

Species Composition, Richness, and Biomass of Understory Vegetation Influence the Gall Rust Disease Incidence and Severity in *Falcataria falcata* L. Greuter and *R. rankin* Plantation

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Gall rust remains a significant challenge for *Falcataria falcata* plantations in the Philippines, significantly impacting tree health and overall plantation productivity. This research aimed to evaluate several understory vegetation parameters such as species composition, species richness, and biomass to determine how these factors relate to the severity of gall rust disease within a *F. falcata* stand. The findings indicate that exotic species, while prevalent, did not uniformly dominate across all vegetation classes. *Imperata cylindrica* and *Saccharum spontaneum* emerged as the two most dominant species. In contrast, medium and high vegetation layers exhibited a mix of both native and exotic species. Among these, *Piper aduncum* and *Melastoma malabathricum* attained high importance value index (IVI) scores. Further analysis revealed a strong correlation between gall rust severity and understory biomass and species richness. Specifically, medium and high vegetation layers – which had greater biomass and more diverse species assemblages – experienced notably higher levels of gall rust infection. The most severe disease symptoms were observed within biomass densities ranging from 2–4 kg/m². These results underscore the crucial need to manage understory vegetation composition, particularly by balancing the proportion of exotic and native species, to mitigate gall rust outbreaks. By carefully regulating biomass density and levels of species richness, plantation managers could enhance *F. falcata* stand health and reduce the risks associated with this destructive fungal disease.

Keywords: biomass, *Falcataria falcata* L., gall rust, species richness, understory vegetation.

INTRODUCTION

Falcata (*Falcataria falcata* L. Greuter and R. Rankin) is widely recognized as one of the most promising timber species in the Philippine wood industry – valued for its rapid growth, adaptability to diverse site conditions, and robust

market demand (Lacandula *et al.* 2017). This species' ability to thrive across various plantations makes it a top choice for landowners aiming to optimize timber yields within short rotation cycles. However, the health of *Falcata* trees – a critical determinant of both productivity and timber quality – faces threats from diseases, particularly gall rust caused by the airborne fungal pathogen *Uromycladium falcatarium*

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(Palma *et al.* 2020). This destructive disease manifests as rough, woody galls on branches, stems, and trunks, leading to shoot dieback, stunted growth, and, in severe cases, tree mortality (Tulod *et al.* 2024). First documented as an epidemic on Mindanao Island in 1990, gall rust spread rapidly across the Philippines – reaching Luzon, the Visayas, and the Zamboanga Peninsula by 1995 (Tulod *et al.* 2024). Its polycyclic nature – characterized by multiple infection cycles within a growing season – amplifies its impact, particularly under environmental conditions favoring fungal proliferation (Palma *et al.* 2023). Extensive research has elucidated the role of abiotic factors in driving gall rust severity. Elevation, for instance, significantly influences disease dynamics, with severe outbreaks reported at varying altitudes across regions: above 900 m in Sabah, between 700–900 m in East Timor, and as low as 400 m in the Philippines (Lacandula *et al.* 2017; Paquit and Rojo 2018). These findings have informed elevation-specific mitigation strategies for *Falcata* plantations (Tulod *et al.* 2024). Similarly, soil properties, water availability, and microclimate have been identified as key contributors to disease incidence (Palma *et al.* 2020). While this body of knowledge on abiotic drivers is robust, biotic factors – particularly the influence of understory vegetation – remain largely overlooked, representing a critical gap in understanding gall rust epidemiology.

Understory vegetation plays an integral role in forest ecosystems, contributing to soil stabilization, nutrient cycling, and enhanced water retention (Luke *et al.* 2019). Beyond these physical benefits, it supports a diverse array of organisms, including insects that may act as vectors or reservoirs for pathogens (Dall'Oglio *et al.* 2016). Emerging evidence suggests that understory vegetation can influence disease dynamics in overstory trees through multiple ecological pathways. For example, taller understory plants may compete with trees for resources, increasing stress and susceptibility to infection (Lonsdale *et al.* 2008). Dense understory cover can also impede air circulation, fostering humid microclimates conducive to fungal growth and spore dispersal (Mitchell *et al.* 2014). Additionally, certain understory species may serve as alternate hosts or facilitators for pathogens, bridging their transmission to overstory trees (Power and Mitchell 2004). Despite these plausible mechanisms, supported by studies in other forest systems, their relevance to gall rust in *Falcata* plantations remains untested, highlighting the need for targeted investigation. This study addresses this knowledge gap by exploring how understory vegetation influences gall rust disease in *Falcata* plantations in Zamboanga, the Philippines. The research focuses on biotic interactions, complementing the extensive literature on abiotic factors, and aims to provide ecological insights with practical applications for plantation management. Specifically, it aimed to [1]

assess the species composition and richness of understory vegetation in *Falcata* plantations in Zamboanga, [2] quantify the incidence and severity of gall rust disease in these plantations, [3] examine the relationship between understory species richness and the incidence and severity of gall rust disease, [4] determine the influence of understory biomass density on gall rust disease, and [5] assess the effect of light availability on understory biomass density within *Falcata* plantations. The findings of this study could have important implications for developing effective plantation strategies to prevent and manage gall rust disease in *Falcata* plantations.

MATERIALS AND METHODS

Study Area

The study was conducted in the Municipality of Tigbao (7° 25' 42" N, 122° 19' 39" E), a fifth-class municipality in Zamboanga del Sur, southwestern Mindanao, the Philippines (Figure 1). The study sites, spanning an altitudinal range of 300–420 m above sea level, are characterized by flat terrain to moderate slopes, typical of smallholder plantation landscapes in the region. Based on the Modified Corona Classification, the climate falls under Type III, with unpronounced seasons – relatively dry from November–April and wet for the rest of the year. The mean annual temperature can drop to approximately 22 °C, with occasional fluctuations due to seasonal rainfall patterns (Corporal-Lodangco and Leslie 2017). The study area is a privately owned plantation dominated by *Falcataria falcata*, a fast-growing species commonly used for timber and reforestation in the Philippines. The understory vegetation forms a mosaic of grassland, ferns, and shrubland communities, reflecting the diverse ecological conditions within the plantation landscape.

Sampling and Measurements

Fieldwork was conducted in November 2022, employing a purposive sampling design to focus on the influence of understory vegetation height on gall rust severity. Understory vegetation was classified into three height categories: low (< 0.1 to < 1.5 m), medium (1.6 to < 2.4 m), and high (> 2.5 m). Following the study of Stickley and Fraterrigo (2021), the understory vegetation was categorized into three ecologically significant stages that reflect its role in buffering near-surface microclimates. In the low class (< 0.1 to < 1.5 m), the sparse vegetation exerts limited influence on microclimatic conditions. In the medium class (1.6 to < 2.4 m), the transitional vegetation begins to modify local humidity and light levels, indicating a gradual improvement in microclimate buffering. Finally, the high class (> 2.5 m) represents a dense understory that

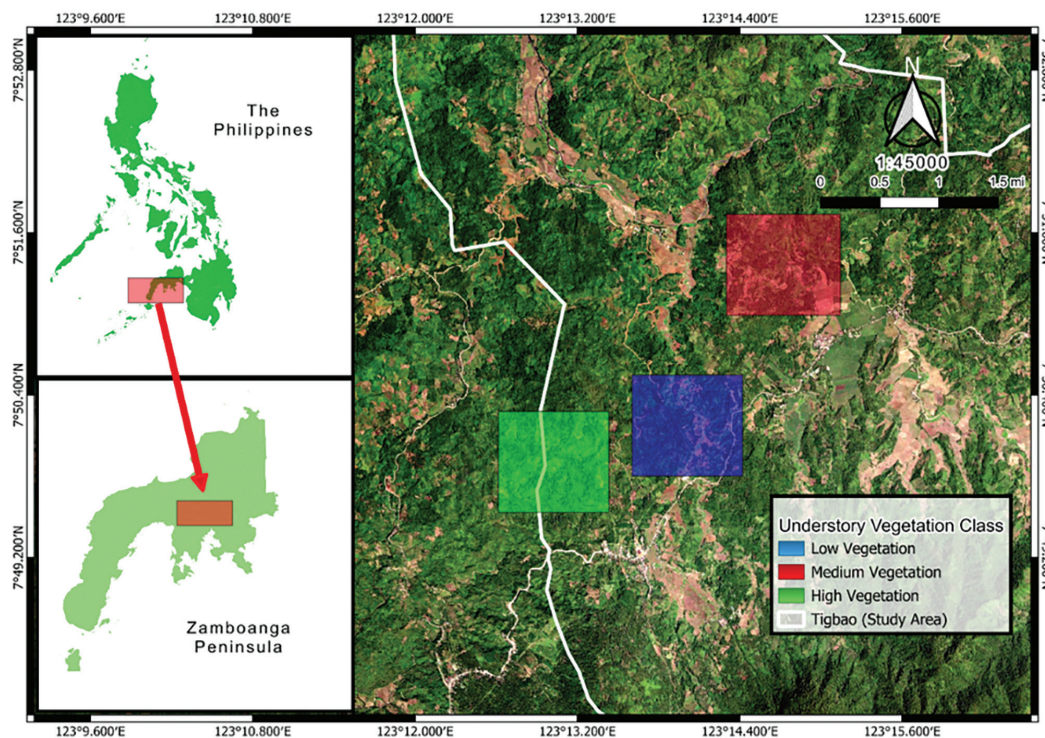


Figure 1. Geographic location of the study area (map generated using QGIS 3.34 Prizren software).

markedly alters the microclimatic environment, providing substantial buffering against temperature extremes and other environmental fluctuations.

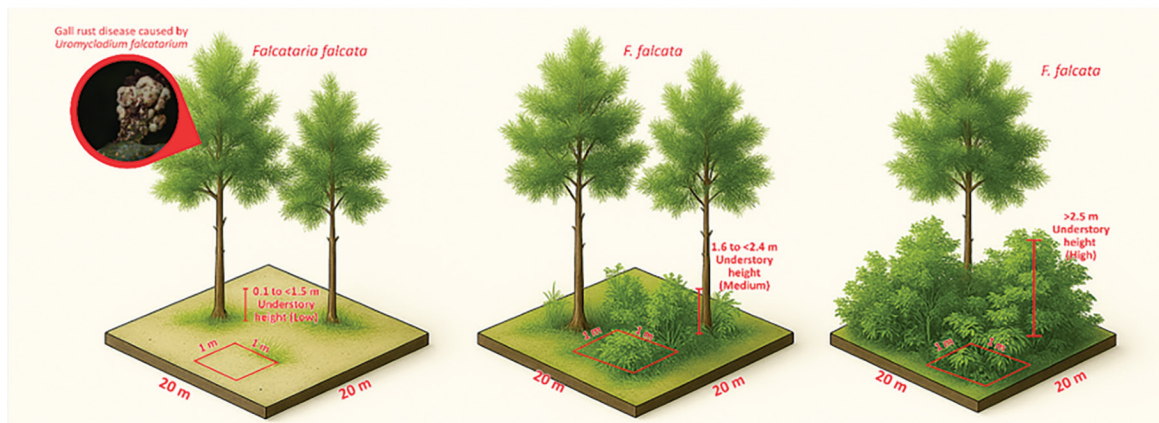
Five plantation sites – each at least 2 ha – were selected per vegetation category, totaling 15 plantations. Within each plantation, three 20 x 20 m sampling plots were established, resulting in 45 plots. Each plot contained four 1 x 1 m subplots for biomass estimation. To ensure comparability, sites were matched for key characteristics: [1] stand age, [2] canopy cover of *F. falcata*, and [3] soil type. All sites were within the Tigbao municipality to minimize environmental heterogeneity, allowing a focused analysis of understory effects, whereas species richness and composition were assessed across the entire 20 m x 20 m plot.

Gall Rust Assessment

Gall rust severity was assessed based on crown infection, as the disease predominantly affects crowns in *F. falcata* in the study area, with stem infections observed but less severe. Incidence was calculated as the percentage of infected trees per plot, using the rating scale by Palma *et al.* (2020) (Appendix A Table A1). Severity per tree was assessed using a scale adapted from Lacandula *et al.* (2017) and Łakomy and Iwańczuk (2010) (Appendix A Table A2), with binoculars assisting in taller trees (Figure 3).



Figure 3. Assessment of gall-rust in the *F. falcata* plantation at Barangay Tigbao, Tigbao, Zamboanga del Sur. The upper-left inset displays spherical (globose) and spindle-shaped (elongated) galls that have developed on infected branches.



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[a]



[b]

[c]



[d]

Figure 2. Sampling layout and understory vegetation classes: [a] schematic of a 20 m x 20 m plot with four 1 x 1 m subplots at the center (marked by crosses); [b] low vegetation (< 1.5 m); [c] medium vegetation (1.6 to < 2.4 m); [d] high vegetation (> 2.5 m). Photos were taken during the November 2022 fieldwork.

$$\text{Severity index} = \frac{\text{Sum of all the disease rating}}{\text{Total number of ratings} \times \text{Max. disease grade}} \times 100 \quad (1)$$

The assessment was conducted in November 2022, reflecting disease intensity at that time and plantation age.

Characterization of Study Sites

The light environment was characterized using hemispherical photographs taken at the center of each plot under overcast skies. A Nikon D3500 camera with a fisheye lens was positioned 1.37 m above ground, aligned vertically, with the images oriented northward. Percent light transmission (photosynthetically active radiation or PAR) was estimated using the Gap Light Analyzer software [Version 2.1; Frazer *et al.* (2000)], providing quantitative data on canopy openness and light penetration influencing understory growth and microclimate.

Understory Vegetation and Richness

Within each 20 m x 20 m plot, all woody and ground species were sampled, stratified by height and habit type. Species were categorized into: [1] woody plants (trees and shrubs ≥ 0.5 m) and [2] ground plants (herbs, vines, lianas, grasses, and tree saplings < 0.5 m). All individuals were counted; identified to species level using regional taxonomic keys; and measured for abundance, density, frequency, and cover. Cover was assessed using the Daubenmire method (Bonham *et al.* 2004), which assigns cover classes based on visual estimation (Appendix A Table A3).

Understory Vegetation Biomass

Biomass was sampled within four 1 m x 1 m subplots located in each 20 m x 20 m plot. For woody stems, diameters were measured at 5 mm above ground level for individuals 0.1–1.3 m tall, and at breast height (DBH, 1.3 m) for those taller than 1.3 m. Total tree height (H) was recorded with a clinometer or laser rangefinder. Aboveground biomass (AGB) was then estimated using the height-inclusive allometric model of Chave *et al.* (2014):

$$AGB = 0.0673 \times (\rho \times DBH^2 \times H)^{0.976} \quad (2)$$

where ρ is wood density [g/cm^3 , sourced from Krisnawati *et al.* (2011)], DBH is diameter at breast height (cm), and H is height (m).

A. mangium was chosen as a proxy due to the predominance of exotic understory species and the absence of species-specific equations at the time of the study, avoiding destructive sampling. However, this extrapolation may introduce potential errors, as *A. mangium* may not fully represent the diverse growth forms and wood densities of understory species.

Ground plants (< 0.5 m) were destructively sampled in the same subplots. Total fresh weight was recorded in the field, and a 5 g subsample was oven-dried at 80 °C to constant weight. Total dry weight was calculated as:

$$\text{Total dry weight (kg/m}^2\text{)} = \frac{\text{Total fresh weight (kg)} \times \text{Sub} - \text{sample dry weight}}{\text{Sub} - \text{sample fresh weight (g)} \times \text{Sample area (g)} (\text{m}^2)} \times 100 \quad (3)$$

Data Analysis

All data analyses were performed using R software (R Core Team 2022). The Baxter (2014) formula was used to determine the understory species composition, as well as species importance value within the understory vegetation in *Falcata* plantations. The following formulas were as follows:

Abundance (A_i) = total number of individuals of species i

$$\text{Density} = \frac{A_i}{\text{Area}} \quad (4)$$

$$\text{Density} = \frac{D_i}{\text{Total plant density}} \times 100 \quad (5)$$

$$\text{Frequency} = \frac{\text{Number of quadrats of species } i}{\text{Total number of quadrats sampled}} \quad (6)$$

$$\text{Relative frequency} = \frac{F_i}{\text{Total plant frequency}} \times 100 \quad (7)$$

$$\text{Cover} = \text{Total \% cover of individuals of the species} \quad (8)$$

$$\text{Relative cover} = \frac{\text{Cover for a species } i}{\text{Total plant cover}} \times 100 \quad (9)$$

$$\text{Importance value} = \text{Relative density} + \text{Relative frequency} + \text{Relative cover} \quad (10)$$

In order to evaluate differences in gall rust disease severity among understory vegetation classifications, a linear model (lm) was employed using the lme4 package in R. The significance of classification effects on gall rust severity was subsequently determined through F-tests, applying the ANOVA or analysis of variance function in the car package (Fox *et al.* 2012). A similar approach was implemented to investigate differences in species richness across understory vegetation classes: the lm function in lme4 was used, and the resulting classification effects were likewise tested for significance via F-tests using the ANOVA function (Fox *et al.* 2012). Relationships between gall rust severity and species richness were then modeled through linear regression, following Mangiafico and Mangiafico (2017). Additionally, the lm model in lme4 was employed to assess differences in understory biomass density among vegetation classifications, and these effects were again validated using the ANOVA function in the car package (Fox *et al.* 2012).

Further examination focused on the relationship between gall rust disease severity and understory biomass density, which was assessed using polynomial logistic regression models. Model comparisons were conducted with the ANOVA function in R and the compareLM function within the rcompanion package (Mangiafico and Mangiafico 2017). The compareLM output includes a table of fit statistics such as Akaike's information criterion (AIC) and r-squared values, facilitating direct comparison among models. The model yielding statistical significance and the lowest AIC was chosen as the best fit. Pseudo-r-squared values for the selected logistic regression models were subsequently estimated with the Nagelkerke function in the rcompanion package (Mangiafico and Mangiafico 2017).

A comparable analytical approach was used to explore the relationship between understory biomass density and log-transmitted PAR. Again, polynomial logistic regression models were applied, and the ANOVA function, along with compareLM, was utilized to compare competing models. As before, the model demonstrating significance with the lowest AIC was considered the optimal choice. The Nagelkerke function was employed once more to compute pseudo-r-squared estimates, elucidating the explanatory power of the logistic regression models (Mangiafico and Mangiafico 2017).

RESULTS

Understory Species Composition

Understory species composition varied significantly across the three vegetation height classes, reflecting differences in ecological conditions and species dominance (Appendix B Tables B1–3). In the low vegetation class (< 1.5 m), six species were recorded, predominantly exotic grasses from the Poaceae family. *Imperata cylindrica* (IVI = 92.54) and *Saccharum spontaneum* (IVI = 59.21) dominated, both known for their invasive traits in tropical ecosystems (Hammond 1998; Usmadi *et al.* 2020). The only native species, *Oplismenus compositus*, had a low importance value index (IVI) of 27.46, suggesting suppression by exotic grasses. The medium vegetation class (1.6 to < 2.4 m) was more diverse, with 15 species across nine families. Native *Melastoma malabathricum* (IVI = 73.40) and exotic *Piper aduncum* (IVI = 48.04) were dominant, indicating a balance between native and exotic species. The high vegetation class (> 2.5 m) also had 15 species, with *P. aduncum* (IVI = 60.61) again dominant, followed by *M. malabathricum* (IVI = 40.39). This class showed a mix of native and exotic species, with native species like *Ficus minahassae* (IVI = 25.57) contributing to diversity.

Severity of Gall Rust by Vegetation Classification

Gall rust severity varied significantly across vegetation classes ($F = 148.8, p < 0.0001$). The high vegetation class exhibited the highest mean severity at 58.73% (95% CI: 53.83–63.63), followed by the medium class at 41.80% (95% CI: 39.94–43.66), and the low class at 19.58% (95% CI: 18.07–21.09) (Figure 4; Appendix B Table B5). Incidence also followed a similar trend, with the high class showing a "very common" status (mean incidence 58.7%),

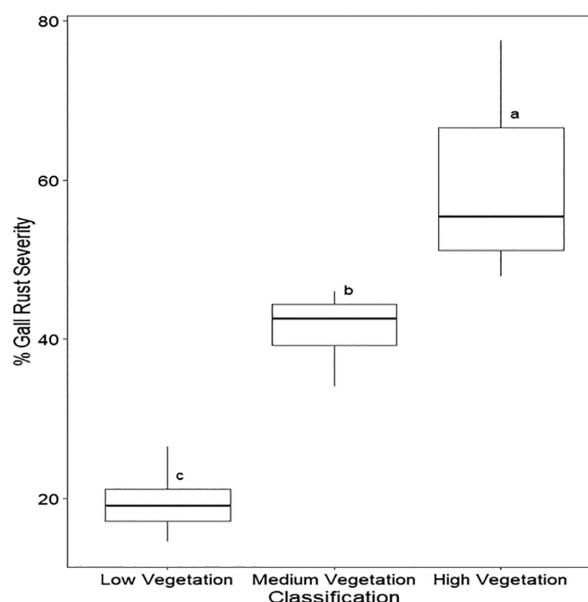


Figure 4. Mean percent gall rust severity by understory vegetation class (low: < 0.1 to < 1.5 m; medium: 1.6 to < 2.4 m; high: > 2.5 m). Box-and-whisker plots with error bars representing 95% confidence intervals. Filled lines indicate mean values.

the medium class "common" (41.8%), and the low class "occasional" (15.8%).

Understory Species Richness

Species richness differed significantly across classes ($F = 411.6, p < 0.0001$). The high vegetation class had the highest mean richness at 10 species (95% CI: 9.3–10.7), followed by the medium class with six species (95% CI: 5.6–6.4), and the low class with two species (95% CI: 1.5–2.5) (Figure 5).

Severity of Gall Rust by Species Richness

A significant positive relationship was observed between gall rust severity and species richness (pseudo- $R^2 = 0.81, p < 0.001$). As species richness increased, so did gall rust severity, suggesting a potential amplification effect (Figure 6).

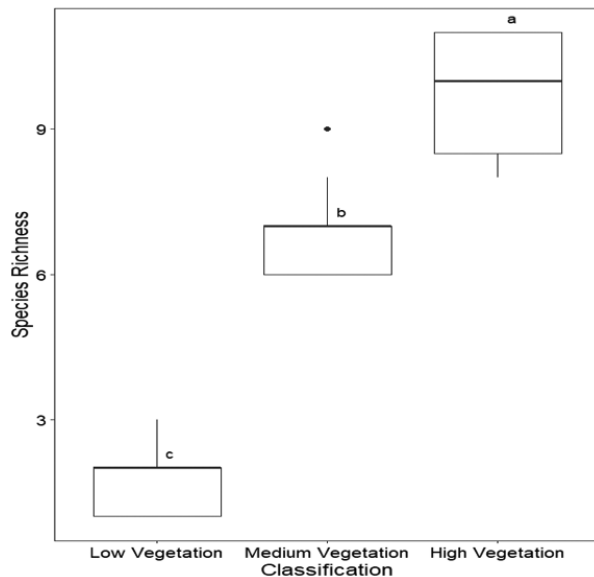


Figure 5. Mean species richness by understory vegetation class. Box-and-whisker plots with error bars representing 95% confidence intervals. Filled lines indicate mean values.

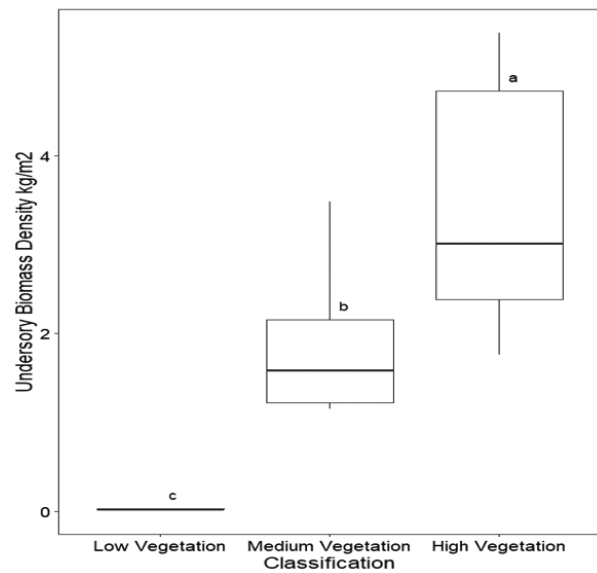


Figure 7. Total understory vegetation biomass (kg/m^2) by vegetation class. Box-and-whisker plots with error bars representing 95% confidence intervals. Filled lines indicate mean values.

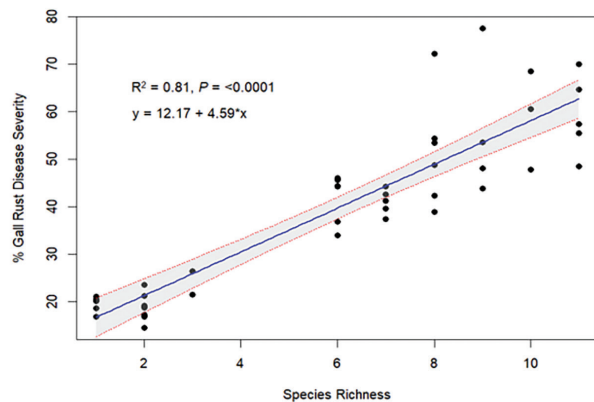


Figure 6. Linear regression of percent gall rust severity vs. species richness among understory vegetation classes in *F. falcata* plantations ($n = 45$). The red line represents the 95% confidence interval.

Understory Biomass Density

Biomass density varied significantly across classes ($F = 58.90$, $p < 0.0001$). The high vegetation class had the highest mean biomass at 3.41 kg/m^2 (95% CI: 2.75–4.07), followed by the medium class at 1.81 kg/m^2 (95% CI: 1.43–2.19), and the low class at 0.02 kg/m^2 (95% CI: 0.018–0.022) (Figure 7).

Severity of Gall Rust by Biomass Density

A significant polynomial relationship existed between gall rust severity and biomass density (pseudo- $R^2 = 0.87$, $p < 0.001$). Severity peaked at biomass densities of $2\text{--}4 \text{ kg/m}^2$ and declined above 4 kg/m^2 , suggesting an optimal range for pathogen proliferation (Figure 8).

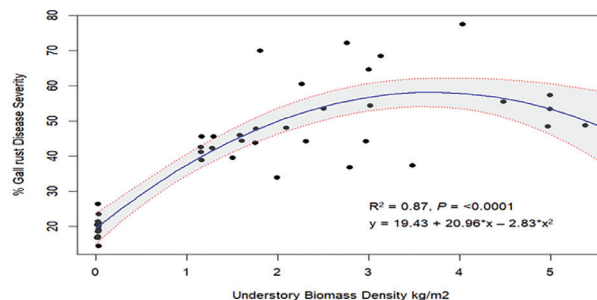


Figure 8. Polynomial regression of percent gall rust severity vs. total understory biomass (kg/m^2) among vegetation classes ($n = 45$). The red line represents the 95% confidence interval.

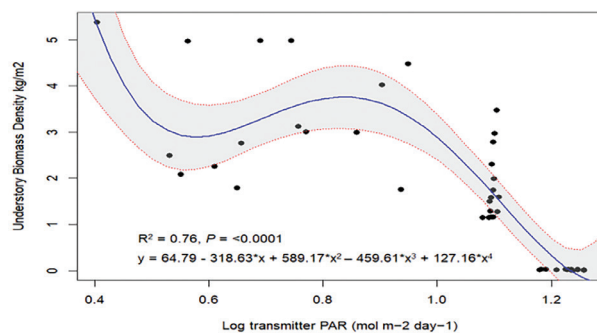


Figure 9. Polynomial regression of understory biomass density (kg/m^2) vs. log-transformed PAR ($\text{mol m}^{-2} \text{ d}^{-1}$) among vegetation classes ($n = 45$). The red line represents the 95% confidence interval.

Effect of Light on Biomass Density

A significant polynomial relationship was observed between biomass density and log-transformed PAR (pseudo- $R^2 = 0.76$, $p < 0.0001$). Higher light transmission correlated with decreased biomass density, emphasizing the role of canopy gaps in understory growth (Figure 9).

Incidence and Severity across Sites

Site-specific data (Appendix B Table B4) showed consistent trends, with high vegetation classes exhibiting higher gall rust incidence ("very common") and severity (51.62–67.61%) compared to medium ("common", 39.69–43.87%) and low classes ("occasional", 16.80–21.55%).

DISCUSSION

Influence of Understory Vegetation Height on Gall Rust Severity

The significant variation in gall rust severity across understory vegetation height classes underscores the critical role of vegetation structure in shaping disease dynamics in *F. falcata* plantations. The high vegetation class (> 2.5 m) exhibited the highest severity (58.73%, 95% CI: 53.83–63.63), likely due to its dense structure creating a humid microclimate conducive to *Uromyces falcatae* proliferation. Dense understory vegetation reduces air circulation and increases moisture retention, conditions known to favor fungal pathogens in tropical ecosystems (Lonsdale *et al.* 2008). In contrast, the low vegetation class (< 1.5 m) showed the lowest severity (19.58%, 95% CI: 18.07–21.09), possibly due to greater light penetration and reduced humidity, which may inhibit fungal growth (Eastburn *et al.* 2011).

The single assessment in November 2022 limits the study's ability to capture seasonal or temporal variations in gall rust dynamics. For instance, disease severity may increase during the wet season (May–October) due to higher humidity and rainfall, which are optimal for fungal spore dispersal and infection (Sileshi *et al.* 2012). Future studies should incorporate multiple sampling events across seasons to better understand these temporal dynamics and their interaction with understory vegetation.

Role of Species Richness in Disease Dynamics

The positive relationship between species richness and gall rust severity (pseudo- $R^2 = 0.81$, $p < 0.001$) suggests an amplification effect, where diverse understory communities may increase disease prevalence by providing more potential hosts or reservoirs for the pathogen (Halliday and Rohr 2019). This finding contrasts with the dilution effect hypothesis, which posits that higher biodiversity reduces disease risk by decreasing the probability of pathogen transmission among susceptible hosts (Johnson and Thielges 2010). In this study, the high vegetation class, with a mean richness of 10 species, likely included species susceptible to *U. falcatae* such as *Piper aduncum*, which may act as an alternative host or facilitator. However, this relationship is associative,

not causal, due to the observational nature of the study. Experimental manipulations such as controlled removal of specific understory species are needed to confirm causality and disentangle species identity effects from richness effects.

Biomass Density and the Role of Invasive Species

Understory biomass density was highest in the high vegetation class (3.41 kg/m², 95% CI: 2.75–4.07), driven by the dominance of invasive species like *Piper aduncum*. The polynomial relationship between biomass density and gall rust severity (pseudo- $R^2 = 0.87$, $p < 0.001$) indicates an optimal range (2–4 kg/m²) for pathogen proliferation, with a decline above 4 kg/m². This pattern may reflect a balance between microclimate favorability and competition dynamics. At 2–4 kg/m², the understory may create a humid, shaded environment ideal for *U. falcatae*, whereas higher densities may lead to increased competition among understory species, reducing resources available for pathogen spread (Dillon and Meentemeyer 2019).

The dominance of *P. aduncum* in medium and high classes (IVI = 48.04 and 60.61, respectively) highlights its role as a potential ecological facilitator of gall rust. Invasive species often alter microclimates by increasing humidity and reducing light penetration – conditions that favor fungal pathogens (Schoenborn *et al.* 2023). Research on invasive weeds has demonstrated that some species can serve as alternate and alternative hosts for pathogen populations (Kumar *et al.* 2021), a phenomenon that may also be relevant to *P. aduncum*. However, its role is complex, as some studies suggest it may also facilitate native species regeneration by providing favorable microhabitats (Jawani and Tulod 2024). Management strategies targeting *P. aduncum* should weigh these dual roles, potentially integrating selective removal with native species reintroduction to maintain ecological balance while reducing disease risk.

Applying this generalized equation to understory species such as *Piper aduncum* and *Melastoma malabathricum* can introduce error because it may not fully capture their distinctive growth forms and wood density variability; despite this limitation, it was selected as the best available proxy due to its broad calibration across diverse tropical forest conditions and its incorporation of both structural and wood property variables (Chave *et al.* 2014).

Light Availability and Biomass Dynamics

The significant relationship between biomass density and log-transformed PAR (pseudo- $R^2 = 0.76$, $p < 0.0001$) underscores the role of light availability in driving understory growth. Canopy gaps, reflected by

higher PAR values, allowed more light to reach the forest floor, promoting understory biomass accumulation (Montgomery and Chazdon 2001). This aligns with previous findings that light is a limiting resource in dense plantations, and canopy openness directly influences understory productivity (Nicotra *et al.* 1999). In *F. falcata* plantations, where canopy cover was controlled at 70–80%, small variations in canopy density significantly affected understory biomass, indirectly influencing gall rust severity through microclimate changes.

Management Implications

The associative relationships observed suggest several management strategies for *F. falcata* plantations. Controlling understory height, particularly in the high vegetation class, could reduce humidity and light limitation, mitigating gall rust severity. Selective removal of invasive species like *P. aduncum* may decrease disease risk, though careful monitoring is needed to avoid disrupting native species regeneration. Maintaining biomass density below 2 kg/m² or above 4 kg/m² could minimize disease risk, balancing pathogen favorability with competitive dynamics. However, these strategies require experimental validation to confirm causality and assess long-term ecological impacts.

Plantation managers should also consider integrating native understory species to enhance biodiversity and potentially dilute disease risk, as suggested by the dilution effect hypothesis (Johnson and Thielges 2010). For instance, promoting native shrubs like *M. malabathricum*, which showed resilience in medium and high classes, could provide ecological benefits while reducing reliance on invasive species. Additionally, regular monitoring of gall rust incidence and severity across seasons can inform timely interventions such as pruning infected branches or applying fungicides during high-risk periods.

CONCLUSION

This study examines the relationship between understory vegetation and gall rust disease in *F. falcata* plantations in Tigbao, Zamboanga del Sur, the Philippines. Exotic species, particularly *I. cylindrica* and *P. aduncum*, dominated the understory, whereas native species like *Melastoma malabathricum* were more common in denser vegetation. Taller understory vegetation and greater species richness were strongly correlated with increased gall rust incidence and severity, likely from favorable microclimates like higher humidity. Selective removal of invasive such as *P. aduncum* and emerging invaders like *Spathodea campanulata* could reduce disease risk. Remote sensing helps monitor their spread via

multispectral signatures (Ramoncito and Jawani 2024). Biomass density – driven by invasives – also influenced disease, with a 2–4 kg/m² optimal range for the pathogen. Light availability indirectly affected rust by shaping understory biomass.

These results highlight the need for integrated strategies managing understory structure, invasive species, and microclimate. Future work should explore seasonal dynamics through multi-temporal sampling. Specifically, trials should stratify elevation, light, and soil moisture to precisely quantify each factor's independent effect on gall rust for improved guidelines. Addressing these gaps will let managers develop evidence-based practices to enhance plantation resilience against the disease, ensuring sustainable forestry in tropical regions.

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APPENDICES

Appendix A: Disease Rating Scales and Cover Classes

Table A1. Rating scale for gall rust disease incidence per plot.

Percent incidence	Status
< 10	Rare
10–25	Occasional
25–50	Common
50–75	Very common
> 75	Widespread

Table A2. Rating scale for gall rust severity per tree.

Rating	Percentage of crown with galls	Qualitative rating
0	No symptoms	Healthy
1	< 10%	Lack
2	11–25%	Weak
3	26–60%	Average
4	> 60%	High

Table A3. Daubenmire cover class per plot.

Cover class	Range of coverage (%)	Midpoint of range (%)
1	0–5	2.5
2	5–25	15.0
3	25–50	37.5
4	50–75	62.5
5	75–95	85.0
6	95–100	97.5

Appendix B. Understory Species Composition and Characteristics of *F. falcata* Plantation Sites

Table B1. Understory species composition in the low vegetation class.

Scientific name	Family name	Origin	Habit	RD	RF	RC	IVI
<i>Imperata cylindrica</i>	Poaceae	Exotic	Grass	26.67	46.67	19.21	92.54
<i>Saccharum spontaneum</i>	Poaceae	Exotic	Grass	26.67	13.33	19.21	59.21
<i>Dactyloctenium aegyptium</i>	Poaceae	Exotic	Grass	6.67	20.00	19.21	45.88
<i>Arachis pintoii</i>	Fabaceae	Exotic	Herb	20.00	6.67	14.12	40.79
<i>Paspalum conjugatum</i>	Poaceae	Exotic	Grass	13.33	6.67	14.12	34.12
<i>Oplismenus compositus</i>	Poaceae	Native	Grass	6.67	6.67	14.12	27.46
Total				100	100	100	300

Table B2. Understory species composition in the medium vegetation class.

Scientific name	Family name	Origin	Habit	RD	RF	RC	IVI
<i>Melastoma malabathricum</i>	Melastomataceae	Native	Shrub	37.04	20.00	16.36	73.40
<i>Piper aduncum</i>	Piperaceae	Exotic	Shrub or small tree	20.37	13.33	14.34	48.04
<i>Saccharum spontaneum</i>	Bignoniaceae	Exotic	Tree	9.26	8.33	11.93	29.53
<i>Etlingera philippinensis</i>	Zingiberaceae	Native	Herb	5.56	5.00	5.00	15.56
<i>Leea aculeata</i>	Vitaceae	Native	Shrub	3.70	5.00	6.35	15.06
<i>Ficus minahassae</i>	Moraceae	Native	Tree	1.85	6.67	6.16	14.68
<i>Xanthosoma sagittifolium</i>	Araceae	Exotic	Herb	3.70	5.00	5.20	13.90
<i>Synedrella nodiflora</i>	Asteraceae	Native	Herb	1.85	5.00	6.74	13.59
<i>Ficus septica</i>	Moraceae	Native	Tree	1.85	5.00	5.97	12.82
<i>Costus speciosus</i>	Costaceae	Exotic	Herb	1.85	5.00	5.20	12.05
<i>Anthurium andraeanum</i>	Araceae	Exotic	Herb	1.85	3.33	6.54	11.73
<i>Paspalum conjugatum</i>	Poaceae	Exotic	Grass	3.70	5.00	2.12	10.82
<i>Chromolaena odorata</i>	Asteraceae	Exotic	Herb	1.85	5.00	3.46	10.32
<i>Pueraria phaseoloides</i>	Fabaceae	Exotic	Vine	3.70	3.33	2.31	9.35
<i>Arachis pintoii</i>	Fabaceae	Exotic	Herb	1.85	5.00	2.31	9.16
Total				100	100	100	300

Table B3. Understory species composition in the high vegetation class.

Scientific name	Family name	Origin	Habit	RD	RF	RC	IVI
<i>Piper aduncum</i>	Piperaceae	Exotic	Shrub/Small tree	28.72	15.63	16.26	60.61
<i>Melastoma malabathricum</i>	Melastomataceae	Native	Shrub	15.96	10.42	14.02	40.39
<i>Spathodea campanulata</i>	Bignoniaceae	Exotic	Tree	11.70	5.21	12.71	29.62
<i>Ficus minahassae</i>	Moraceae	Native	Tree	10.64	5.21	9.72	25.57
<i>Diplazium esculentum</i>	Athyriaceae	Native	Fern	2.13	8.33	5.79	16.26
<i>Leea aculeata</i>	Vitaceae	Native	Shrub	3.19	6.25	4.67	14.11
<i>Synedrella nodiflora</i>	Asteraceae	Native	Herb	2.13	7.29	4.49	13.91
<i>Flemingia strobilifera</i>	Fabaceae	Exotic	Shrub	3.19	6.25	4.30	13.74
<i>Anthurium andraeanum</i>	Araceae	Exotic	Herb	2.13	8.33	2.24	12.70
<i>Macaranga grandifolia</i>	Euphorbiaceae	Native	Tree	3.19	3.13	6.36	12.67
<i>Costus speciosus</i>	Costaceae	Exotic	Herb	2.13	7.29	2.99	12.41
<i>Xanthosoma sagittifolium</i>	Araceae	Exotic	Herb	2.13	5.21	4.67	12.01
<i>Ficus septica</i>	Moraceae	Native	Tree	3.19	2.08	4.30	9.57
<i>Pityrogramma calomelanos</i>	Pteridaceae	Native	Fern	2.13	5.21	1.87	9.21
<i>Pueraria phaseoloides</i>	Fabaceae	Exotic	Vine	3.19	2.08	3.36	8.64
<i>Etlingera philippinensis</i>	Zingiberaceae	Native	Herb	4.26	2.08	2.24	8.58
Total				100	100	100	300

Table B4. Characteristics of five *F. falcata* plantation sites.

Falcata plan- tation	Plot class	Elevation (m)	Falcata trees/ha	Understory richness	Biomass density (kg/m ²)	Incidence	Severity (%)
Site 1	Low	294	600	2	0.02	Occasional	19.60
	Medium	294	450	7	1.44	Common	43.87
	High	294	375	9	4.95	Very common	53.88
Site 2	Low	301	500	1	0.03	Occasional	19.64
	Medium	301	425	7	1.74	Common	42.35
	High	301	250	9	3.09	Very common	51.62
Site 3	Low	297	525	1	0.03	Occasional	16.80
	Medium	297	375	6	2.08	Common	40.21
	High	297	375	9	4.00	Very common	60.14
Site 4	Low	292	525	3	0.03	Occasional	20.34
	Medium	292	400	9	1.82	Common	39.69
	High	292	300	11	2.27	Very common	67.61
Site 5	Low	323	500	2	0.02	Occasional	21.55
	Medium	323	450	6	1.98	Common	42.89
	High	323	275	9	2.74	Very common	60.42

Table B5. Summary of gall rust incidence and severity by vegetation class.

Vegetation class	Incidence	Mean severity (%)	95% CI
Low	Occasional	19.58	18.07–21.09
Medium	Common	41.80	39.94–43.66
High	Very common	58.73	53.83–63.63