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Infestation Levels of Fruit Flies on Red Chili Pepper (*Capsicum annuum* L.) In Different Altitude

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Abstract

Fruit flies (Diptera: Tephritidae) are among the most economically important pests of horticultural crops, yet the ecological drivers shaping their infestation patterns along altitudinal gradients remain insufficiently understood in tropical agroecosystems. This study examined how altitude influences fruit fly infestation on red chili (*Capsicum annuum* L.) across major chili-producing regions of West Sumatra, Indonesia. Field surveys were conducted at 33 locations ranging from 15 to 1571 m above sea level between October 2024 and March 2025. Infestation levels were quantified at both plant and fruit scales, and the relationship between altitude and infestation intensity was evaluated using regression and correlation analyses. The results revealed a consistent increase in infestation with elevation. Plant infestation rose from 31.4% in lowland areas (0-600 m) to 59.8% in pre-montane zones (600-1500 m) and reached 91% in lower-montane regions (1500-1800 m). Fruit infestation followed a similar pattern, increasing from 1.3% to 7.6% across the same altitudinal gradient. Statistical analysis indicated a strong positive relationship between altitude and plant infestation ($R^2 = 0.560$, $p < 0.0001$), while fruit infestation exhibited a moderate but significant correlation with altitude ($R^2 = 0.308$, $p < 0.001$). These findings demonstrate that altitudinal variation strongly shapes pest pressure in chili agroecosystems, likely through associated changes in microclimatic conditions and host plant traits. Incorporating altitudinal risk patterns into pest monitoring programs may improve the effectiveness of integrated pest management strategies in tropical mountainous farming systems.

Keywords: Altitudinal gradient, *Capsicum annuum*, fruit fly infestation, pest population dynamics, tropical agroecosystems

1. Introduction

The sole "practice" that sustains human life on Earth is agriculture (Pretty, 1999). Therefore, one of the key drivers of economic growth in West Sumatra province is the agriculture industry, which employs 50.69% of the province's population (BPS West Sumatra, 2020) and contributes 21.71% of the gross regional product (BPS, 2022). Over the past decade, fruits of the genus Capsicum, which are highly profitable vegetable crops with multiple uses, have become a crucial national strategic commodity (Aprilia et al., 2023; Stella & Simamora, 2021). According to Michael (2019), productivity depends solely on human input (farmers) and environmental factors (soil nutrients and water), as well as climatic elements (temperature, altitude, relative humidity, and CO_2 levels). Insect populations are known to be impacted by altitude-related environmental factors (Lambkin et al., 2011). Temperature, humidity, and host occurrence are influenced by altitude and are closely linked to the phenology of tephritids, in particular, and of insects in general. As altitude increases, insect richness, evenness, and population abundance decrease because habitat suitability declines. Insects that have adapted to higher altitudes typically have fewer generations, longer periods between life-cycle stages or diapause episodes, and modifications in lifespan, sexual maturity, and heat tolerance. The abundance and diversity of many insect groups, such as beetles (Coleoptera) (Nunes et al., 2016), moths and butterflies (Lepidoptera) (Ngowi et al., 2019), wasps (Hymenoptera) (Ribeiro, Silvestre, and Garcete-Barrett, 2019), and flies (Diptera) (Rohner et al., 2015), are known to decline at higher elevations. Studies showed that longer life cycles (longer adult lifespan, slower reproductive rates), patchy seasonal occurrence, and survival in favorable microclimate habitats enable C. capitata populations to survive, persist, and thrive at elevations up to 2000 m above sea level.

The tephritid family is highly diverse, with more than 4,000 species across 500 genera. Approximately 1500 fruit fly species are among the most harmful fruit pests worldwide; over 35% of these species are detrimental, and 10% are considered dangerous pests (Schutze et al., 2015). Hardy originally identified 66 species of fruit flies in Indonesia in 1985. According to a later study by Hidayat et al. (2023), Java has the most fruit fly species (102), followed by Sulawesi (96) and Sumatra (77). West Sumatra province has 40 fruit fly species, the second-highest number in Indonesia, with B. dorsalis being the most common. More than 250 host plant species are susceptible to infestation by this tropical multivoltine, highly polyphagous frugivorous pest (Schutze et al., 2015), of which 70% are horticultural plants. It poses a serious threat to the province's vegetable production (Budiyanti et al., 2019; Hidayat et al., 2023). Furthermore, Hassani et al. (2016) found that several biotic and abiotic variables influence the phenology patterns and population densities of B. dorsalis. Altitude has a significant impact on temperature, humidity, and host availability, all of which are only present at specific elevations (Duyck, David, and Quilici, 2006). Hassani et al. (2016) demonstrated that C. capitata was more prevalent in medium-altitude regions and B. dorsalis was more prevalent in low-altitude regions, indicating niche partitioning by altitude.

In this work, we anticipated that the more complex fruit fly population and the degree of injury are related to changes in altitude. This study's primary goal was to illustrate how altitude affects the degree of fruit flies' infection. The fact that some fly species respond differently to altitudinal variation, thereby altering the populations of frugivorous insect herbivores, means this is not true for all dipterans.

2. Materials and Methods

Survey sites

33 sites in West Sumatra, ranging in elevation from 15 to 1571 meters, were used for this investigation between October 2024 and March 2025. In West Sumatra province, The survey activities for local chili varieties were conducted in four regencies/cities: Agam Regency (altitude range: 0 to 2891m asl), Solok (altitude range: 329 to 1,458m asl), Tanah Datar (altitude range: 400 to 1000m asl), and Padang Pariaman (altitude range: 10-1000m asl). According to Michael (2019), altitude classes are: lowland (0–600), pre-mountainous (600–1500), low mountain (1500–1800), mid-mountain (1800–2700), high mountain (2700–3300), and sub-alpine (>3300). These classifications also include the corresponding maximum and lowest temperatures and precipitation.

Survey location	Sub-district	Village	Coordinates	Altitude	Chili variety	Land area m^2
Tanah Datar Regency	Sungai Tarab	Pasia laweh	0° 23' 26" S, 100° 31' 55" E	977	Akar	400
		Kumango	0° 23' 19" S, 100° 32' 27" E	852	Akar	550
			0° 23' 19" S, 100° 33' 27" E	860	Rawit	380
	Lintau Buo Utara	Lubuk jantan	0° 27' 33" S, 100° 44' 35" E	308	Keriting	600
			0° 27' 31" S, 100° 44' 33" E	320	Kobay	500
	Lintau Buo Utara	Batu bulek	0° 22' 43" S, 100° 40' 16" E	1131	Akar	1000
			0° 22' 40" S, 100° 39' 53" E	1133	Rawit Kutu	300
	Batipuh	Batipuh Baruah	0° 28' 28" S, 100° 27' 6" E	680	Akar	700
		Batipuh Baruah	0° 28' 17" S, 100° 26' 42" E	714	Akar	400
Solok	Danau Kembar	Simpang tanjungnan IV	1° 3' 16" S, 100° 43' 55" E	1547	Keriting	900
		Simpang Tanjungnan IV	1° 3' 22" S, 100° 43' 7" E	1571	Kopay	1100
		Simpang Tanjungnan IV	1° 3' 19" S, 100° 43' 42" E	1544	Akar	800
	Gunung Talang	Air Batumbuk	1° 1' 10" S, 100° 39' 18" E	1370	Akar	600
		Air Batumbuk	1° 1' 14" S, 100° 39' 35" E	1356	Akar	600
Agam	Matur	Matua Mudik	0° 17' 32" S, 100° 16' 17" E	1065	Keriting	400
	Duo Koto	Lubuk Basung	0° 14' 53" S, 100° 11' 38" E	465	Kuhay	2400
	Tanjung Raya	Koto Gadang Anam	0° 15' 27" S, 100° 10' 19" E	466	Akar	5000
			0° 15' 31" S, 100° 10' 21" E	468	Kuhay	700
	West Padang Panjang	Bukit Surungan	0° 27' 1" S, 100° 24' 0" E	849	Rawit	400
			0° 27' 1" S, 100° 23'58" E	841	Keriting	1000
	Sepuluh Koto	Koto Baru	0° 23' 56" S, 100° 24'26" E	1108	Keriting	2500
			0° 23' 48" S, 100° 24'15" E	1175	Keriting	700
			0° 23' 46" S, 100° 24'34" E	1166	Keriting	1200
	Banuhampu	Cingkariang	0° 20' 55" S, 100° 22'54" E	1016	Rawit	1400
			0° 20' 54" S, 100° 22'54" E	1015	Keriting	600
			0° 21' 8" S, 100° 23'20" E	1043	Keriting	2200
Padang Pariaman	Lubuk Alung	Lubuk Alung	0° 40' 39" S, 100° 16' 50" E	26	Kuhay	1500
		Lubuk Alung	0° 40' 23" S, 100° 17' 27" E	28	Kuhay	1000
		Lubuk Alung	0° 40' 21" S, 100° 17' 25" E	26	Kuhay	400
		Lubuk Alung	0° 43' 2" S, 100° 16' 3" E	15	Kuhay	1700
	V Koto Timur	Padang Alai	0° 29' 3" S, 100° 13' 41" E	327	Keriting	10000
	Balingka	IV Koto	0° 19' 49" S, 100° 18' 49" E	1168	Rawit Sutan	240
			0° 19' 44" S, 100° 18' 42" E	1164	Rawit Sutan	280

Sampling

At each sample location, all fruit was collected, transported, and incubated in the laboratory according to previously reported protocols (Copeland et al., 2002). At the same time as the survey, nearby chili crops were inspected, and a random count was made. Three criteria were used to select criterion locations deliberately: First, secondary data from earlier research were used to identify regional chili varieties (Suliansyah, Ekawati, and Hariandi, 2023). Second, the area under cultivation is 400 square meters or more. In the end, the generative phase fruits were randomly selected from the plants, and occasionally, freshly fallen fruits that had not broken down or been harmed by soil organisms were plucked from the bottom. Interestingly, the farmers on each chili plantation had a range of pepper chili plants that were used to make the product. Each chili plantation's growers grew a variety of chili pepper plants used in the item. Identifying chili host plants in the field using the manual of Budiyanti et al. (2024). GPS coordinates and elevation measurements were recorded for each sampling location (Drew, 2011; Astriyani, 2014; Choudhary et al., 2015).

Statistical analysis and observations

Since there are more host fruit species in West Sumatra province, more samples were collected there, and the height gradient is greater than on the other islands, we decided to conduct an in-depth study there to understand the link between fruit flies and altitude. To ensure that infestation rates were representative of the field, we calculated the percentages of fruit and plant infestations. The average number of catches per trap was compared and categorized using Duncan's multiple-range test. Analysis of variance (ANOVA) was performed using SPSS software version 25.0.

Fruits infestation (%): The number of infected chili fruits per 10 plants divided by the total number of fruits by the following formula (Kakar et al., 2014):

$$\text{Fruits infestation (\%)} = \frac{\text{No. of infested fruits}}{\text{Total number of fruits}} \times 100$$

Plants infestation (%): The total number of infested chili plants divided by 20 chili plants by the following formula (Kakar et al., 2014):

$$\text{Plants infestation (\%)} = \frac{\text{No. of infested plants}}{20} \times 100$$

3. Results and Discussion

Infestation of chili by fruit flies by altitudes and regencies

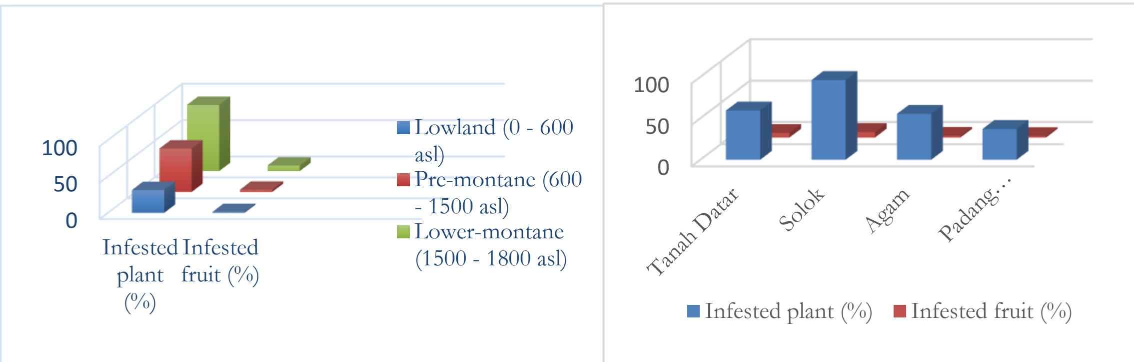

Figure 1. Average infestation levels by altitude and regencies

With an emphasis on both plant-level and fruit-level infestations, the present study examined the impact of altitude on the prevalence of fruit fly infestations of chili plants (*C. annuum* L.). Three altitude zones were used to study the association between altitude and fruit fly infestation in chili crops: Lowland (0–600 m asl), Pre-montane (600–1500 m asl), and Lower-montane (1500–1800 m asl). The results in Figure 1 showed a clear and consistent trend: infection levels rise with altitude at both the plant and fruit levels. Chili plant infestation peaked in lower-montane regions (91%), rose dramatically in pre-montane zones (59.8%), and was lowest in lowland areas (31.4%). Fruit infestation showed a similar pattern, increasing from 1.3% in the lowland zone to 3.2% in pre-montane regions and 7.6% at lower montane levels. These results suggest that pest pressure is positively correlated with altitude. Compared to other regencies, Solok has the greatest infection rates for both plants and fruit (96.2% and 6.6%, respectively), whereas Padang Pariaman has the lowest infestation rates (37.1% and 1.8%, respectively). As altitude increases, there is a discernible upward trend in both plant and fruit infection, particularly in plant infestation. It is more prevalent in lower montane regions (1500–1800 m). The four regencies' infestation rates differ in statistically significant ways.

These findings contribute to a growing body of evidence suggesting that altitude plays a significant role in abiotic factors shaping pest-host interactions. The impact on the host plants' morphology, phenology, size, physiology, chemistry, and spatial arrangement may be caused by altitude (Kronfuss, 1999). Therefore, the infection rate of *B. dorsalis* declines with highland altitude, and cooler climates are likely to have a reduced risk of its introduction (Hassani et al., 2022). The findings of Odanga et al. (2018) and Geurts et al. (2014), which showed that fruit infestation levels varied with *B. dorsalis* population variation, reaching their greatest at lower altitudes and being relatively low at higher altitudes (>1500 asl) and almost nonexistent above 1700 m, were corroborated by this result (Finnie et al., 2021). Another aspect is that fruit fly performance may be adversely affected by lower nutrient levels that are accessible to plants at high altitudes (Rasmann et al., 2014). Apart from that, many secondary metabolites of defensive plants, including terpenes, phenolics, coumarins, and alkaloids, typically fluctuate along altitudinal gradients (Benevenuto et al., 2020). At higher altitudes, there is a tendency for chemical defenses to decline because herbivore selection is less intense. Altitude is also linked to modifications in fruit fly physiology, such as flight activity, diapause intensity, and energy reserve control, which can affect the insects' ability to survive, grow, and develop (Papanastasiou et al., 2011). On the other hand, fruit fly growth durations are often inversely proportional to temperature; lower altitudes should see shorter fruit fly development (Bolzan et al., 2017). Since it has a significant impact on larval growth, developmental time, and survival, the nutritional makeup of Tephritidae host fruits explains their suitability for larvae (Hafsi et al., 2016). The host range in the field is mostly explained by larval development, which is associated with female preference (Masselière et al., 2017; Facon et al., 2021). Furthermore, habitat structure (e.g., size and diversity) may decrease at high altitudes (Lawton et al., 1987; Odanga et al., 2018), which may impact which fruits are available to certain fruit fly species (Hodkinson, 2005; Ye & Liu, 2007; Leblanc et al., 2012).

The relationship between altitudes and plant infestation

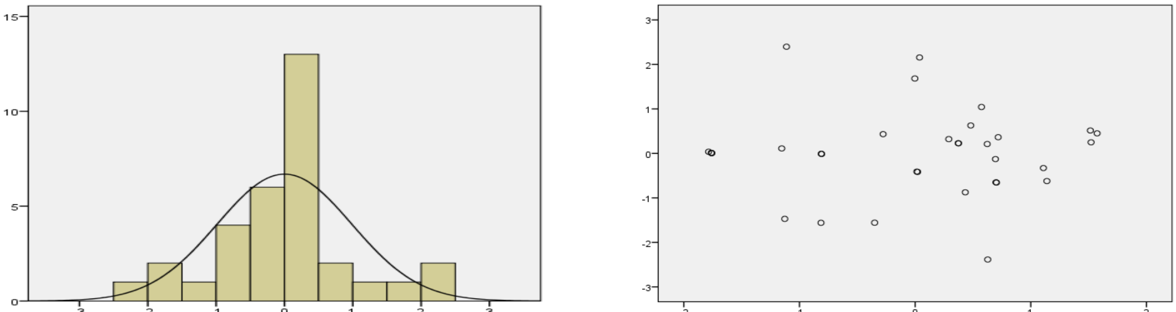

Figure 2. Histogram and Scatterplot of the dependent variable of the infested plant

The results in Figure 2 show that elevation and the proportion of infection for plants are significantly positively correlated. Altitude accounted for almost 56% (R2 = 0.560) of the variance in the proportion of affected plants, according to the linear regression analysis. At the plant level, height and infestation were strongly positively correlated, as indicated by the Pearson correlation coefficient of r = 0.748 and the very significant p-value (< 0.0001). In particular, the regression model indicates that the proportion of afflicted plants rose by around 4.6% for every 100 meters of elevation gain. This result is consistent with other studies that indicate altitudinal gradients can significantly impact the dynamics of insect pests by altering the microclimate, host plant distribution, and natural enemy composition (Hodkinson, 2005; Prajapati et al., 2020). Certain physiological or physical traits of chili plants may alter at greater elevations, thereby increasing their susceptibility or appeal to fruit flies. Furthermore, as comparable trends have been noted for other Diptera species in montane settings, the microclimatic conditions at higher elevations, such as higher humidity and lower temperatures, may promote the survival and activity of Bactrocera spp. (Duyck, Sterlin, and Quilici 2004; Clarke et al. 2005).

The relationship between altitudes and fruit infestation

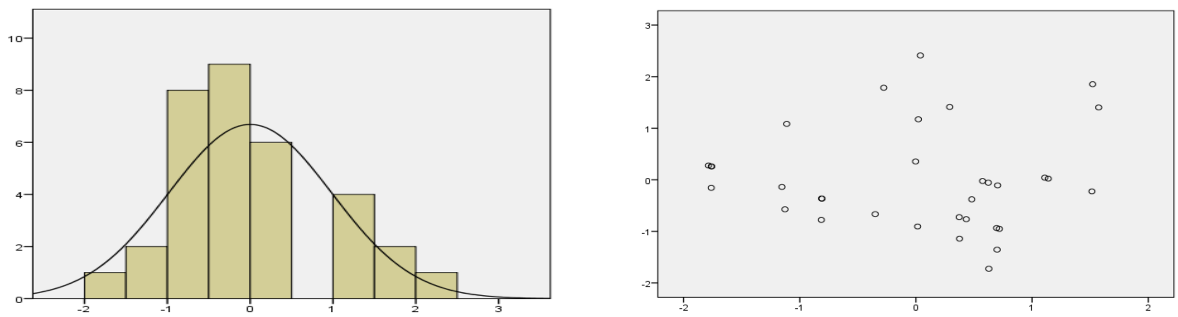

Figure 3. Histogram and Scatterplot of the dependent variable of infested fruit

The findings in Figure 3 clearly demonstrate a substantial positive correlation between elevation and the percentage of fruits infected. Elevation accounted for around 33% (R2 = 0.308) of the variation in a parallel study of fruit-level infestation, which showed a moderately positive connection (r = 0.555, p < 0.001). Infestation increased at a slower pace than plant infestation, increasing by around 0.35% for every 100 meters of elevation gain. Despite being significant, this weaker relationship implies that while elevation affects both infestation levels, other factors, such as fruit maturity, cultivar-specific traits, and local pest management practices, may also have an impact on fruit infestation (Vargas, Piñero, and Leblanc 2015). The behavioral patterns of B. dorsalis and related species, which frequently use host plant cues at the plant canopy level during oviposition and dispersal stages, may be the reason for the higher explanatory power of elevation on plant-level infestation as opposed to fruit-level infestation (Clarke, 2011). Furthermore, certain microhabitat elements within each elevation zone, such as shade, humidity, and the presence of natural enemies or competing host plants, may lessen the degree of fruit infestation (Bateman, 1972; Díaz-Fleischer et al., 1999)

Weather Comparison: Agam, Padang Pariaman, Tanah Datar, Solok

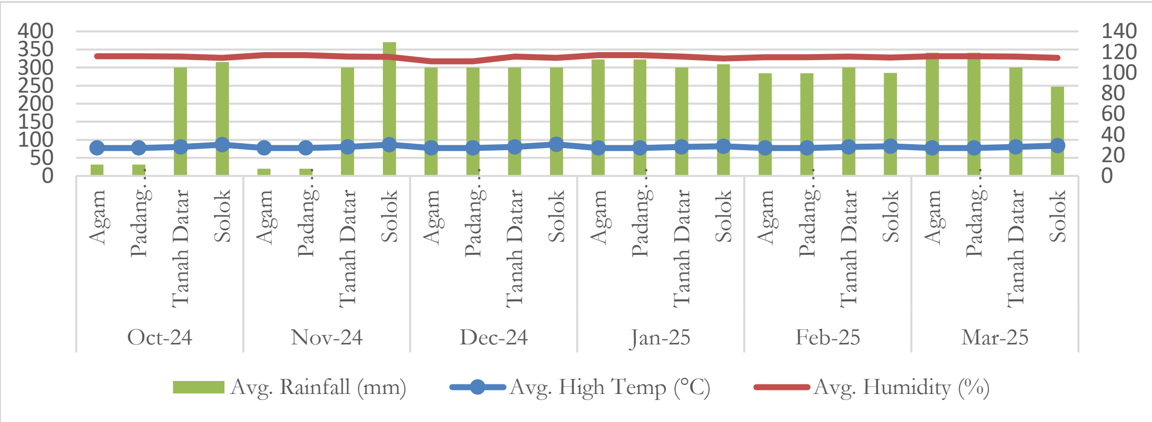

Figure 4. Weather Comparison: Agam, Padang Pariaman, Tanah Datar, Solok (Oct 2024 - Mar 2025)

Warm temperatures, heavy rainfall, and high humidity, all typical of the West Sumatra region, are shared by all four regencies in Figure 4. The districts see rather consistent temperatures, with daytime highs of 27°C to 30°C and nighttime lows of 22°C to 24°C. Compared to the other regencies, Agam and Tanah Datar experienced comparatively moderate temperatures with less variation over the months. Temperatures were greatest in Padang Pariaman, especially during the early months. Due to its somewhat colder geographic position, Solok had the lowest temperatures, particularly during some months. Another factor is that, particularly in the later months of the year, the humidity is rather high, averaging between 85% and 90%. The humidity was consistently greater in Agam and Tanah Datar. The humidity levels at Padang Pariaman and Solok were marginally lower, albeit they varied by month. Aside from that, the wettest months of the year have the most rainfall, which progressively declines starting in February. The wettest months in Solok and Agam are November and March. A protracted rainy season is indicated by the average of 16 to 26 wet days per month across all districts.

Regional variations in elevation and meteorological characteristics are strongly related to the reported variance in fruit fly infestation throughout West Sumatra's four regencies. The highest infestation levels (96.2% of plants and 6.6% of fruits) were found in Solok, which had the highest average temperature (≈30.3 °C) and the most rainfall (315 mm), confirming earlier findings that higher temperatures promote B. dorsalis development, survival, and fecundity (LUO Zhi-xin et al., 2009; Ye & Liu, 2007; Abro et al., 2023). Agam and Padang Pariaman, on the other hand, demonstrated less infection due to their greater humidity (89–90%) and comparatively lower temperatures (≈27 °C), suggesting that wetter, colder weather may discourage insect activity. Nonetheless, Agam's remarkably high fruit infestation in montane zones (7.6%) raises the possibility that delayed harvests at higher elevations and microclimatic conditions may increase sensitivity by extending fruit exposure (Kamala Jayanthi and Verghese, 2011). The necessity for location-specific pest control measures is highlighted by these findings, which are consistent with research showing the synergistic effects of elevation, temperature, and rainfall distribution on B. dorsalis population dynamics (Ziyuan Li et al., 2024).

4. Conclusion

In conclusion, this data lends credence to the idea that altitude has a significant role in determining the damage levels and population dynamics of fruit flies in West Sumatra. These findings also underline the ecological complexity of pest dynamics across altitude gradients and suggest that considering altitude when designing integrated pest management (IPM) strategies, localized monitoring, and tailored management interventions in pre-montane and montane agricultural zones.

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