chinensis* and *M. lutea* shade tree species are very common in smallholder farmers' coffee gardens in central Uganda (Sibelet 2009; Kiyingi & Gwali 2012; Gwali et al. 2015; Wu 2016; Bukomeko et al. 2018; Ahimbisibwe et al. 2022). However, both tree species have been reported to be associated with one of the most important insect pest of coffee in Uganda, the Black Coffee Twig Borer (BCTB), *Xylosandrus compactus* (Kucel et al. 2011; Kagezi et al, 2013a; Wu 2016; Bukomeko et al. 2018; Ahimbisibwe et al. 2022). Therefore, care should be taken when integrating these tree species in the coffee agroforestry systems (Kagezi et al. 2013b).

Table 1: Shade tree species composition, abundance and diversity for Kaweri Coffee Plantation, Mubende district, central Uganda

Family	English name	Scientific name	Local name (luganda)	Type	Section				Overall	Trees/ha	%age
					Kitagweta	Kyamutuma	Luwunga	Nonve			
Solanaceae	African-holly	*Solanum giganteum* Jacq.	Setaaba	Shrub	2	73	4	0	79	19.8	26.4
Fabaceae	Chinese Albizia	*Albizia chinensis* Osb. Merr.	Mugavu omuzungu	Tree	14	9	10	4	37	9.3	12.4
Bignoniaceae	Markhamia	*Markhamia utea* (Benth.) K.Schum.	Musambya	Tree	4	4	11	5	24	6.0	8.0
Moraceae	Fig tree	*Ficus mucuso* Welw. ex Ficalho.	Kabalira	Tree	0	17	0	0	17	4.3	5.7
Ebenaceae	Giant Diospyros	*Diospyros abyssinica*	Mpimbya	Tree	0	7	0	8	15	3.8	5.0
Euphorbiaceae.	Jumping seed tree	*Sapium ellipticum* (Hochst.) Pax	Musasa	Tree	1	10	0	1	12	3.0	4.0
Fabaceae	West African albizia	*Albizia zygia* Macbr.	Nongo	Tree	1	7	2	1	11	2.8	3.7
Moraceae	Sacking tree	*Antiaris toxicaria* Lesch.	Kirundu	Tree	0	7	2	2	11	2.8	3.7
Fabaceae	Red-hot-poker tree	*Erythrina abyssinica* Lam. ex DC.	Muyirikiti	Tree	0	10	0	1	11	2.8	3.7
Rhamnaceae	Umbrella tree	*Maesopsis eminii* Engl.	Musizi	Tree	9	2	0	0	11	2.8	3.7
Moraceae	Sandpaper tree	*Ficus exasperate* Vahl	Luwawu	Tree	4	0	6	0	10	2.5	3.3
Moraceae	Backcloth tree	*Ficus natalensis* Hochst.	Mutuba	Tree	9	0	0	1	10	2.5	3.3
Anacardiaceae	Mango	*Mangifera indica* Linn.	Muyembe	Tree	3	0	7	0	10	2.5	3.3
Fabaceae	Albizia	*Albizia coriaria* Oliv.	Mugavu	Tree	1	8	0	0	9	2.3	3.0
Bignoniaceae.	Nile flame	Spathodea campanulata P. Beauv.	Kifabakazi	Tree	0	7	0	2	9	2.3	3.0
Asteraceae	Bitter leaf	*Vernonia amygdalina* Del.	Mululuza	Shrub	0	7	1	0	8	2.0	2.7
Proteaceae	Silky oak	*Grevillea robusta* A. Cunn. ex R.Br.	Guliveliya	Tree	4	0	1	0	5	1.3	1.7
Myrtaceae	Guava	*Psidium guajava* Linn.	Mupeera	Shrub	0	0	3	0	3	0.8	1.0
Euphorbiaceae	Candlenut	*Aleurites moluccana* (L.) Willd	Kabakanjagala	Tree	0	2	0	0	2	0.5	0.7
Moraceae	Fig tree	*Ficus ovata* Vahl	Mukookowe	Tree	0	2	0	0	2	0.5	0.7
Phyllanthaceae	Pheasant-berry	*Margaritaria discoidea* (Baill.) Webster.	Kamenyambazi	Tree	0	0	0	2	2	0.5	0.7
Meliaceae	Budongo Mahogany	*Entandrophragma angolense* Welw	Mukusu	Tree	0	1	0	0	1	0.3	0.3
TOTAL					**52**	**173**	**47**	**27**	**299**	**74.8**	**100.0**

Table 2: Comparison of tree density, species richness and diversity across the sections at Kawei Coffee Plantation, Kaweeri, Mubende district, central Uganda

Section	Average tree density (trees/ha)	Species Richness	Shannon diversity (H)
Kitagweta	52	11	2.07
Kyamutuma	173	16	2.138
Luwunga	47	10	2.033
Nonve	27	10	1.989
Chi square	176.8662	2.1064	0.0058
Df	3	3	3
$\chi2$	<.0001	0.5506	0.9999

3.2 Effect of shade tree diversity on the damage caused by pests on Robusta coffee

Eight (8) insect pests were encountered in the Kaweri Coffee Plantation including, the black coffee twig borer (BCTB), *Xylosandrus compactus* (Eichhoff), coffee leaf miners (CLM), *Leucoptera coffeella* (Guérin-Mèneville & Perrottet), coffee leaf skeletonizer (CLS), *Leucoplema dohertyi* (Warren), tailed caterpillars, *Epicampoptera andersoni* (Tams), leaf eating beetles, coffee berry moth (CBM), *Prophantis smaragdina* (Butler), canopy mealybugs (CMB), *Planococcus* spp. and coffee berry borer (CBB), *Hypothenemus hampei* (Ferrari). Our finding is in line with other research studies that have demonstrated the importance of these insect pests in damaging Robusta coffee in Uganda (e.g. Egonyu et al. 2009; Kagezi et al. 2013b; Wang et al 2015; Kagezi et al. 2016a; NaCORI/MAAIF/UCDA, 2022; Olango et al. 2023). These pests are frequently perceived by researchers and farmers to be the primary reason responsible for the poor yields in Robusta (Wang et al. 2015; Kobusinge et al. 2018). In particular, *X. compactus* has been reported as the most important biotic factor contributing to the yield gap observed in Robusta coffee in Uganda (Wang et al., 2015). Latest survey conducted in the five major Robusta coffee growing districts of Uganda showed that 20.2% of the primary branches were infested by *X. compactus* (Olango et al. 2023). This insect pest attacks the berry-bearing primary branches (twigs) of coffee, causing them to wilt and die within a few weeks (Greco & Wright 2015) and since the infested twigs do not produce harvestable coffee (Egonyu et al. 2009; Kagezi et al. 2013a; Greco & Wright, 2015), farmers therefore risk losing 20% of their coffee harvests. This could be translated into a significant loss of the coffee export volumes and thus, foreign exchange (Kagezi et al. 2016b).

Our results further showed that shade tree species diversity influenced the damage caused by the various insect pests differently (Fig. 2). This agrees with Field et al. (2020) who reported that the population dynamics and damage caused by pests and diseases may be influenced by shade tree diversity differently. This implies that Robusta coffee can experience both associational resistance (reduced damage in diverse stands) and associational susceptibility (higher damage in diverse stands) depending on the insect herbivore in question (Plath et al. 2012; Guyot et al. 2016). This information is therefore necessary to inform coffee farmers whether a more diverse coffee farm is beneficial in terms of reducing damage and abundance of pests or diseases or not (Pollmann 2022).

Linear regression analysis results showed that the damage caused by both *X. compactus* and *E. andersoni* on Robusta coffee declined significantly ($p \leq 0.05$) with increasing shade tree diversity (Fig. 2a and 2b). This implies that high shade tree diversity reduced the damage caused by these two insect pests. Our finding is in agreement with Bukomeko et al. (2018) who reported lower damage by *X. compactus* on Robusta coffee grown under higher density of tree species exuding copious sap if injured, such as *Ficus natalensis* and *Carica papaya*. This could in part be due to the presence of less preferred trees compared to hosts trees (Kucel et al. 2011; Kagezi et al. 2016b; Bukomeko et al. 2018), making it difficult for the pest to find the host (Speight 2014; Kebede & Mulugeta 2021). For *E. andersoni*, reduction in infestation on Robusta coffee in a more diverse shade tree system could be attributed to the fact that this insect species is a specialist pest (Anikwe & Okelana 2006). Hence, the coffee crop benefited from associational resistance which indicates that hetero-specific neighbors may reduce damage to a focal plant by lowering specialist herbivore loads (Barbosa et al. 2009). But also there could also be a possibility that more diverse systems harbor and maintain higher abundance and diversity of natural enemies that control the pests (Stamps & Linit 1997; De la Mora et al. 2008; Ayalew et al. 2022).

On the other hand, damage caused by all the other insect pests increased with increasing shade tree species diversity but only significant ($p \leq 0.05$) for *Planococcus* spp. (Fig. 2c) and *P. smaragdina* (Fig. 2d). This implies that damage caused by these insect pests is promoted by shade tree species diversity. Since *Planococcus* spp. is a generalist pest attacking a number of plant hosts (Roda et al. 2013; Dong et al. 2018), increase in damage due to increasing shade tree species diversity observed in our study could be attributed to a "spill over" of herbivores as defined by the "associational susceptibility" hypothesis (White & Whitham 2000; Barbosa et al. 2009). Generalist herbivores develop large populations on preferred host plants before shifting to other plants (Brown & Ewel 1987; Wada et al. 2000; White & Whitham, 2000). Additionally, performance of these herbivores may also increase with a diverse diet from the increased shade tree species diversity (Unsicker et al. 2008; Plath et al. 2012), which may also increase population growth and therefore abundance. However, the increase in damage of *P. smaragdina*, a specialist herbivore (Bohlen 1973; Crowe 2004) with increasing shade tree diversity contradicts the resource concentration hypothesis which predicts that increasing plant diversity increases the difficulty for specialized herbivores to find suitable hosts since they are more diluted (resource concentration hypothesis; Root 1973). A similar response was also reported by Plath et al. (2012) on the specialist pyralid caterpillar (*Eulepte gastralis*). This could therefore imply that the effect of shade tree diversity on the damage of these specialist herbivores is via the "resource dilution: effect (Otway et al. 2005; Hambäck et al. 2014).

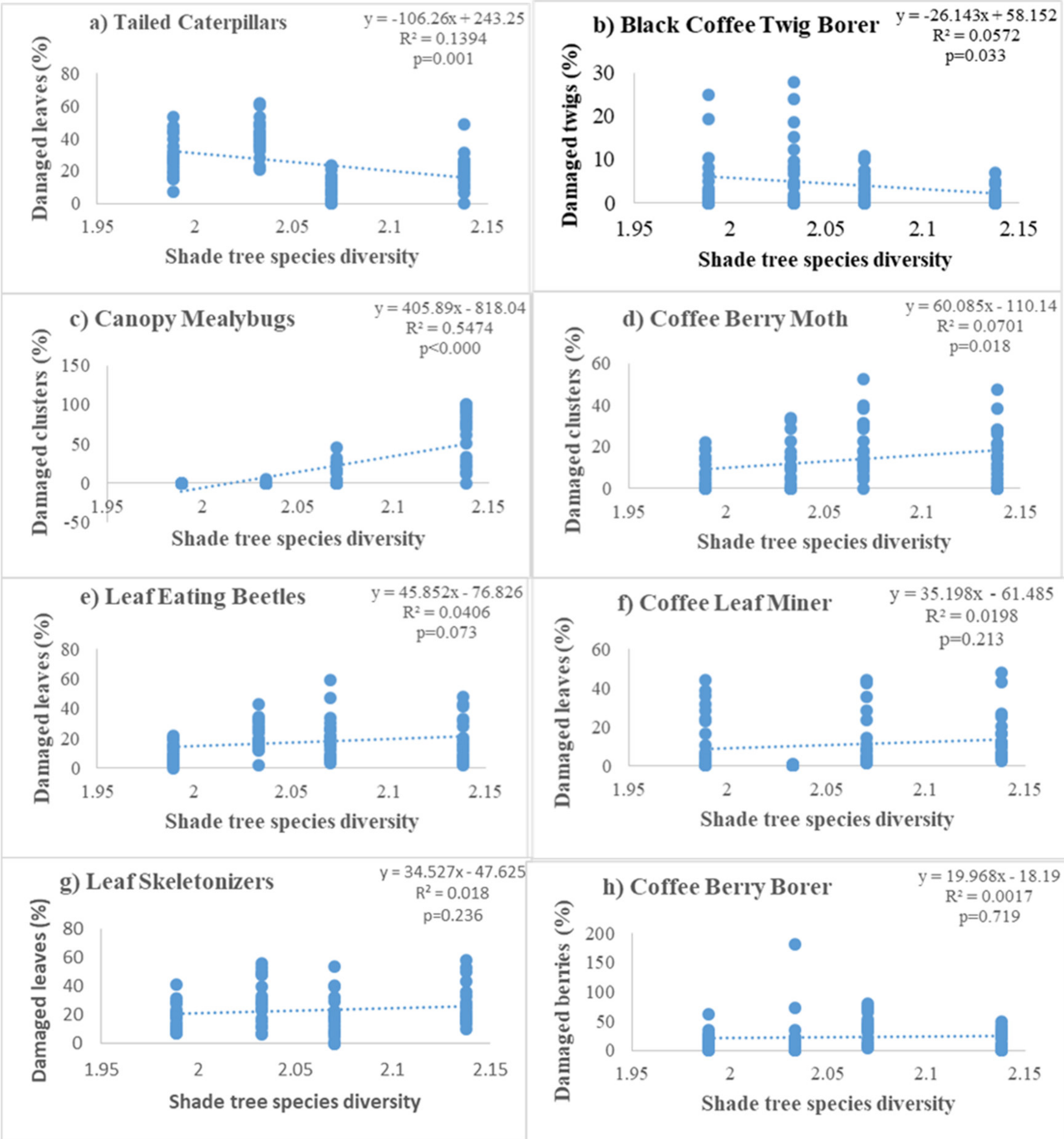

Figure 2:Relationship between the damage caused by the various insect pests of Robusta coffee and shade tree species diversity in Kaweri Coffee Plantation, Mubende district, central Uganda

3.3 Effect of shade tree diversity on the incidence of diseases of Robusta

Our results showed that only two diseases, coffee leaf rust (CLR) caused by *Hemilleia vastatrix* (Berk. and Br.) and red blister disease (RBD) caused by *Cercospora coffeicola* (B. & CKE.) were recorded on Robusta coffee. Several research studies have also recorded these two diseases on Robusta coffee in Uganda (E.g. Wang et al., 2015; Kagezi et al. 2016a; NaCORI/MAAIF/UCDA 2022; Olango et al. 2023). Latest survey conducted in the five major Robusta coffee growing districts of Uganda showed that the average incidence of *C. coffeicola* was 51.6% with a severity of 1.92 whereas, average incidence of *H. vastatrix* was 32% with severity of 1.5 (Olango et al. 2023). *H. vastatrix* is the most important fungal pathogen of coffee and the causal agent of recurrent disease epidemics that have invaded nearly every coffee growing region in the world (Talhinhas et al. 2017; Avelino et al. 2018). On the other hand, *C. coffeicola* is rapidly gaining economic importance on Robusta coffee in Uganda (Kagezi et al. 2016a; NaCORI/MAAIF/UCDA, 2022; Olango et al. 2023).

Linear regression analysis results showed that the incidence of both *H. vastatrix* and *C. coffeicola* decreased significantly ($p \leq 0.05$) with increasing shade tree species diversity (Fig. 3). Our finding is in agreement with several earlier research studies (e.g. Beer et al. 1998; Staver et al. 2001; Soto-Pinto et al. 2002; Zewdie et al. 2021; Ayalew et al. 2022; Avelino et al. 2023) and this could be due to several reasons. For *H. vastarix*, a combination of different tree traits in diverse agroforestry systems could collectively influence the spread of uredinio-spores (Avelino et al. 2023; Gagliardi et al. 2023). For example, simple dentate and evergreen leaves reduce through-fall kinetic energy thus, shortening the potential dispersal distance of mature uredinio spores to new host tissue whereas, rough leaves with wrinkles, ridges or trichomes can increase the capture of uredinio-spores (Avelino et al. 2023). Research also showed that large trees of greater and closed canopy as well as high tree density reduce the through-flow wind speed thereby decreasing dispersal of uredinio-spores to new hosts (Boudrot et al. 2016; Gagliardi et al. 2020; Daba et al. 2022; Avelino et al. 2023).

On the other hand, the incidence of *C. coffeicola* was observed to significantly reduce with increasing shade tree diversity (Staver et al. 2001) probably in part due to the fact that this disease is favored by high air temperatures and light exposure (Echandi 1969; da Silva et al. 2016). In fact, diverse shade tree species have been reported to reduce air and soil temperatures as well as light levels (Lin 2007; Ehrenbergerová et al. 2017; Bote et al. 2018; De Lombaerde et al. 2022). This fact is further supported by the phenomenon that more diverse stands are associated with release of higher amounts of nutrient inputs (Nesper et al. 2017) and this could in part contribute to increased plant vigor and hence resistance to the disease (Nelson, 2008). This is particularly important where the soils are limiting in Nitrogen and Potassium (Wrigley 1988; Kohler et al. 1997; Nelson 2008).

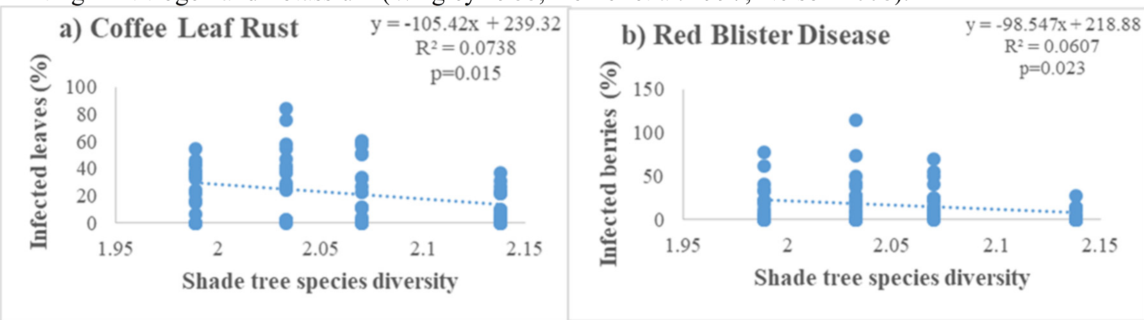

Figure 3: Relationship between the incidence of disease of Robusta coffee and shade tree species diversity in Kaweri Coffee Plantation, Mubende district, central Uganda.

4. Conclusion

Our study results showed contrasting effects of shade tree species diversity on the incidence and damage of pests and diseases of Robusta coffee, *Coffea canephora*. Damage caused by the black coffee twig borer, *Xylosandrus compactus* and tailed caterpillars, *Epicampoptera andersoni* as well as the incidence of coffee leaf rust, *Hemilleia vastatrix* and red blister disease, *Cercospora coffeicola* decreased significantly ($p \leq 0.05$) with increasing shade tree species diversity. On the other hand, damage caused by all the other insect pests increased with increasing shade tree species diversity but only significant ($p \leq 0.05$) for the coffee berry moth, *Prophantis smaragdina* and canopy mealybugs, *Planococcus* spp. This implies that the use of shade trees in coffee systems as a strategy for regulating pests and diseases is highly dependent on the pest or disease in question. There is therefore a need to thoroughly understand these dynamics when designing the Robusta coffee agroforestry systems for effective and sustainable ecologically-informed management of these pests and diseases.

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