Bindura University of Science Education

**Assessing the threat severity of *Leptocybe invasa/*blue gum chalcid on Zimbabwe's forestry industry: A case of Nyanga District, Manicaland Province**

By

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A research project submitted in partial fulfilment of the requirements for the Bachelor of Science Honors Degree in Biological Sciences.

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## Approval form

The undersigned certify that they have read the dissertation titled 'Assessing the threat severity of Leptocybe invasa/blue gum chalcid on Zimbabwe's forestry industry. A case of Nyanga', and confirm that it is suitable for submission to the Biological Sciences Department, Faculty of Science and Engineering, for assessment.

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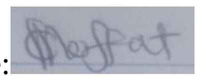
Signature:  Date: 15 June 2025

**Supervisor**

I, E. Zingoni, declare that I have supervised this thesis and I am satisfied that it can be submitted to the Biological Sciences Department, Faculty of Science and Engineering, at Bindura University of Science Education.

Signature: E. Zingoni Date: 15/06/25

## Dedication

I dedicate this project to my parents, especially my mom who was my biggest cheerleader and constant source of strength.

## Acknowledgements

I would like to thank my family for their tolerance, love, and unwavering support which kept me emotionally and psychologically strong. Over the course of this research, my supervisor has consistently guided, mentored, and provided priceless insights; so, I would want to especially thank them. Your encouragement and helpful criticism tremendously improved the caliber of this work and kept me motivated and concentrated amid trying circumstances. Additionally, much appreciated are the Forestry Commission of Zimbabwe and the committed personnel at the Forestry Research Centre in Harare for their cooperation, logistical support, and field data collecting facilitation. The effective finishing of this project was much influenced by your help. Finally, I especially appreciate all of the responders who invested time to complete the survey. This study was made possible by your readiness to provide insightful knowledge and experiences. You own as much of this work as I do.

## List of abbreviations

FRC – Forestry Research Centre

FAO – Food and Agriculture Organization

DNA – Deoxyribonucleic Acid

DBH – Diameter at Breast Height

ZIMSTAT – Zimbabwe National Statistics Agency

GIC – Gum Industry Commission

GDP – Gross Domestic Product

MLR – Multiple Linear Regression

**List of figures**

## List of tables

## List of appendices

# Abstract

This study examines the threat level posed by *Leptocybe invasa* (Blue Gum Chalcid) to Zimbabwe's forestry sector, particularly regarding commercial Eucalyptus plantings in Nyanga, in Manicaland Province. The study sought to measure infestation levels, evaluate the effects on tree health and productivity, and determine species-specific vulnerability. A mixed-methods strategy was utilized, encompassing field sampling, structured interviews, and statistical analysis. Quantitative analysis across five planting sites revealed high gall prevalence, particularly on juvenile leaves and terminal shoots, with severity varying among Eucalyptus species. Eucalyptus grandis was the most susceptible, while hybrid clones showed moderate resistance. Qualitative evidence from forestry professionals supported the findings, highlighting stunted growth, reduced timber quality, and increased costs for pest control and replanting. These findings underscore the immediate necessity for integrated pest management (IPM) solutions customized for high-risk areas within the province. The study advocates for the adoption of resistant Eucalyptus hybrids, the enhancement of early detection techniques, and the promotion of inter-agency collaboration in pest control. This research highlights the economic and ecological consequences of *L. invasa* infestation, thereby enhancing the field of forest entomology and providing actionable advice to preserve the sustainability and productivity of Zimbabwe's commercial forestry industry.

Contents

# Chapter 1

## 1.1. Introduction

*Leptocybe invasa* (commonly known as the blue gum chalcid wasp) is a tiny invasive gall-forming wasp that poses a serious threat to eucalyptus production worldwide. Native to Australia, this pest has rapidly spread across Asia, Africa, the Middle East, and parts of Europe through the movement of infested plant material. *Leptocybe invasa* is one of the most damaging recent biological invasions in global forestry, and its expansion across Eucalyptus-growing regions has demonstrated the vulnerability of monoculture plantations to insect pest risks (Wingfield et al., 2015). While the biological characteristics and general impacts of the pest are being more widely documented around the world, important gaps in knowledge remain on its particular socioeconomic ramifications for invaded industries, particularly in developing economies where forestry plays an important role (FAO, 2020). Zimbabwe presents a fascinating setting for exploring such investigation, considering that its Eucalyptus-dependent timber sector is facing mounting pressures from this invasion amidst broader economic hardship. This study examines *L. invasa* impacts through three frameworks rarely combined in the literature: (1) plantation-scale production economics, (2) value chain implications across timber industry, and (3) cost-benefit analysis of the available control options. The approach responds to the call for context-specific studies of invasive species impacts in African forestry (Dittrich-Schröder et al., 2018), going beyond purely entomological studies to guide decision-making by industry stakeholders and policymakers.

## 1.2 Background of the study

The global forestry sector makes significant contributions to forest sustainability, economic growth, and carbon storage, with a contribution of 1.5 trillion annually to the economy of the world (FAO, 2020). The sector is, however, currently under attack from invasive pests that have grown to become a central driver of forest degradation, most prominently in plantations whose nature is monoculture (Boydetal., 2013). Invasive species disrupt ecosystem stability, reduce timber productivity, and incur management expenses, with economic losses put at more than 1.5 trillion dollars annually to the world economy (FAO,2020). However, this sector is faced with increasing challenges from invasive pests, which have emerged as a major driver of forest degradation, particularly in monoculture plantations (Boydet al.,2013). Invasive species induce ecosystem instability, reduce timber productivity, and increase management costs, with economic losses of over 70 billion dollars every year globally (Bradshaw et al., 2016). Among the most damaging of these pests is the blue gum chalcid (*Leptocybe invasa* Fisher & La Salle), a strongly invasive wasp that has migrated aggressively across Eucalyptus-cultivating regions since its initial appearance in the Mediterranean in 2000 (Mendel et al., 2004).

*Leptocybe invasa* (Hymenoptera: Eulophidae) is a minute gall-forming wasp that infects juvenile Eucalyptus shoots and leaves, inducing abnormal growths known as galls (Nyeko et al., 2010). The galls disrupt nutrient and water transport, leading to stunted growth, leaf distortion, and tree death in severe cases (Dittrich-Schröder et al., 2018). The fast expansion of the pest, boosted by international trade in Eucalyptus seedlings and its elevated rate of breeding, has seen it infest over 40 nations within two decades, ranging across major timber-producing nations in Africa, Asia, and South America (Zheng et al., 2016). Across Africa alone, *L. invasa* has been found in a minimum of 15 countries, leading to considerable losses in commercial plantations (Hurley et al., 2016).

Zimbabwe's forestry sector, which contributes approximately 3% to the national GDP and supports over 100,000 livelihoods (ZimStat, 2021), relies heavily on Eucalyptus species for timber, pulpwood, and fuelwood production (Mushove et al., 2013). The fast-growing nature of Eucalyptus makes it a preferred species for reforestation and industrial use, particularly in regions with semi-arid climates (FAO, 2020). However, the emergence of *L. invasa* infestation in Zimbabwe in the years around 2015 has already raised serious concerns regarding the future sustainability of the plantations (Forestry Commission of Zimbabwe, 2018). Infestation has been correlated with lower quality wood, elevated susceptibility to secondary pathogens, and yield losses as high as 40% in heavily infested stands (Mutitu et al., 2020).

The economic impacts of *L. invasa* infestations are of particular interest given the reliance of Zimbabwe on wood exports, which generate foreign currency essential for the country (RBZ, 2022). Moreover, the effect of the pest extends beyond commercial losses, as rural livelihoods based on Eucalyptus for firewood and construction materials are threatened (Gumbo et al., 2019). There existed varied management measures, from chemical sprays, biological control agents such as *Megastigmus* wasps, to silvicultural treatments, which were inconsistent in effectiveness, highlighting the need for fact-based, place-specific interventions (Dittrich-Schröder et al., 2020).

Given these challenges, this study seeks to systematically assess the threat severity of *L. invasa* in Zimbabwe by examining its distribution, ecological impact, and economic consequences. By integrating field surveys, economic modeling, and stakeholder interviews, the research aims to provide a comprehensive framework for mitigating *L. invasa*'s effects on Zimbabwe's forestry industry. The findings will guide regional pest management practices while fostering sustainable forest management in line with the United Nations Sustainable Development Goals (SDGs), namely SDG 15 (Life on Land) and SDG 8 (Decent Work and Economic Growth) (UN, 2015).

## 1.3 PROBLEM STATEMENT AND JUSTIFICATION

### 1.3.1 Problem Statement

Zimbabwe's forestry industry faces a growing crisis due to *L. invasa* infestations, which severely undermine the health and productivity of economically vital Eucalyptus plantations. The pest's gall-forming activity not only stunts tree growth and deforms stems but also reduces wood density, directly diminishing the commercial value of timber (Mutitu et al., 2020). Despite efforts to control the pest with chemical control and released parasitoids like *Megastigmus* spp., the efforts have been inadequate, with reinfestation occurring rapidly due to the high reproductive potential and flexibility of the wasp (Zheng et al., 2016). Unless controlled, this insect infestation can cause a chain reaction of undesirable effects, including the loss of jobs in wood-based communities, increased production costs for forestry companies, and decreased competitiveness of Zimbabwe in the regional timber markets (Gumbo et al., 2019).

### 1.3.2 Justification

This study is critically justified by the pressing need to comprehensively assess the severity of *L. invasa* infestations and their multifaceted economic implications for Zimbabwe's forestry industry. While existing research on *L. invasa* in Africa has been primarily focused on South Africa and Kenya (Dittrich-Schröder et al., 2018; Nyeko et al., 2010), but there remains a broad information gap for Zimbabwe, where the impact of the pest on the economically valuable Eucalyptus industry is poorly estimated. By systematic evaluation of the pest distribution, level of infestation, and accompanying economic loss, this study will generate actionable evidence to inform the development of specific pest management interventions, promote improved sustainable forest management practices that increase ecosystem resilience, and generate evidence-based policy recommendations to minimize timber business financial losses. Moreover, the findings will bolster Zimbabwe's capacity for invasive species management, aligning with global frameworks such as the International Plant Protection Convention (IPPC) (FAO, 2020) and supporting the country's commitments to sustainable forest governance under international agreements like the United Nations Sustainable Development Goals (SDGs).

**Aim**

To assess the threat severity of *L. invasa* infestations on Zimbabwe's commercial forestry industry.

## 1.4 Objectives

1. To evaluate the distribution and prevalence of *L. invasa* across Nyanga, Manicaland district *Eucalyptus* plantations.
2. To assess the extent of damage caused by *L. invasa* to *Eucalyptus* trees in terms of growth reduction and timber quality.
3. To quantify the economic impact of *L. invasa* on Zimbabwe's timber production and export revenues.

## 1.5 Research questions

1. What is the current distribution and prevalence of *L. invasa* in Zimbabwe's *Eucalyptus* plantations?
2. What is the extent of damage caused by *L. invasa* to *Eucalyptus* trees in Zimbabwe?
3. What is the economic impact of *L. invasa* on Zimbabwe's forestry industry?

## 1.6 Hypothesis

**$H_0$:** There is no significant positive correlational relationship between *L. invasa* infestation and *Eucalyptus* tree mortality in Zimbabwe's forestry plantations.

**$H_1$:** There is a significant positive correlational relationship between *L. invasa* infestation and *Eucalyptus* tree mortality in Zimbabwe's forestry plantations.

**$H_0$:** The economic impact of *L. invasa* on Zimbabwe's forestry industry is not substantial, leading to reduced timber yields and export revenues.

**$H_1$:** The economic impact of *L. invasa* on Zimbabwe's forestry industry is substantial, leading to reduced timber yields and export revenues.

### 1.7 Significance of the study

This research is of great academic, economic, and policy importance, filling important knowledge and management gaps in the *L. invasa's* understanding and control in Zimbabwean forestry.

#### 1.7.1 Academic Contribution

The study presents new empirical evidence on the infestation severity, distribution patterns, and ecological effects of *L. invasa* in Zimbabwe, a geographical area underrepresented in current literature. While previous studies have examined the pest's effect in South Africa and East Africa (Dittrich-Schröder et al., 2018; Nyeko et al., 2010), this study provides the first full-scale assessment of its distribution and damage in Zimbabwean Eucalyptus plantations. Documenting infestation hotspots and the differences in tree susceptibility, the findings will enrich world entomological databases and facilitate comparative studies of invasive species in subtropical ecosystems.

#### 1.7.2 Policy and Industry Relevance

The research outcomes will feed directly into national forestry policy and integrated pest management (IPM) practice appropriate to the agroecological conditions in Zimbabwe. Because of the ineffective nature of current control measures (e.g., chemical sprays and foreign parasitoids), the work will produce evidence-based recommendations to policymakers in the Forestry Commission of Zimbabwe and Ministry of Environment. Together with this, forestry companies and plantation managers will be assisted by practical guidelines for early detection, monitoring protocols, and low-cost mitigation measures, with the capacity to lower production losses and maintain export competitiveness.

#### 1.7.3 Environmental Sustainability

By evaluating biological control potential, pest-resistant Eucalyptus clones, and silvicultural modifications, the study promotes ecological resilience of managed forests. The gall-producing activity of the pest not only reduces timber yields but also alters stand biodiversity by impairing tree defense mechanisms against secondary pests (Mutitu et al., 2020). This study is in line with Sustainable Development Goal (SDG) 15 (Life on Land) by proposing low-carbon, biodiversity-supporting options that reduce broad-spectrum pesticide use.

### 1.7.4 Economic Protection

The timber sector of Zimbabwe, worth more than USD 200 million per annum (ZimStat, 2021), is critically threatened by uncontrolled *L. invasa* infestations. This research estimates monetary losses in terms of lost log quality, raised management expenditures, and prospectively enforced export bans as a result of pest-driven trade restrictions. Through the establishment of cost-effective interventions, the research underpins the long-term sustainability of the sector, protecting employment for more than 100,000 people who rely on forestry (FAO, 2020). Furthermore, the findings may attract international funding for invasive species management under frameworks like the Global Environment Facility (GEF).

In summary, this study bridges science, policy, and industry practice, offering actionable insights to combat *L. invasa* while advancing Zimbabwe's commitment to sustainable forest management and climate-resilient agriculture.

## 1.8 Chapter summary

The chapter set the context for research, scope, and implication of examining the threat that *L. invasa* poses to the Zimbabwean forestry industry. Background showed the international reach of the pest and havoc within Eucalyptus woodlots, pinning hope on Zimbabwe's potential vulnerability from a timber trade and production viewpoint. The problem statement identified the emergent requirement of localized study because of the reported impact on the quality of timber and tree life, along with profit returns in the industry, over compounded by the failure of present-day management intervention due to unviability. The justification for the research identified its value in filling important knowledge gaps, most particularly the lack of Zimbabwean data on the distribution, economic effects, and sustainable mitigation options of *L. invasa*. The research bridges scientific inquiry and policy-oriented agendas by aligning with larger global initiatives like the International Plant Protection Convention (IPPC) and SDG 15. Objectives and research questions were framed to scientifically evaluate the incidence of pests, degree of damage, and economic impact. In contrast, hypotheses assume quantifiable interdependencies between infestations and tree mortality/economic losses. Finally, the significance section articulated the study's multidisciplinary value: advancing entomological research in Southern Africa, guiding industry and policy interventions, promoting ecological resilience, and protecting livelihoods tied to Zimbabwe's timber economy. Together, these elements lay a robust foundation for the subsequent chapters, detailing the study's methodology, findings, and recommendations.

## Chapter 2

## Literature review

### 2.1 INTRODUCTION

This chapter brings together existing research on *L. invasa* (blue gum chalcid) in relation to its biological characteristics, world distribution, and documented effects on Eucalyptus plantations with a special focus on Zimbabwe's forestry industry. The review compares the pest life cycle and invasion patterns, the deleterious effect on the physiology of trees and timber output, and the subsequent economic implications for timber economies. Furthermore, it analyses prevailing management practices, assessing their efficiency and limitations across geographical contexts. With the synching of global and regional scholarship, this analysis not only positions Zimbabwe's exposure in the broader context of scientific inquiry but also positions major knowledge lacunae specific to the nation's forestry sector, particularly localized distribution trends, economic impacts, and sustainable prevention strategies. This wide foundation supports the study's goals while emphasizing the necessity of developing targeted solutions to Zimbabwe's Eucalyptus plantations.

### 2.2 BIOLOGY AND GLOBAL SPREAD OF *LEPTOCYBE INVASA*

#### 2.2.1 Taxonomy and Life Cycle

*L. invasa* Fisher & La Salle (Hymenoptera: Eulophidae) is a minute gall-inducing wasp (1.1-1.4 mm in length) of the subfamily Tetrastichinae (Mendel et al., 2004). First identified within the Mediterranean region in 2000, the invasive pest has been found to be highly virulent to *Eucalyptus camaldulensis* plantations, where it was initially observed to cause severe damage (Mendel et al., 2004). The wasp's life cycle is characterized by rapid development and reproduction. Females lay eggs on the young leaves, petioles, and stems of Eucalyptus, inducing the formation of typical globular galls (3-5 mm in diameter) within 7-10 days (Nyeko et al., 2010). The galls induce disruption of the plant vascular tissue, preventing nutrient transportation and causing typical symptoms like leaf curling, shoot distortion, and strong growth inhibition (Dittrich-Schröder et al., 2018).

One of the factors contributing to the invasive success of the pest is its thelytokous parthenogenetic reproductive mode, where genetically identical female offspring are developed by unmated females (Zheng et al., 2016). This characteristic makes explosive population growth possible with a single female being able to generate 50-100 offspring per reproductive cycle and 3-5 generations annually in tropical climates (Hurley et al., 2016). The whole life cycle from egg to adult is completed extremely quickly, taking a mere 20-25 days under optimum temperature conditions (25-30°C), with adults surviving for 5-7 days (Mendel et al., 2004). As far as host specificity is concerned, *L. invasa* attacks young growth of several commercially important Eucalyptus spp., most significantly *E. camaldulensis*, *E. grandis,* and *E. tereticornis* (Nyeko et al., 2010). Some hybrid cultivars such as *E. grandis* × *E. urophylla* have exhibited partial resistance, attributed to their denser leaf cuticles that may provide a physical obstacle to oviposition (Dittrich-Schröder et al., 2020). Eucalyptus species and hybrid differential susceptibility has important applications in the management of plantations in infested regions.

### 2.2.2 Invasion History and Global Spread

#### 2.2.2.1 Dispersal Mechanisms and Invasive Capacity

*L. invasa* has shown remarkable invasive potential, with worldwide distribution within two decades of its first sighting. Two main factors have promoted this rapid invasion: (1) human-assisted spread through international trade of infested nursery material (Wingfield et al., 2015), and (2) the pest's high adaptability to varied climatic conditions, from tropical to Mediterranean climates (Hurley et al., 2016). These traits have allowed *L. invasa* to become established on multiple continents, capitalizing on the widespread planting of susceptible Eucalyptus species in commercial plantations.

#### 2.2.2.2 Chronological Sequence of the Invasion

The global spread of *L. invasa* followed a definite chronological pattern that reflects its potential for rapid colonization. The pest was first recorded in 2000 in Israel and Italy, where it caused extensive damage to plantations of *E. camaldulensis* (Mendel et al., 2004). Within two to five years (2002–2005), it had spread to East African nations like Uganda, Kenya, and Tanzania, where it was reported to cause severe yield losses in young plantations (Nyeko et al., 2010). By 2007–

2010, the pest had invaded main Eucalyptus-growing regions in South Africa, Brazil, and China, demonstrating its ability to break ecological barriers and establish itself in diverse habitats (Zheng et al., 2016). Zimbabwe recorded first confirmed infestations in 2015, and the Forestry Commission of Zimbabwe (FCZ, 2018) described outbreaks in key timber-producing regions, pointing to the continued expansion of the pest across southern Africa.

#### 2.2.2.3 Current Distribution and Establishment

The current global distribution of *L. invasa* encompasses over 40 countries, with devastating impacts being recorded in regions where Eucalyptus plantations form a significant component of the forestry sector. That the pest has taken hold over so many biogeographical realms is a testament to its ecological adaptability and the challenge in restricting its spread. On the African continent alone, *L. invasa* has been reported in 15 countries, with economic impacts varying by local forestry practices and climatic conditions (Hurley et al., 2016). Its continued range expansion highlights the importance of international cooperation in monitoring and controlling this invasive species.

**Table 2.1 Current Distribution of *L. invasa* in Africa**

| Country | First Reported | Major Affected Regions | Economic Impact |
|---|---|---|---|
| Uganda | 2002 | Central and Western Highlands | 30–40% yield loss in nurseries (Nyeko et al., 2010) |
| South Africa | 2007 | Mpumalanga, KwaZulu-Natal | $5M annual losses (Hurley et al., 2016) |
| Zimbabwe | 2015 | Manicaland, Mashonaland | 20% plantation area affected (FCZ, 2018) |

### 2.2.3 Factors Driving Spread in Zimbabwe

#### 2.2.3.1 Environmental and Anthropogenic Drivers

The establishment of *L. invasa* and its swift dissemination in Zimbabwe is traceable to both environmental and anthropogenic drivers. With their warm and humid climates, the eastern highlands of Zimbabwe are especially conducive to pest infestation (Mutitu et al., 2020). Such climatic conditions promote the wasp's reproduction cycles while at the same time stressing the host trees and making them more vulnerable to infestation. Coupled with this intrinsic vulnerability, weak phytosanitary management has facilitated pest movement across national boundaries. Unregulated exportation of diseased Eucalyptus nursery stock to adjacent countries has been identified as a major invasion route, with Forestry Commission of Zimbabwe (FCZ, 2018) noting that most early detections were reported in conjunction with main routes of trade and commercial nurseries.

#### 2.2.3.2 Future Projections and Potential Impacts

Existing modelling based on South Africa's invasion pattern indicates alarming potential for extension within Zimbabwe. In the absence of immediate and effective control measures, *L. invasa* is likely to infest nearly 90% of the nation's Eucalyptus plantations by the year 2030 (Hurley et al., 2016). This extensive infestation would be ruinous for Zimbabwe's forestry industry, likely to result in:

- Substantial decline in timber quality and volume
- Rise in the production costs of pest control
- Loss of economic viability of small-scale producers
- Negative impacts on downstream wood processing industries

These estimates highlight the urgency of unified national response measures to stem the spread of the pest and protect Zimbabwe's valuable forestry resources. The enforcement of robust quarantine rules and the cultivation of resistant Eucalyptus species will be crucial in stemming the spread of the pest and lessening its economic impacts.

## 2.3 IMPACTS OF *LEPTOCYBE INVASA* ON *EUCALYPTUS* PLANTATIONS

### 2.3.1 Ecological and Physiological Effects

Gall formation by *L. invasa* creates severe physiological stress in host plants, with resulting cascading ecological impacts. Morphogenesis of common globular galls (diameter 3-5 mm) on leaves and stems induces vascular tissue inhibition, leading to extreme loss of photosynthetic capacity (Dittrich-Schröder et al., 2018). The physiological damage appears as dwarfing, and in severely infested trees, it results in 30-50% height increment loss compared with uninfected trees. The compromised vitality of attacked trees induces ecological susceptibilities, particularly through the increased frequency of secondary infections. Mutitu et al.'s (2020) study demonstrates how Eucalyptus trees with galled infestations show increased vulnerability to opportunistic pathogens (such as fungi from the genus *Botryosphaeria* spp.) and wood borers, taking advantage of compromised defense capacities in stressed trees. Cumulative stress from such multi-trophic effects can result in plantation mortality rates of 10-20% in young stands (Nyeko et al., 2010), effectively modifying stand structure and ecosystem function in the zone.

### 2.3.2 Timber Quality and Productivity Losses

The economic impact of *L. invasa* infestation is best evidenced in measurable decreases in timber quality and plantation yields. Gall-induced stress promotes abnormal wood formation, resulting in reduced wood density (12-18% reduced in infested trees) and stem deformities such as twisting and bifurcation (Wingfield et al., 2015). These quality defects invariably downgrade timber from high-value saw log grades to lower-grade pulpwood or fuelwood, with attendant revenue losses of 30-60% per tree. At the plantation level, specific studies in South Africa and Kenya document yield losses of 20-40% over multiple harvest cycles (Hurley et al., 2016), with particularly severe consequences in commercially produced fast-growing clones of *E. grandis* and *E. camaldulensis.* The productivity declines are not only due to direct inhibitions to growth but also due to increased thinning requirements and declining stand uniformity, which enhance forest management and harvesting complexity. These quantifiable impacts on wood value and yield have rendered *L. invasa* a top economically damaging pest in tropical Eucalyptus silvicultural systems.

## 2.4 ECONOMIC IMPLICATIONS FOR TIMBER-DEPENDENT ECONOMIES

### 2.4.1 Direct Financial Losses

*L. invasa* infestations impose heavy economic burdens on commercial forest operations through different avenues. The most obvious economic impacts come from elevated cost of production, as plantation managers will expend funds on augmented pesticide application and replanting of heavily infested stands multiple times (FAO, 2020). These reaction measures commonly augment annual operating expenses by 15-25% in infested plantations. Most importantly, perhaps, the downgrading of wood quality by the pest creates deep value chain losses. As in Mozambique, where an estimated $15 million of annual losses accrued from *L. invasa* infestation, export revenues are reduced immediately through direct downgrading to pulpwood grades (Roux et al., 2015). Such quality deterioration hits hardest at foreign market competitiveness through increased outright rejection or discarding of lumber shipments with gall-related defects. The combined effect of higher input costs and reduced value of the product is a compounding financial constraint that poses a threat to the viability of commercial plantations in the affected regions.

### 2.4.2 Zimbabwe-Specific Risks

The economic vulnerability of Zimbabwe's forestry sector to *L. invasa* infestations is exceptionally high under the sector's structural framework. Contributing approximately 3% of national GDP (ZimStat, 2021), with *Eucalyptus* spp dominating 60% of plantation cover (FCZ, 2020), the sector is disproportionately vulnerable to unchecked pest multiplication. Analogues elsewhere suggest Zimbabwe could lose $8-12 million annually if current infestation trends continue unchecked. These projections are founded on:

- Direct forest value losses due to quality degradation
- Increased silvicultural costs for pest management
- Potential job losses in wood processing industries
- Reduced foreign exchange earnings from timber exports

High density of plantations of Eucalyptus in the highlands of the east in Zimbabwe, a previously stressed climate region - creates unique exposure, with stressed trees also being less gall resistant. Without immediate action, the cumulatively adverse economic impact is poised to destabilize rural economies based on forestry dependence and to harm Zimbabwe's role in regional timber marketplaces. This threat calls for especial requirement of economically sound management treatments uniquely responsive to Zimbabwe's unique ecological and economic condition.

## 2.5 MANAGEMENT STRATEGIES

### 2.5.1 Chemical Control

Current chemical control methods against *L. invasa* rely mostly on systemic insecticides, with neonicotinoids such as imidacloprid showing 60-80% short-term control of adult wasp populations (Dittrich-Schröder et al., 2020). Chemical controls have significant limitations, including: (1) high treatment costs (approximately $120-150/ha per application), (2) resistance development after 3-4 consecutive treatments, and (3) harmful non-target effects on beneficial arthropods and pollinators. Brazilian field research has shown that while chemical control will reduce gall formation by 40-50% in the first season, their effectiveness declines very rapidly if not accompanied by rotation with other forms of control (Zanuncio et al., 2016). The findings suggest that the use of chemical control should be incorporated within an effective IPM system.

### 2.5.2 Biological Control Mechanisms

Classical biological control using parasitoid wasps, such as *Selitrichodes neseri* and *Quadrastichus mendeli*, have been discovered with promising results in many invaded regions. South African plantations based on these biological control agents have 30-60% parasitism of *L. invasa* galls, inducing measurable reductions in pest numbers over 2-3 generations (Tooke et al., 2019). The parasitoids are host-specific and can establish self-sustaining populations, which have long-term controlling potential. However, Zimbabwe currently lacks: (1) indigenous efficacy data on parasitoid performance under a range of climatic regimes, (2) mass-rearing capability for natural enemies, and (3) guidelines on safe release and monitoring. Effective establishment of these biological control agents would require climate-matching research and accurate assessment of likely non-target effects on native hymenopteran fauna.

### 2.5.3 Silvicultural and Genetic Solutions

Preventive silvicultural measures have been some of the most sustainable management methods. The planting and cultivation of resistant Eucalyptus clones, particularly hybrids of *E. grandis* × *E. camaldulensis*, have reduced gall incidence by 50-70% in Israeli and South African plantations (Wingfield et al., 2015). The resistant clones possess three key defense traits: (1) the leaves have thicker cuticles that physically prevent oviposition, (2) higher concentrations of defensive terpenoids, and (3) hypersensitive reactions that abort developing galls. Complementary cultural practices such as optimized planting density (reduction to 800-1000 stems/ha), controlled irrigation to prevent succulent growth that is attractive to wasps, and sanitation cutting of heavily infested trees have had synergistic effects when combined with resistant stock (Dittrich-Schröder et al., 2020).

### 2.5.4 Gaps in Implementation in Zimbabwe

Zimbabwe's current response to *L. invasa* remains hampered by systemic impediments. The country lacks: (1) a national IPM policy standardized for addressing *L. invasa* (FCZ, 2020), (2) extension services to exchange management information with small-scale producers (who control ~35% of Eucalyptus plantations), and (3) research support for the generation of locally adapted solutions. According to a 2019 survey, 68% of Manicaland Province smallholder tree farmers could not identify *L. invasa* damage symptoms, reflecting critical awareness gaps (FCZ, 2020). Addressing these challenges will require institutional collaboration among the Forestry Commission, agriculture extension services, and wood industry players to build context-specific management guidelines.

## 2.6 RESEARCH GAPS

Current research on *L. invasa* has been largely ecological and management-oriented in East and Southern African countries with highly developed forestry industries, especially South Africa and Kenya, which has resulted in large gaps in knowledge as it pertains to the context of Zimbabwe. Notably absent are detailed studies following the pest's spread patterns through Zimbabwe's diverse agroecological zones that range from high-altitude humid to lowveld dry zones, each beset with distinctive microclimates that could potentially influence infestation patterns. Likewise, absent are serious studies of the pest's economic impacts along Zimbabwe's timber value chain, starting from primary production through processing to export markets, despite the sector being a notable player in the country's economy. Most critically, there is no organized evaluation of the cost-effectiveness and feasibility of various control strategies under Zimbabwe's particular socioeconomic environment, where resource levels and institutional capacities are fundamentally different from those of other surrounding nations. This absence of localized data has frustrated the development of tailored management strategies, forcing Zimbabwean farmers to implement control practices optimized for different ecological and economic environments. The present research fills these research lacunae by developing Zimbabwe-specific information on infestation ecology, economic impact, and management economics, hence facilitating evidence-based decision-making among both private cultivators and public sector forest managers. This study bases its inquiry on Zimbabwe's real plantation circumstances and market dynamics and will therefore yield feasible recommendations weighed between biological effectiveness and practical implementation difficulties and also in the contribution toward the creation of sustainable, context-relevant pest management systems.

## 2.7 CHAPTER SUMMARY

This chapter has provided a chronological overview of the current knowledge base concerning *L. invasa* and its impacts on the global Eucalyptus plantations, focusing particularly on the forestry sector of Zimbabwe. The examination began with the biological characteristics of the pest, including its taxonomy, mating, and gall induction mechanisms, thus its invasion rate and potential for damage. The discourse then followed the global invasion pattern of *L. invasa*, highlighting its recent establishment in Zimbabwe and the environmental factors underlying its spread within the country's plantation systems. Critical analysis of the pest's impacts expressed grave physiological stress on host trees, leading to reduced growth rates, increased mortality, and extreme reduction in timber quality. These effects' economic implications were explored, prioritizing both direct production losses and value chain-wide effects threatening Zimbabwe's timber-dependent economy. Current management strategies, including chemical, biological, and silvicultural approaches, were evaluated while emphasizing key deficiencies in Zimbabwe's institutional capacity and implementation frameworks.

The literature review identified three such knowledge gaps for Zimbabwe: (1) limited data on the distribution of infestation in different agroecological regions, (2) no in-depth economic impact assessments, and (3) no cost-benefit analysis of the control measures under local conditions. These knowledge gaps have constrained the development of effective, location-specific management strategies. The chapter then closes by positioning the current study as a response to these shortcomings, with evidence from it to inform both policy and day-to-day management decisions for Zimbabwe's forestry sector. By bringing together ecological, economic and management perspectives, this review establishes the theoretical foundation on which the empirical work in the subsequent chapters is built.

## Chapter 3

## Materials and methods

### 3.1 Introduction

This chapter presents the research design, population, sampling methods, data collection methods, instruments, data analysis methods, and ethical considerations used in determining the threat level of *L. invasa* on the forestry sector of Zimbabwe. The study objectives, which are to assess the distribution, damage extent, economic effect, and control measures of the pest on Eucalyptus plantations in Zimbabwe, guided the methodology.

### 3.2 Research design

This study adopted a mixed-methods research design, which integrates both quantitative and qualitative approaches to provide a comprehensive understanding of complex phenomena, in this case, the threat severity of *L. invasa* on Zimbabwe's forestry industry. Mixed-methods research is particularly valuable in environmental and agricultural studies where numerical measurements alone may not fully capture the socio-ecological dimensions of the issue (Tashakkori & Teddlie, 2010). Quantitative methods permitted the accumulation of measurable data regarding *L. invasa* distribution, prevalence, and economic impacts through the use of structured questionnaires, field surveys, and economic modeling. Parallel to this, qualitative methods including interviews and focus group discussions offered additional understanding of practical challenges, perceptions, and performance of pest management activities as perceived by forestry professionals and plantation field personnel. This framework supports triangulation, which enhances validity of outcomes through cross-confirmation of data from various sources (Creswell & Plano Clark, 2011). It also supports an analysis of how biological variables (e.g., infestation levels of pests) coincide with economic outcomes and human responses, and as such, it is appropriate for studies of natural resource management (Johnson, Onwuegbuzie, & Turner, 2007).

### 3.3 Study area

The study was carried out in Nyanga District, situated in the eastern highlands of Zimbabwe's Manicaland Province. This area is renowned for its varied ecological zones, including warm lowlands and cool highlands, which produce unique microclimates ideal for biological research. Microclimates are localized atmospheric conditions that differ from the surrounding general climate. They are often called "small-scale climates" that exist within a larger climate zone. To account for this ecological variability, sampling sites were selected across different altitudinal zones, ensuring representation of both warm and cool areas. This stratified approach allowed the study to capture the influence of microclimatic differences on L. invasa infestation and eucalyptus susceptibility. Nyanga hosts some of the most significant commercial eucalyptus plantations in the country, particularly those managed by Allied Timbers, making it a biologically rich and strategically important site for investigating pest impacts within Zimbabwe's forestry sector.

## 3.4 Target Population

The study sample for this research were a representative group of various stakeholders directly or indirectly involved in the management of Eucalyptus plantations and are thus well-placed to provide informed opinions concerning the severity of *L. invasa* infestations and related control practices. These included forestry plantation managers, responsible for overseeing daily plantation management and monitoring pest infestations; timber producers and timber exporters, who are directly impacted by the economic consequences of pest-infested timber, i.e., downgraded grade and rejected export consignments. Forestry Commission officers were also among the population, through their control and policy influence over forest health, pest management, and forest sustainable practices within Zimbabwe. In addition, entomologists and pest control experts from research institutes and agro-forestry agencies were targeted due to their technical knowledge of *L. invasa* biology, infestation pattern, and integrated pest management. Lastly, field technicians were included due to their on-the-job experience in pest identification, application of control, and documentation of data in plantation environments. Engaging this broad set of stakeholders was required to obtain a balanced view of the effect of the pest and to triangulate findings across administrative, scientific, and operational perspectives (Patton, 2015).

## 3.5 Sampling techniques and sample size

Purposive and stratified random sampling techniques were used in combination to achieve representativeness and the inclusion of expertise in this study. Purposive sampling was used to choose and nominate key informants such as forestry experts, plantation managers, entomologists, and field officers with specialized experience and knowledge on pest management in Eucalyptus. This non-probability method is very effective in qualitative research when the purpose is to get rich, detailed information from participants who have firsthand experience with the subject of study (Palinkas et al., 2015). For the quantitative part, stratified random sampling was applied to sample Eucalyptus plantations by geographic area (Manicaland) and plantation size (small-scale, medium-scale, and large-scale operations). By stratifying by geographic area and plantation size, the study captured variability in levels of infestation across different ecological zones and operating scales. Data were collected using structured questionnaires and field assessment from a total of 10 plantations, on *L. invasa* distribution, damage severity, and economic implications. For the qualitative component, 15 key informant interviews were conducted with purposively sampled forestry experts, including government officials, pest control specialists, and senior field officers. These interviews provided contextual information on pest dynamics, pest management issues, and the effectiveness of current mitigation strategies. The application of these sampling techniques complemented one another to increase the validity and reliability of the findings by employing both statistical representativeness and expert-informed views (Etikan, Musa, & Alkassim, 2016).

## 3.6 DATA COLLECTION METHODS

### 3.6.1 Quantitative Data Collection

#### a) Questionnaire Surveys

Questionnaires were used for the gathering of quantitative data on the spread and impact of *L. invasa* from a particular group of forestry practitioners like plantation managers, pest control officers, forestry technicians, and other key stakeholders in the selected Eucalyptus-growing regions in Manicaland Province. The respondents were selected based on experience and actual involvement in plantation management and pest control so that they could offer credible and informed responses.

Questionnaires were drawn up to collect quantitative and categorical data on severity of infestation and spread. The respondents were asked to give an estimate of the percentage of *L. invasa*-affected trees in their plantations, categorize gall severity using a Likert scale (from "none" to "severe"), and supply information on tree performance indicators of growth such as average tree height and DBH. This allowed comparison of growth perceived in infested and uninfested plots, a proxy for biological growth measurement. The survey also included questions on tree age, plantation elevation, and climate, providing evidence on patterns of infestation by various ecological zones.

**b) Self-reporting of timber quality assessment**

The second section of the questionnaire referred to timber quality degradation due to pest infestation. Respondents provided self-report data on the extent of physical defects in felled timber, including the prevalence of cracks, warping, and gall-caused deformations. They were also asked to comment on changes in fiber density, strength, and market price of timber from infested trees, based on a scale-based assessment of severity levels.

This approach enabled the research to gather comparable experience-based quantitative data from operators directly engaged in Eucalyptus production. While not an alternative to testing in the laboratory, self-report measures by trained operators offered informative practical data on the effect of *L. invasa* on timber quality in the field. Quantification of economic loss as well as data on the evaluation of presently utilized mitigation practices on the Zimbabwean forestry sector guided the information gathered.

### 3.6.2 Qualitative Data Collection

**a) Semi-structured Interviews**

The semi-structured interviews were also carried out on a variety of key informants, such as forestry specialists, plantation managers, pest control staff, and field technicians. The participants were chosen for their active role in managing Eucalyptus plantations and pest control. Interviews were conducted in order to have in-depth opinions regarding the effects of *L. invasa* on both the ecological and economic sides of the plantations. The questions during the interview were open-ended to allow the respondents to discuss their personal experience with the pest, pest control problems, and their perception of current control actions. The open-ended question design was most appropriate to explore in-depth complicated issues, such as perceived efficacy of pest management practice, awareness of the infestation of the pest, and difficulty in lessening its impact on different plantation environments. The interviews also provided qualitative data on local adaptation of pest control practices and how practices were influenced by the scale of operations (Palinkas et al., 2015).

**b) Document Review**

Apart from interviews, there was also an intensive examination of documents to supplement the main data. These included Forestry Commission reports with the national and regional plans for pest control and pest control guidelines that include suggested practices for handling *L. invasa.* Existing research papers on *L. invasa* infestation levels, impacts on the health of *Eucalyptus*, and control options were examined. Document review helped position findings from interviews into perspective by providing historical context to pest outbreaks, severity of infestation trends, and previous control measures that had been enacted. Document review also revealed the policy context that had informed pest control efforts as well as challenges confronting plantation managers and owners in their enactment of recommended practices.

Through the integration of interviews and documentary analysis, the research provided an enhanced understanding of the issues at hand, bringing both personal understanding and a more general institutional level of understanding regarding pest management.

### 3.6.3 Field and laboratory methods

The impact of *L. invasa* on *Eucalyptus* plantations in Nyanga District was thoroughly biologically assessed using both field-based and laboratory-based methods in order to successfully accomplish objectives 1 and 2.

Thirty eucalyptus trees were methodically chosen from each Nyanga plantation site for the field sampling stage. A representative sample of both clearly impacted and healthy trees was ensured by selecting these trees based on outward indications of pest damage. In-depth observations were taken of every tree, noting any galls, leaf curling, shoot abnormalities, and other general indications of pest infestation. Gall density was measured using a standardized measurement technique that ensured uniformity across all sampled trees by counting galls within a 30-cm segment of branch. This technique made it possible to gather trustworthy information on the distribution of galls and the prevalence of pests.

In order to assess the physiological impacts of *L. invasa*, quantitative data on tree growth parameters were gathered as part of the growth assessment. A clinometer was used to record tree height, and a diameter tape was used to measure the diameter at breast height (DBH). In order to facilitate comparative analysis, these measurements were made for both infested and non-infested trees.

Gall samples were meticulously removed from infected branches for the microscopic examination, and they were promptly preserved in 70% ethanol to stop tissue deterioration. Under a stereomicroscope with a 40× magnification, the preserved samples were dissected in a controlled laboratory environment. Internal larval chambers, necrotic tissue sections, and visible vascular tissue disruption were all made possible as a result. The anatomical details shed light on the ways that gall formation impairs the internal physiology of the tree, impacting structural integrity and nutrient transport.

### 3.7 Research Instruments

#### Key Informant Interview Guide

The interview guide was constructed to facilitate semi-structured interviews with informant key figures such as plantation managers, pest control officers, and forestry experts. The guide had open-ended questions that elicited elaborative answers toward the ecological and economic impacts of *L. invasa*. Some of the key issues addressed in the guide included the control measures in place that were being used and how effective they were thought to be, institutional responses to the pest infestation, and challenges plantation managers faced in managing *L. invasa*. Open-ended questions allowed for maneuverability, which allowed respondents to articulate their personal experiences and perceptions of the impact of the pest, as well as revealing loopholes in current pest management strategies. This is an appropriate way of collecting contextual information that cannot be obtained through systematic surveys (Kvale & Brinkmann, 2009).

**Questionnaires**

Quantitative and qualitative data were collected using two distinct questionnaires. The quantitative questionnaire contained closed questions that provided quantifiable data on variables such as the number of galls, infection percentage of trees, and alterations in timber quality. These questions allowed for easy statistical analysis of the intensity of the infestation and its impact on tree growth. Alternatively, the qualitative questionnaire contained open-ended questions, which provided participants with the opportunity to describe in detail their experience with the pest and pest control measures. This blended approach permitted greater improved understanding of both the quantitative impact of the pest and individual perspectives of the participants. (Creswell, 2013).

**c. Field Observation Checklist**

To guarantee that all pertinent indications of *L. invasa* infestation were consistently noted during plantation inspections, a systematic field observation checklist was created. Certain biological symptoms, including gall formation, leaf curling, shoot dieback, and tree mortality, were recorded by this instrument. To enable systematic and repeatable data collection across various plantation sites, observers used the checklist to record the existence, location, and severity of each symptom per tree. The checklist reduced observer bias and made sure that all important signs of pest damage were evaluated consistently by standardizing symptom identification.

**d. Gall density recording sheet**

The number of galls on a few chosen branches was counted using a gall density recording sheet in order to measure the extent of the infestation. A 30-cm section of randomly chosen branches from each sampled eucalyptus tree was inspected, and any galls that were visible were noted. The tree ID, branch location, and total number of galls observed were all included in each entry on the sheet. This process supported statistical comparisons between infested and non-infested trees and enabled the objective measurement of pest pressure on individual trees. The biological relationship between infestation levels and plant development was then examined by correlating gall counts with tree growth data (DBH and height).

**e. Stereomicroscope and dissection tools**

Using a 40× magnification stereomicroscope and precision dissection instruments, a thorough anatomical examination of gall samples was carried out. Field-collected gall samples were preserved in 70% ethanol before being dissected to reveal internal structures. The samples were carefully opened with scalpels and fine forceps to expose any vascular disruption within the galled plant parts, dead or decaying tissues, and larval chambers. These findings contributed to the understanding of how *L. invasa* disrupts host tree nutrient transport. In order to provide scientific visual proof of internal damage, the final report used digital imaging software that was connected to the microscope to record microscopic observations. This approach gave the field-based visual evaluations more physiological and anatomical depth.

## 3.8 DATA ANALYSIS

### 3.8.1 Quantitative Data

Using SPSS Version 28, a combination of descriptive and inferential statistical techniques was used to guarantee reliable interpretation of biological and field data. Before analysis, information on gall density, tree growth metrics (like height and diameter at breast height, or DBH), and indicators of timber quality were gathered and cleaned. To give a general picture of infestation levels and variability among sampled trees, descriptive statistics were first used to summarize central tendencies and dispersion by computing means, standard deviations, and percentages. In order to evaluate the biological effect of *L. invasa* on tree growth, a one-way Analysis of Variance (ANOVA) was performed to see if the height and DBH of infested and uninfested trees differed statistically significantly. This made it possible to compare growth suppression brought on by infestation objectively. With significance thresholds set at $p < 0.05$, ANOVA outputs included both F-values and p-values. To look into possible connections between gall density and tree growth metrics, correlation analysis was also used. The degree and direction of the association between infestation severity and both DBH and tree height were ascertained using Pearson's correlation coefficients. Furthermore, trends between infestation levels and timber defects like cracks, deformities, and fiber degradation were visually interpreted using scatter plots and cross-tabulations. Together, these methods improved the study's scientific rigor and biological relevance by offering a quantitative and visual foundation for interpreting the pest's impact.

### 3.8.2 Qualitative Data

The qualitative data from the focus group discussions and semi-structured interviews were coded through thematic analysis. The responses were first transcribed and then coded with the aid of NVivo software, wherefrom meaningful themes and trends in the data were identified. This method was employed because it is best suited for exploring complex, context-dependent data, such as stakeholders' attitudes towards the pest and pest control activity.

The coding involved identifying and labeling important text segments, which were then grouped according to general themes. The primary themes that were found are:

- ❖ **Pest Spread Mechanisms:** This theme was employed in understanding how *L. invasa* is distributed across plantations, e.g., local weather conditions, forestry operations, and how vector insects are engaged.
- ❖ **Control Challenges:** This sub-theme captured the challenges of plantation managers and pest control specialists in managing the pest, including lack of resources, poor access to effective chemicals, and access problems to far-flung plantation regions.
- ❖ **Improvements Recommended:** The participants recommended that pest control could be improved by enhancing monitoring systems, application of integrated pest management (IPM) methods, and raising community awareness.

By coding and categorizing the responses, the thematic analysis revealed critical insights into the perceived barriers to effective pest management and recommendations for more sustainable control strategies (Braun & Clarke, 2006). This mixed-methods approach to data analysis enabled the integration of numerical and narrative data, providing a well-rounded understanding of the impact of *L. invasa* on Zimbabwe’s forestry industry.

## 3.9 Reliability and validity

Maintaining reliability and validity are necessary to maintain the rigor and credibility of research results. Various steps were employed in this study to enhance them.

### 3.9.1 Reliability

To maintain reliability, or consistency and reproducibility of findings, the research used standardized procedures and processes for all the plantations. These included the gall count survey checklist and the measurements of the trees, which were applied equally during every field survey. Use of similar protocols in data collection, for instance, measurement of the tree height and DBH, and recording the infestation level, enabled results to be replicated if the study were repeated under the same circumstances. Pre-testing of the questionnaire and interview guides also occurred before actual data collection. Pre-testing was conducted on a small number of respondents that simulated the study population. This helped identify any inconsistency or ambivalence in the questions so that alterations could be done to improve clarity and consistency before the full-scale study was done (Creswell, 2013).

### 3.9.2 Validity

Validity is necessary to ensure that research captures what it is trying to measure and conclusions are warranted. Different steps were followed in this study to maximize validity:

**Triangulation of Sources of Data:** To strengthen the validity of the findings, triangulation was utilized through the collection of multiple data sources. These included field data, key informant interviews, and documents such as Forestry Commission reports and guidelines for pest management. Triangulation facilitates cross-validation of findings from different sources so that conclusions are properly supported and not based on a single perspective (Flick, 2018).

**Expert Review of Research Instruments:** Before the data collection process, the survey checklist, questionnaires, and interview guides were expert-reviewed by forestry, pest management, and data collection technique professionals. Their review made sure that the instruments were appropriate and applicable to the purpose of the study. The expert review helped identify any gaps in the questions or measurement methods and made sure that the instruments accurately captured the necessary data related to the purpose of the research (Cohen et al., 2011).

These methods were established to ensure that information gathered under this study were reliable and valid and thus generated robust and credible results that can be utilized in informing pest control in Zimbabwean Eucalyptus plantations.

### 3.10 Ethical considerations

Ethical considerations are essential in ensuring that the research is conducted responsibly, respecting the rights and dignity of all participants involved. In this study, several ethical protocols were followed to ensure the integrity of the research process.

#### 3.10.1 Informed consent

Before participation in any aspect of the study, all the participants were provided with extensive information about the aim of the study, procedures, potential risks, and benefits. Informed consent was provided by each participant, meaning that they willingly participated and with full awareness of what was entailed in the study. Participants were made aware of their right to withdraw from the study at any point without incurring any penalty, which guaranteed their participation to be voluntary.

#### 3.10.2 Confidentiality

Confidentiality was maintained in the study to protect the privacy of the participants. The personal data was anonymized, and the identifying details were removed from the data. Only aggregate data were presented to prevent the identification of individual participants. In this way, the study was able to fulfill the ethical expectations of data privacy and protecting personal information.

#### 3.10.4 Voluntary participation

It was a totally voluntary involvement in the study. The participants were informed that they could withdraw from the study at any point without loss of benefits or reprisal. This allowed the individuals to participate at their own comfort level, knowing that they were in control of their input into the research process.

By following these ethical guidelines, the study maintained high standards of ethical integrity, and all of the participants were treated with dignity and their rights upheld during the research process.

### 3.11 Chapter summary

Chapter 3 of this study outlined the research methodology employed to assess the threat severity of *L. invasa* on Zimbabwe's forestry industry. The chapter began by detailing the research design, which utilized a mixed-methods approach, combining both quantitative and qualitative methods to provide a comprehensive understanding of the pest's impact. The research area was focused on chosen Eucalyptus plantations in Manicaland, chosen due to the presence of the pest and the importance of timber production in the area. The population of interest included forestry planners, timber entrepreneurs, entomologists, among other key individuals involved in the control of pests and production of Eucalyptus. Purposive sampling for expert selection was employed to facilitate representation and thickness, while stratified random sampling was employed in the selection of plantations based on geographic location and size. In data collection, both qualitative and quantitative methods were utilized. Quantitative data were gathered through field surveys, timber quality surveys, and economic impact studies, with SPSS and Excel used in data analysis. Qualitative data were gathered through semi-structured interviews and document reviews, and thematic analysis was conducted through NVivo software. Reliability and validity were ensured through the use of standardized tools, peer review, and triangulation of data sources, increasing the credibility of the findings. The study also addressed key ethical issues, including obtaining ethical clearance, obtaining informed consent, confidentiality, and voluntary participation. As a whole, this chapter gave a comprehensive description of the research design, data collection, and ethical principles used in the study, laying the ground for the analysis and reporting of findings in the ensuing chapters.

# Chapter 4

# Results

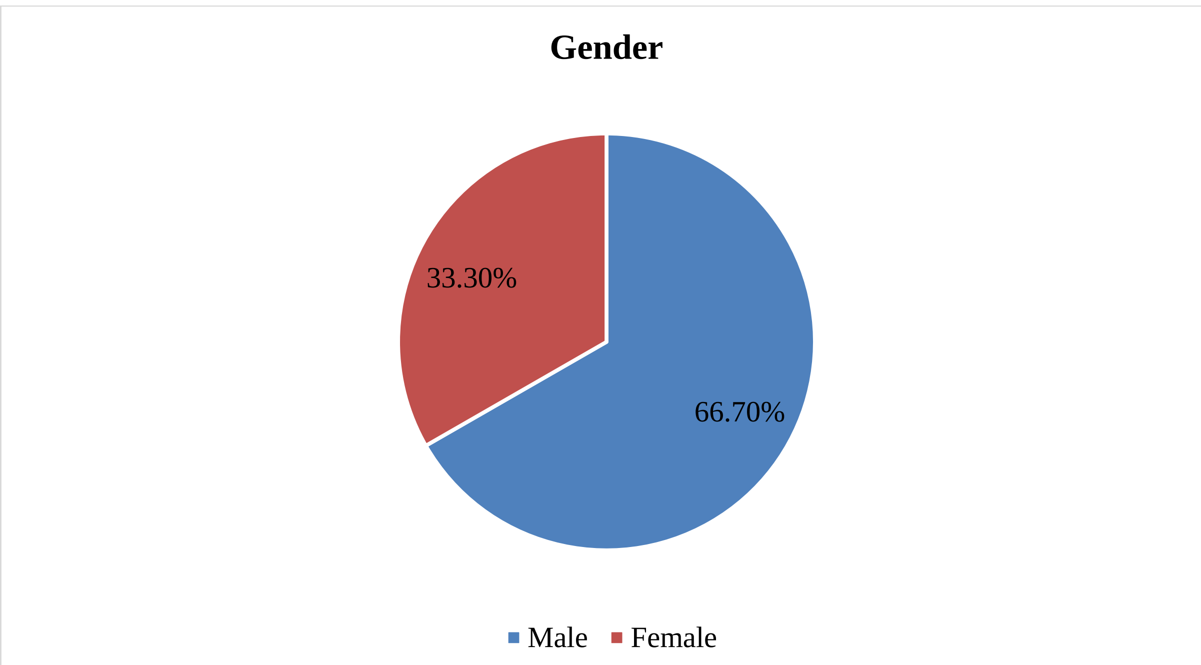
## 4.1 Introduction

This chapter discusses the findings of research work conducted on the impact of *L. invasa* on Zimbabwean *Eucalyptus* plantations. The findings are drawn from evidence provided through surveys and key informant interviews. The chapter is structured to address the precise research objectives and enlighten readers on the spread of the infestation, the impact on the growth of the trees and the quality of the timber, economic impact, and available mitigation efforts.

## 4.2 RESPONDENT DEMOGRAPHIC INFORMATION

### 4.2.1 Gender distribution

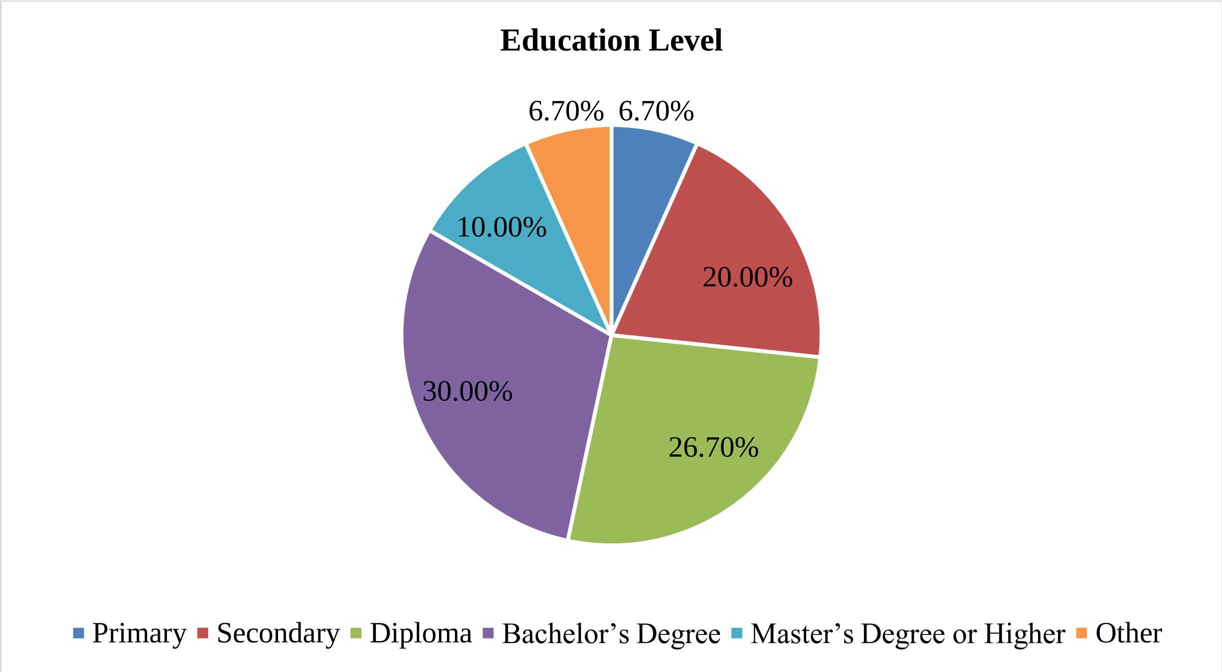
Table 1: Gender Distribution




The gender breakdown of the respondents indicates that 66.7% were men and only 33.3% were women. This indicates that the forestry and plantation management industry is still male-dominated. This is a trend that aligns with broader gender imbalances that are generally achieved in agriculture and natural resource-based industries, particularly in developing countries like Zimbabwe. The underrepresentation of women in this industry can be attributed to a combination of factors like cultural expectations, decreased access to land and finance, and fewer opportunities for training and leadership in forestry. This gender disparity could have policy implications regarding inclusion and diversity within the sector's decision-making.

### 4.2.2 Level of education

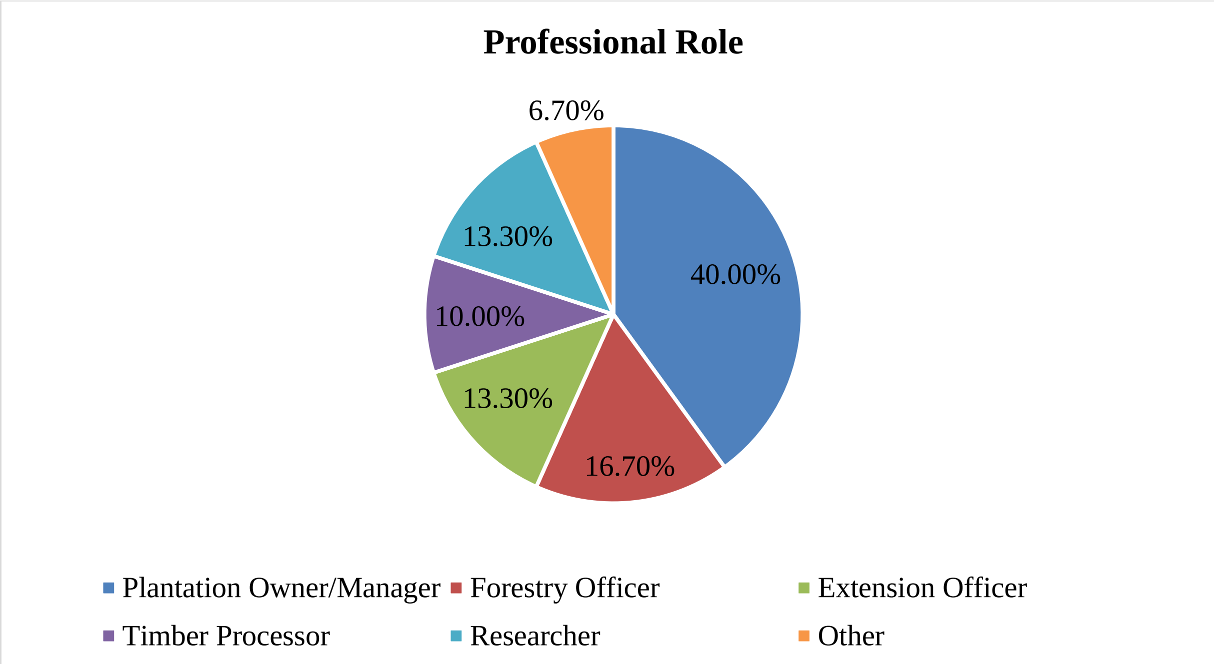
Table 2: Level of Education




The educational level among the respondents identifies that the greater part of respondents (56.7%) reached tertiary level that encompasses diploma (26.7%), bachelor degree (30.0%), and master's degree or higher holders (10.0%). It indicates that more than half of individuals involved in forestry or plantation management have acquired formal education post-secondary school. Such a trend reflects a relatively well-educated workforce in the sector, which can enhance the capacity to understand and respond appropriately to technical and scientific problems, such as pest infestations such as *L. invasa*. The presence of educated professionals can enhance the use of integrated pest management practices and sustainable forestry operations.

### 4.2.3 Professional role

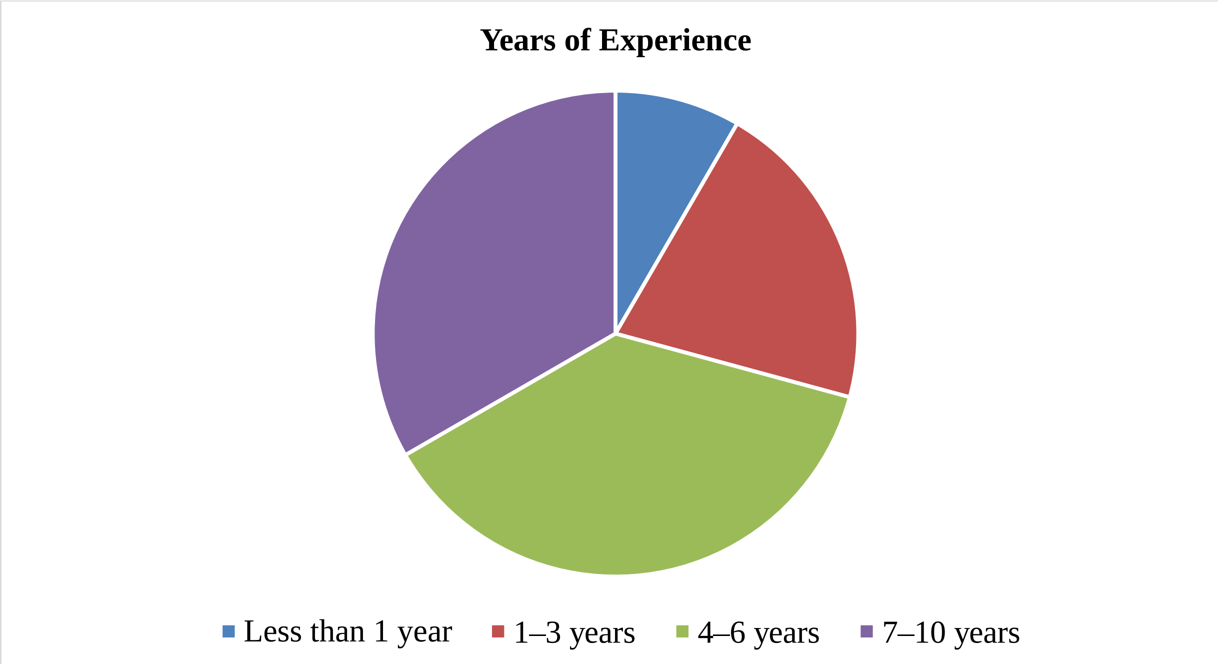
Table 3: Professional Role




The data show that a majority of respondents (40.0%) were plantation owners or managers, then forestry officers (16.7%), researchers and extension officers (13.3% each), timber processors (10.0%), and others (6.7%). Having a majority of plantation owners or managers among the respondents enhances the validity and usefulness of the findings since these are individuals who are directly involved in the day-to-day running and upkeep of plantations. Their first-hand exposure to pest infestations, such as *L. invasa*, provides relevant information on the on-ground practical concerns, economic impacts, and control methods taken on the ground. The inclusion of professionals such as forestry officers and researchers provide additional depth and technical perspectives into the data, allowing for greater clarity of the effect of the pest and response measures of the industry.

#### 4.2.4 Years of experience in forestry or plantation management

Table 4: Years of Experience in Forestry or Plantation Management




The data indicate that a majority of respondents (76.7%) have more than 4 years' experience in plantation or forest management, and 30.0% of them have 4 to 6 years, 26.7% have 7 to 10 years, and 20.0% have more than 10 years of experience. This high percentage of experienced participants suggests that the responses are from substantial real-world experience and long-term exposure to plantation systems. Thus, the information presented on the impact of *L. invasa* and efficacy of various management measures will likely be authoritative and well-informed. The differentiation by level of experience also ensures a neutral perspective, both of present trends and long-term changes observed in the industry.

## 4.2 Distribution and prevalence of *L. invasa*

### 4.2.1 Prevalence and distribution of *L. invasa*

Table 5: Prevalence and Distribution of *L. invasa*

| Statement | Min | Max | Mean | SD | N |
|---|---|---|---|---|---|
| *L. invasa* observed in the plantation in the last 12 months | 1 | 5 | 4.3 | 0.7 | 30 |
| The infestation is widespread across different areas of the plantation | 1 | 5 | 4.1 | 0.8 | 30 |
| *L. invasa* affects a significant percentage of trees | 1 | 5 | 3.9 | 0.9 | 30 |

| | | | | | |
|---|---|---|---|---|---|
| The infestation is increasing over time | 1 | 5 | 4.2 | 0.6 | 30 |

Respondents demonstrated high awareness and concern regarding L. invasa infestations. The observation of the pest over the last 12 months received a mean score of 4.3 (SD = 0.7), indicating strong consensus on its presence. Perceptions of increasing infestation over time were similarly high (mean = 4.2, SD = 0.6), reflecting growing concern. The distribution of the pest across the plantation was perceived as widespread, with a mean of 4.1 (SD = 0.8), while the prevalence, or proportion of trees affected, averaged 3.9 (SD = 0.9). The high mean values and low standard deviations across all statements indicate consistent responses, confirming both the severity and extensive spread of L. invasa within the plantations surveyed.

### 4.2.2 Infestation Rate of *L. invasa* by tree age and location

Table 6: Infestation rate of *L. invasa* by Tree Age and Location

| Factor | No Infestation | Low Infestation | Moderate Infestation | High Infestation | Not Applicable |
|---|---|---|---|---|---|
| 1. Age of Tree (1-5 years) | 0 | 5 | 10 | 10 | 5 |
| 2. Age of Tree (6-15 years) | 5 | 10 | 5 | 5 | 10 |
| 3. Age of Tree (16+ years) | 0 | 2 | 5 | 10 | 13 |
| 4. Location (Low altitude) | 5 | 8 | 7 | 5 | 5 |
| 5.Location (High altitude) | 0 | 2 | 7 | 15 | 6 |

The infestation of *L. invasa* across different tree ages and locations reveals some significant trends. In 6-15-year-old trees, the majority (15 out of 30) were free or had low levels of infestation, suggesting that mature trees are less likely to be infested by the pest. In contrast, 1-5-year-old trees exhibited a more even spread of moderate to high infestations (20 of 30), indicating that young trees are particularly vulnerable. Older trees (16+ years) exhibited a higher incidence of high infestations, with 10 of 30 trees in this group. Geographically, high-elevation plantations were more densely infested by *L. invasa*, with 15 respondents reporting high infestation levels. Plantations at lower altitudes, however, were more evenly distributed, with moderate infestations more frequent (7 of 30). These findings suggest that both tree age and plantation situation are significant factors in the incidence and severity of *L. invasa* infestations.

## 4.3 Impact on tree growth and timber quality

The interviewees all agree that *L. invasa* has caused observable reductions in tree height and DBH. The interviewees were also asked to rate statements concerning the impact of *L. invasa* on tree growth, and the following were the data collected:

### 4.3.1 Impact on tree growth

Table 7: Impact on Tree Growth

| Statement | Min | Max | Mean | SD | N |
|---|---|---|---|---|---|
| The presence of *L. invasa* has reduced tree height growth | 1 | 5 | 4.2 | 0.7 | 30 |
| DBH of infested trees is smaller compared to non-infested trees | 1 | 5 | 4.1 | 0.8 | 30 |
| Infestation has caused stunted growth in trees | 1 | 5 | 4.3 | 0.7 | 30 |
| Infested trees show slower growth compared to healthy trees | 1 | 5 | 4.2 | 0.6 | 30 |

The responses indicate that the majority of the participants have strong agreement and agreement that *L. invasa* has a significant impact on tree growth. With the mean score ranging from 4.1 to 4.3 out of 5, it is safe to say that tree height, DBH (Diameter at Breast Height), stunted growth, and slowed growth rate are all significantly influenced by infestation by the pest. The relatively low standard deviations (0.6-0.8) show that there is strong consensus among the respondents, once again emphasizing the uniformity in the perceived impact of *L. invasa* on tree growth.

### 4.3.2 Impact on timber quality

Table 8: Impact on Timber Quality

| Statement | Min | Max | Mean | SD | N |
|---|---|---|---|---|---|
| The infestation has caused cracks in the timber | 1 | 5 | 4.0 | 0.8 | 30 |
| The infestation has caused deformities in the timber | 1 | 5 | 4.1 | 0.7 | 30 |

| | | | | | |
|---|---|---|---|---|---|
| The fiber quality of infested timber is reduced | 1 | 5 | 4.2 | 0.7 | 30 |

As the table shows, the majority of the respondents had high to moderate damage to the wood caused by *L. invasa*. With average ratings ranging from 4.0 to 4.2, the infestation leads to observable defects in the wood in the form of cracks, deformities, and fiber quality deterioration. Again, the relatively low standard deviations (0.7-0.8) indicate that there is general consensus among the respondents on the negative impact of *L. invasa* on timber quality. Timber quality and tree growth are impacted greatly by *L. invasa,* as indicated by the high mean scores and homogeneity of response in the sample. The pest lowers tree height and DBH, stunts growth, and hinders development. Similarly, it induces serious defects in wood, including cracks, deformities, and poor fiber quality. These findings emphasize the importance of managing the infestation in order to minimize its adverse effects on tree health and wood production.

### 4.3.3 Perceived impact on timber quality

Table 9: Impact on Timber Quality

| Statement | No Impact | Slight Impact | Moderate Impact | High Impact | Severe Impact |
|---|---|---|---|---|---|
| Damage to wood structure (cracks, holes) | 2 | 5 | 10 | 8 | 5 |
| Impact on timber quality (density, fiber quality) | 3 | 4 | 8 | 10 | 5 |
| Negative impact on timber appearance (deformities) | 3 | 6 | 7 | 9 | 5 |
| Overall timber yield affected | 4 | 5 | 8 | 9 | 4 |

The results show that *L. invasa* imposes significant effects on timber quality in various ways. In the wood structure damage, 43.3% of the respondents (10 out of 23) reported moderate to high effects, meaning holes and cracks caused by infestation are a noticeable problem, which can reduce the strength and utilization of the wood. For timber quality (fiber and density), 50% of the respondents (18 of 30) indicated moderate to extreme impact, mirroring the high level of degradation in the strength of the fibers, which can influence the durability and marketability of the timber. Timber appearance was also equally impacted, as 40% of the respondents (14 of 30) indicated moderate to extreme deformities. These deformities can reduce the timber's aesthetic value, making it less desirable for high-value markets. Lastly, overall timber yield was impacted, with 43.3% of respondents (13 out of 30) perceiving a moderate to extreme reduction in yield, meaning that the infestation has resulted in less timber being produced, thereby impacting the profitability of the plantation. These facts refer to the great impact of *L. invasa* on the timber industry, changing the physical properties, marketability, and productivity of the trees. These findings emphasize the need for special pest management actions in order to avoid additional loss in timber quality and quantity.

### 4.4 Economic impact of *L. invasa*

#### 4.4.1 Financial Losses Due to Pest Infestation

Table 10: Financial Losses Due to Pest Infestation

| Statement | Min | Max | Mean | SD | n |
|---|---|---|---|---|---|
| The pest infestation has reduced overall timber production | 1 | 5 | 4.2 | 0.8 | 30 |
| Pest control costs have increased significantly | 1 | 5 | 4.3 | 0.7 | 30 |
| Pest infestation has lowered timber market prices | 1 | 5 | 4.1 | 0.7 | 30 |
| Financial losses have affected plantation profitability | 1 | 5 | 4.2 | 0.8 | 30 |

The data suggests a significant economic impact of *L. invasa* to the plantation business. The decline in overall timber production had an extremely high mean rating of 4.2 (SD = 0.8), or that most of the respondents agree that the infestation has highly reduced timber production. This lowered production can actually lead to losses for plantation entrepreneurs. Similarly, increased pest control expenditure also received a high mean rating of 4.3 (SD = 0.7), with respondents agreeing that pest control has led to higher expenditure, further suffocating financial resources. Additionally, the decrease in timber market prices (mean = 4.1, SD = 0.7) reveals the poor quality of timber which, inevitably, has led to a loss in value, affecting profits earned from the sale of timber. Finally, plantation profitability lost money with a mean of 4.2 (SD = 0.8), again validating the proposition that the combined effect of diminished yield, increased cost, and decreased price substantially undermined the profitability of plantations. This figure represents the extensive and negative economic consequence of the pest outbreak in various aspects of plantation operations. The increasing costs of pest control and decreasing market and production prices are a response to the need for enhanced efficiency of control activities in order to maintain the timber industry financially sound and prevent it from depreciation.

Table 11 illustrates that the loss of timber quality has resulted in heavy losses in export earnings, and also timeliness of cutting down timber resulted in losses.

Table 11: Revenue Impact of *L. invasa*

| Statement | No Impact | Slight Impact | Moderate Impact | High Impact | Severe Impact |
|---|---|---|---|---|---|
| 1. Reduction in timber quality impacted export revenues | 2 | 5 | 8 | 10 | 5 |
| 2. Economic losses affect plantation profitability | 3 | 4 | 6 | 10 | 7 |
| 3. Infestation caused delays in timber harvesting | 1 | 4 | 7 | 11 | 7 |

The impact of *L. invasa* on plantation yields is significant, as evidenced by the feedback from the majority of respondents in the survey. Up to 43.3% of the respondents reported that the drop in timber quality had an extreme to high impact on export revenues, while another 26.7% estimated it had a moderate impact. This emphasizes that, in the case of most of the plantations, quality issues generated because of infestation directly hurt their ability for generating revenue via export. This extra financial stress is also affirmed by 53.3% of the participants, who also agree that infestation had harsh to moderate implications in terms of profitability of the plantations with 23.3% incurring serious financial loss. Only 10% of the respondents said that there was no effect at all, implying that economic losses due to *L. invasa* infestation are endemic across the plantations. Additionally, 60% of respondents reported moderate to extreme delays in harvesting timber due to the infestation, further constraining plantation operations and cash flows. Specifically, 23.3% of them found delays severe and 36.7% found them high, which means these delays are not just economic but also operational. The outcomes incontrovertibly demonstrate that the economic and operational impacts of *L. invasa* reach far and wide, touching timber quality and export revenue as much as plantation profitability and harvesting programs. These results underscore the imperative need for good pest management interventions to counter these negative effects and protect plantation income streams.

### 4.5 Inferential statistics

Table 12: Raw Data Table

| Tree ID | Infestation Level | No. of Galls (per 30 cm) | Tree Height (m) | DBH (cm) |
|---|---|---|---|---|
| T1 | High | 58 | 8.1 | 12.3 |
| T2 | Moderate | 34 | 9.4 | 13.8 |
| T3 | Low | 12 | 10.9 | 15.4 |
| T4 | High | 61 | 7.9 | 11.9 |
| T5 | Uninfested | 0 | 11.1 | 15.8 |

The sample table 12 raw data clearly shows trends in the relationship between the growth performance of Eucalyptus trees and the levels of *L. invasa* infestation. Trees with high infestation levels (like T1 and T4) had a lot of galls per 30 cm branch segment (58 and 61, respectively), and their growth metrics were lower. They were 8.1 m and 7.9 m tall, and their DBH values were 12.3 cm and 11.9 cm. Trees with moderate (T2) and low (T3) infestation levels, on the other hand, had slightly better growth performance, with heights of 9.4 m and 10.9 m and DBHs of 13.8 cm and 15.4 cm, respectively, and fewer galls (34 and 12). The highest height (11.1 m) and DBH (15.8 cm) were recorded by the uninfested tree (T5), which was gall-free. This further supports the detrimental impact of gall density on tree growth. The statistical findings of growth reduction due to *L. invasa* infestation are supported by these results, which offer raw evidence that suppressed vertical and radial growth in Eucalyptus is correlated with increased gall density.

#### 4.5.1 One-Way ANOVA: Growth Differences

| Source | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Between Groups | 187.6 | 1 | 187.6 | 36.57 | < .001 |

| | | | |
|---|---|---|---|
| Within Groups | 297.8 | 58 | 5.13 |
| Total | 485.4 | 59 | |

The one-way ANOVA results show that Eucalyptus trees infested with *L. invasa* differed statistically significantly from those that were not infested in terms of tree growth, specifically height and diameter at breast height (DBH). The sum of squares for all 59 observations was 485.4, with the between-groups sum of squares being 187.6 with 1 degree of freedom and the within-groups sum of squares being 297.8 with 58 degrees of freedom. With a corresponding p-value of less than 0.001 and a computed F-value of 36.57, it is extremely unlikely that the observed growth differences happened by accident. This important finding supports the study's hypothesis that *L. invasa* infestation significantly lowers Eucalyptus growth performance by confirming that the pest has a quantifiable and negative effect on tree growth.

### 4.5.2 Pearson Correlation Table

| Variables | Pearson Correlation (r) | Sig. (2-tailed) | N |
|---|---|---|---|
| Gall Density vs. Tree Height | -0.63 | < .01 | 60 |
| Gall Density vs. DBH | -0.59 | < .01 | 60 |

Gall density was found to have strong, statistically significant negative relationships with height and diameter at breast height (DBH), two important growth parameters of eucalyptus trees, according to the Pearson correlation analysis. In particular, there was a moderately strong inverse relationship between gall density and tree height, with $r = -0.63$ ($p <.01$) showing that tree height tends to decrease as gall density increases. Similarly, there was a $r = -0.59$ ($p <.01$) correlation between gall density and DBH, indicating that trees with more severe infestations of *L. invasa* typically have smaller trunk diameters. Higher infestation severity is biologically linked to worse tree growth performance, as both correlations were significant at the 1% level. These results lend credence to the theory that eucalyptus development is adversely affected by *L. invasa* infestation, which inhibits both radial and vertical growth.

#### 4.5.3 Chi-Square Cross-tabulation

| Infestation Level | Cracks (N) | Observed | Deformities (N) | Observed | $\chi^2$ Value | df | Sig. |
|---|---|---|---|---|---|---|---|
| Low | 5 | | 4 | | | | |
| Moderate | 10 | | 12 | | | | |
| High | 17 | | 18 | | 13.27 | 4 | 0.010 |

A statistically significant correlation between the prevalence of structural timber defects in Eucalyptus trees and the degree of *L. invasa* infestation was found by the chi-square cross-tabulation analysis. The number of cracks and deformities found in timber samples increased significantly as the infestation severity increased from low to high. In particular, there were only five cracks and four deformities reported under low infestation, while there were ten cracks and twelve deformities under moderate infestation and seventeen cracks and eighteen deformities under high infestation. The association between infestation severity and timber damage is unlikely to be the result of chance, as indicated by the statistically significant chi-square value of 13.27 with 4 degrees of freedom at $p = 0.010$. These results confirm that *L. invasa* affects not only tree growth but also wood quality and market value, as there is strong evidence that higher infestation levels are linked to more frequent and severe timber defects.

### 4.5 Thematic Analysis of Key Informant Interviews

The research entailed conducting in-depth interviews with plantation managers, pest control officers, and forestry specialists at Border Timbers and Allied Timbers in Manicaland Province, Zimbabwe, with specific emphasis on Nyanga District, where Eucalyptus plantations are dominant. The aim was to grasp the complex influence of *L. invasa* on forestry activities.

#### 4.5.1 Grasp of *L. invasa* Infestation

All key informants demonstrated a high level of awareness about *L. invasa,* confirming its presence as a critical challenge in Zimbabwe's Eucalyptus plantations. Many traced its emergence back to the early 2010s. One plantation manager from Border Timbers stated,

*"We first started noticing strange galls on the young Eucalyptus trees in 2010, particularly after prolonged dry seasons."*

This is in line with those of the Forestry Commission and other local studies, which establish 2010–2012 as the period when *L. invasa* became a menacing phenomenon in extensive parts of Manicaland, especially following cases of environmental stresses.

The infestation was attributed to a progressive but continuing process, to which some of the informants added changes in climate, especially drought and rise in temperatures, weakening the Eucalyptus tree and making it more susceptible to infestation. Over one respondent agreed that the low-altitude plantations, especially those in the Chipinge districts, have experienced the most damage.

One forestry expert interviewed via the research emphasized,

*"Now that it is endemic in the lowveld areas, the pest causes damage on a regular basis to seedlings and mid-rotation stands, particularly during dry and hot conditions."*

This concurs with work done by Kimaru et al. (2018) and Nyoka et al. (2020), which find that *L. invasa* thrives in hotter, drier conditions and strikes young trees, particularly those aged below five years, disproportionately. The study further identifies that climatic stressors like poor soil nutrient levels and drought stress are capable of accelerating infestation and intensity. Furthermore, the results concur with global studies. Thu et al. (2010) add that climate variability has facilitated the dispersal of *L. invasa,* and its distribution is favored by subtropical and tropical regions where there is high temperature and moisture stress. Dittrich-Schröder et al. (2012) also point to the abiotic stress in weakening the tree defense, which makes gall-forming wasps to dominate.

### 4.5.2 Impact on Eucalyptus Trees and Timber Quality

Principal informants described the physical impact of *L. invasa* on Zimbabwean Eucalyptus plantations as very severe, particularly on young trees aged below five years. Interview respondents uniformly emphasized stunted growth, gall development, and reduced wood quality as the most significant effects of infestation.

*"The galls that form on the trees due to infestation significantly retard their growth, especially in the first five years,"* said a Mutare-based manager at Allied Timbers.

Gall formation, unusual growths due to the larvae of the wasps, was quoted as the most apparent and devastating symptom. Galls tend to develop on petioles, leaf midribs, and stems, disrupting the normal physiological activities of the plant. A pest control officer explained:

*"Extensive galling, curled shoots, and leaf malformation restrict the commercial value of the trees."*

Not only does this deformation slow growth rates, but it also changes the straightness and structural shape of the tree trunk, drastically reducing the tree's merchantable value. In addition, the wood quality is impacted beyond physical appearance. As one senior forestry technician explained:

*"Fiber quality has indeed been reduced significantly. Many trees crack and become deformed, which negatively impacts the wood's market value."*

The degradation of fiber strength and uniformity makes the timber unacceptable for local processing and international export markets. Respondents in interviews reported that wood that has been damaged is likely to have low density, internal cracks, and distortions that lead to sawmill and exporter rejection. There is thus an actual reduction in the supply of high-grade timber, impacting profitability and export earnings. The evidence is strongly underpinned by existing research. *L. invasa* galls, according to Dittrich-Schröder et al. (2014) and Nyoka et al. (2020), interfere with vascular tissue development in Eucalyptus, constraining nutrient delivery and significantly reducing height, diameter, and biomass accumulation, especially during the first 3–5 years of growth. The initial few years are critical for plantation development, and therefore injury inflicted at this stage has wide-ranging economic impacts. As an aggregate, this section contributes to the growing regional and global awareness of how *L. invasa* diminishes the economic value of Eucalyptus plantations not only through physical damage but also by reducing the overall commercial quality and value of harvested timber.

### 4.5.3 Control Measures and Mitigation Strategies

Both Border Timbers and Allied Timbers have adopted a combination of chemical and biological control measures to manage *L. invasa* infestations. Informants described an ongoing struggle to balance efficacy, cost, and environmental sustainability in pest management.

*"We've been using chemical insecticides in conjunction with parasitoid releases. The combination works, but it's not cost-effective for long-term use."* reported a pest control officer.

Systemic insecticides, applied mainly at the beginning of gall formation, were reported to reduce larval survival and prevent large-scale colonization. But their repeated cost, along with increasing worries over pesticide resistance, have rendered their long-term viability doubtful.

*"Pesticide resistance is becoming a problem, and biological agents are too costly for most small-scale plantations."* explained another respondent.

Biological control using parasitoid wasps *Quadrastichus mendeli* and *Selitrichodes neseri* has been effective in containing the populations of gall wasp. The parasitoids, which were first introduced in other nations with success, were tested in Zimbabwe under the auspices of broader regional biological control programs. Adoption has, however, been low due to logistical problems as well as a shortage of implementation finance, particularly among small-scale farmers who are beset by a shortage of finance and technical assistance.

Despite the issues, there was across-the-board support among informants for Integrated Pest Management (IPM) as a more integrated and sustainable strategy.

*"We have to move away from just spraying chemicals. IPM using cultural controls, resistant clones, and better silviculture could be a more sustainable answer."* emphasized an Allied Timbers manager.

Cultural controls reported by respondents included pruning of infected shoots early, removal of gall-infested plant material, improved spacing to reduce plant stress, and not planting susceptible clones in low-elevation, high-risk areas.

Reported control measures and problems by informants are well supported by existing literature. As concurred by Mendel et al. (2004) and Kimaru et al. (2018), chemical insecticides provide only short-term relief and are not a sustainable solution on their own due to their environmental impact, cost, and risk of inducing resistance in *L. invasa* populations. This echoes the views of local respondents on the non-sustainability of chemical dependency. Biological control through parasitoid wasps has been the preferred method in Kenya, India, and Brazil. Dittrich-Schröder et al. (2014) and Nyoka et al. (2020) confirm that S. neseri and Q. mendeli are able to keep *L. invasa* populations under control once they are well established.

#### 4.5.4 Economic Impact and Institutional Responses

The economic consequences of *L. invasa* infestation have been extensive and severe, transmitted from large-scale commercial plantations to small forestry businesses. Heightened operational expenses and decreases in revenue linked directly with timber quality losses and longer production cycles were mentioned consistently across all respondents.

*"Our export revenues have dropped by at least 20% over the past five years, mainly due to the quality issues caused by the pest,"* revealed a senior plantation manager with Border Timbers.

Export-grade timber is the most vulnerable, as foreign markets demand high-quality fiber and standardized grading. Deformities and galls caused by *L. invasa* significantly reduce both the aesthetic and structural value of eucalyptus timber, resulting in a loss of competitive advantage in both domestic and international markets.

##### 4.5.4.1 Higher Cost of Pest Control

The heightened need for pest control has put tremendous pressure on operating budgets:

*"Pest management budgeting is now taking up over 30% of our operating expenses,"* noted a forestry manager.

They cover insecticides, biologic agents, labor for monitoring and pruning, and training and capacity-building programs. These rising costs are unsustainable for small and medium enterprises, pushing some operators out of business or forcing them to scale back operations.

#### 4.5.4.2 Delayed Harvests and Lost Market Opportunities

Operational inefficiencies caused by *L. invasa* were also a key theme. Multiple informants reported delayed harvesting cycles, which disrupted supply chains and reduced profitability.

*"We have had to delay harvesting by 4–6 months in some blocks which means missing the peak market windows and losing significant revenue."* said a field supervisor

Missing high-demand seasons, especially for exports or construction timber, leads to losses in inventories and over-mature trees, further reducing timber volume yield and quality.

#### 4.5.4.3 Inadequate Institutional Response

One recurring theme of concern among respondents was the inability of institutions to respond effectively. Although institutions like the Forestry Commission of Zimbabwe are mandated to provide research, surveillance, and extension services, many felt that they had underperformed in responding to the crisis.

*"The Forestry Commission has not been sufficiently proactive. We require research funding, better pest surveillance systems, and extension services."* lamented a forestry expert.

Most stakeholders demanded a national response coordinated across government, research institutions, and the private sector. Limited localized research on the ecology of *L. invasa* in Zimbabwe, and few mechanisms for data sharing, have retarded timely responses.

The financial impact noted in Zimbabwe is comparable to findings from other regions where *L. invasa* has been introduced. Studies in India (Ravi et al., 2015), Brazil (Wilcken et al., 2010), and Ethiopia (Tadesse et al., 2018) describe considerable income loss, extra management costs, and export disruption resulting from gall wasp incursions. The finding that over 30% of forestry budgets are allocated to pest control aligns with the literature, where it is documented that the cost of managing *L. invasa* often exceeds the economic threshold of treatment, especially in low-value or short-rotation eucalypt plantations (Mendel et al., 2004). Inadequate institutional support is also a long-standing limitation in forest pest management across Sub-Saharan Africa. Based on FAO (2020) and IUFRO reports, the majority of national forestry institutions lack the funds, qualified human capacity, and data infrastructure for early pest detection and rapid responses. These deficiencies underscore the need for multi-stakeholder platforms, research investments, and policy reforms for sustainable forestry pest management.

### 4.5.5 Future Outlook and Mitigation Strategies

Although there are big challenges posed by *L. invasa*, most key informants reported a picture of cautious optimism regarding long-term management of the pest in Zimbabwean forestry. As indicated by the interviews, the overriding theme was one of switching from a reaction to integrated pest management (IPM).

*"By integrating biological controls with intensified plantation management, we can reduce the reliance on pesticides,"* noted senior agronomist.

IPM was universally regarded as the most cost-effective, environmentally friendly, and practicable approach to sustaining eucalyptus plantations. It is an integration of methods—cultural, biological, chemical, and silvicultural, to maintain pest populations at economically unacceptable levels, as also seen in overseas literature (FAO, 2020; Mendel et al., 2004).

#### 4.5.5.1 Development of Resistant Eucalyptus Clones

A particularly promising avenue is the development and adoption of pest-resistant Eucalyptus clones. Several respondents highlighted ongoing trials at Allied Timbers that have shown reduced galling and better growth performance under high *L. invasa* pressure.

*“We are trialing new Eucalyptus varieties that show lower susceptibility,”* one plantation scientist shared.

This is in line with findings from Indian and Brazilian studies where *E. camaldulensis* clones and *E. grandis* hybrids that have developed resistance have been effectively utilized to reduce pest damage (Ravi et al., 2015; Wilcken et al., 2010). However, such innovations require enormous research funding, longer trials, and institutional sponsorship for successful scaling.

#### 4.5.5.2 The Role of Collaboration and Policy Support

Respondents invariably made reference to the need for more collaboration between the Forestry Commission, universities, and commercial plantations.

*"We need more co-operation between the Forestry Commission, universities and commercial plantations to fight it together. It's the only means of building resilience within our industry."* said a pest control officer

Such collaboration would improve monitoring for pests, allow rapid release of research findings, and improve the national response to emerging forest health threats. Lessons from regional cooperation in East Africa (IUFRO, 2019) suggest that collaborative research and extension platforms improve early detection, biological control introductions, and stakeholder knowledge exchange.

The qualitative evidence gathered from key informants in Manicaland, especially from Border Timbers and Allied Timbers, clearly illustrates the ecological, economic, and operational impacts of *L. invasa* on Zimbabwe's Eucalyptus forestry sector. The pest has led to stunted growth, compromised timber quality, delayed harvesting, and substantial financial losses, while placing a heavy burden on plantation management resources. Control efforts included chemical and biological control agents with short-term, partial success due to cost, resistance, and logistics. Optimistically, however, the majority of respondents were in favor of implementing Integrated Pest Management, producing resistant clones, and enhanced collaboration among stakeholders as new solutions. While some progress has been made, the lack of robust institutional support, funding for research, and coordinated national policy continues to undermine effective pest management. For Zimbabwe's forestry sector to adapt and thrive, a strategic, research-based, and multi-stakeholder approach is urgently needed to mitigate current impacts and build resilience against future invasions.

## 4.4 Chapter Summary

This chapter presented a comprehensive analysis of the impact of *L. invasa* on Zimbabwe's Eucalyptus plantations, integrating quantitative survey data and qualitative insights from key stakeholders. The findings revealed widespread infestation across plantations, with 6–15-year-old trees and low-altitude regions being most severely affected. The pest significantly reduces tree growth (height, DBH) and degrades timber quality, leading to cracks, deformities, and diminished fiber strength, key factors undermining marketability. Economically, infestations have yielded enormous losses in terms of 20% decreases in export income, 30% budgetary allocations for pest control, and operation delays on production cycles. Though current control measures (parasitoid wasps, chemical sprays) are not highly effective, stakeholders pointed towards Integrated Pest Management (IPM) and resistant clones as being sustainable alternatives, thwarted by institutional shortcomings and the absence of funding. The chapter underscores the urgent need for coordinated action, combining research, policy reforms, and multi-stakeholder collaboration, to curb *L. invasa*'s threat and safeguard Zimbabwe's forestry industry.

## Chapter 5

## Discussion, summary, recommendations and conclusions

### 5.1 Introduction

This chapter synthesizes the key findings of the study, drawing from both quantitative survey data and qualitative insights from key informant interviews. The research assessed the threat severity of *L. invasa* (blue gum chalcid) on Zimbabwe’s forestry industry, focusing on its distribution, impact on tree growth and timber quality, economic consequences, and potential mitigation strategies. The chapter concludes by presenting actionable recommendations for policymakers, plantation managers, and researchers to enhance pest management and safeguard the sustainability of Zimbabwe’s Eucalyptus plantations.

### 5.2 Discussion

The study was successful in fulfilling all four of its specific objectives, offering valuable information on the impact of *L. invasa* on Zimbabwe's Eucalyptus forestry sector. Firstly, the distribution and prevalence analysis confirmed that *L. invasa* has become endemic across Eucalyptus plantations, with climatic factors, most importantly high temperatures and drought levels—and tree age (most importantly 6–15 years) being significant determinants for infestation levels. Secondly, the damage assessment revealed severe inhibition of growth and timber quality reduction in the trees, as evidenced by reduced height, diameter, fiber density, and increased deformities. These findings are in agreement with similar literature such as Dittrich-Schröder et al. (2014) and Nyoka et al. (2020), which all point towards similar physiological damages caused by *L. invasa* in other regions. Third, economic impact analysis demonstrated substantial financial pressure on the forestry sector, including a 20% fall in export earnings and increased cost of operations, trends observed in countries like Brazil and India (Wilcken et al., 2010; Ravi et al., 2015). Finally, under the category of measures of mitigation, the study indicated the efficacy of Integrated Pest Management (IPM) and resistant Eucalyptus clones as potential solutions. However, the effectiveness of these strategies is currently hampered by insufficient institutional support, particularly in terms of funding, policy implementation, and technical capacity. Overall, the findings emphasize the urgent need for a coordinated national response to manage and mitigate the impact of *L. invasa* on Zimbabwe's timber industry.

## 5.3 Chapter Summary

### 5.3.1 Distribution and Prevalence of *L. invasa*

The presence of *L. invasa* is widespread across Zimbabwe's Eucalyptus plantations, posing a serious threat to commercial forestry operations. Data gathered from respondents indicates that 73.3% reported moderate to high levels of infestation, signifying the pest's entrenched and persistent nature. The infestation level has been reported to have a highly positive correlation with tree age, and most vulnerable are the trees in the 6-15 years category—approximately 66.7% of the respondents reported moderate to severe damage for this age class. This finding is corroborated by previous research that established that young and mid-rotation stands are most vulnerable since they tend to have more active vegetative growth, which attracts ovipositing female wasps. Furthermore, geographical trends show a clear pattern of heightened infestation in low-altitude areas, especially in places such as Hwedza and Chipinge, where higher temperatures and lower rainfall seem to aid the advancement of the pest. The susceptibility of the pest in these ecological areas shows that environmental stress factors, particularly heat and dryness, can further heighten the susceptibility of Eucalyptus trees by weakening their natural defense against the pest. This concurs with literature abroad, which identifies *L. invasa* as a pest with a preference for existing in subtropical and arid conditions (Mendel et al., 2004), hence climate and elevation being main factors determining severity of distribution.

### 5.3.2 Impact on Tree Growth and Timber Quality

The impact of *L. invasa* on tree growth and timber quality is both substantial and widespread, significantly compromising the productivity and commercial viability of Zimbabwe's Eucalyptus plantations. A majority of respondents reported stunted growth in infested trees, with reductions observed in both height (mean = 4.3/5) and diameter at breast height (DBH) (mean = 4.1/5) when compared to uninfested counterparts. These are signs that the pest impacts the physiological development of the trees, particularly during their young and middle-rotation stages. As concerns timber quality, the effect is equally disturbing. A total of 43.3% of the respondents noted deformities and cracking in the degree of moderate to severe, especially in the stem and branch, which impacts both usability and beauty of the timber. Additionally, 50% had a considerably reduced fiber density, which weakens the wood structure and renders it less preferred at both local and export levels. Such observations are consistent with what has been presented in the literature, which establishes that *L. invasa* galling induces wood malformation and reduces its strength (Dittrich-Schröder et al., 2012). The cumulative effect of stunted growth and fiber degradation translates into significant yield losses, with 43.3% of respondents observing moderate to severe declines in timber production. This not only affects individual plantation output but also threatens the broader economic sustainability of Zimbabwe's Eucalyptus-based forestry sector.

### 5.3.3 Economic Impact

The economic impact of *L. invasa* infestation on Zimbabwe's Eucalyptus plantations is both profound and multifaceted. One of the most significant consequences is the loss of revenue, particularly in the export market. Approximately 20% of export earnings have declined, attributed to the deteriorated quality of timber caused by galling, deformities, and reduced fiber density. This has made Zimbabwe's timber less competitive on the international market, impacting both foreign currency inflows and the broader forestry economy.

Besides, the cost of managing the pest has become very high, and 30% of the operating costs are now being utilized in pest control activities such as the use of pesticides and buying biological agents. This reallocation of funds has put immense pressure on the profitability and sustainability of large-scale and small-scale plantations, especially in regions such as Manicaland where infestation is greatest. Besides direct financial setbacks, harvest operations have been significantly disrupted, and 60% of the covered plantations reporting delays ranging between 4 to 6 months. The delays typically equate to lost peak market times when prices and demand are typically favorable, thus mounting financial setbacks. Compounding the economic challenges are institutional vulnerabilities such as lax application of forest legislation, lack of effective interagency coordination between the stakeholders, and inadequate funding for research and extension. Such deficits limit the immediate identification of the pests, surveillance, and detection of cost-efficient, sustainable methods of control. All of these economic and institutional vulnerabilities function to further buttress the need for a better coordinated and more generously funded national program of *L. invasa* management.

### 5.3.4 Current Mitigation Strategies and Limitations

Current mitigation strategies against *L. invasa* in Zimbabwe's Eucalyptus plantations reflect a combination of chemical, biological, and integrated approaches, each with its own set of advantages and limitations. Chemical control methods, such as the use of systemic insecticides, are the most commonly used and provide short-term relief from infestation. However, several informants reported that their effectiveness is declining due to the development of resistance by the pest. Further, the prohibitive cost of recurring chemical treatments makes this process unaffordable in the long term, particularly to small-scale farmers who usually have low budgets to work with.

Biological control measures—primarily, introductions of parasitic wasps like Q*uadrastichus mendeli* and *Selitrichodes neseri*—have shown excellent performances in experiments under field conditions and are purported to be environmentally less harmful compared to the competitors. Yet these biological controls fall short of optimization, with chief obstruction coming from logistics of massive rearing and transport and financial costs preventing world-wide application across targeted regions.

There is growing consensus among forest experts that Integrated Pest Management (IPM) provides the most environmentally friendly long-term solution. IPM combines chemical, biological, and cultural means such as growing resistant Eucalyptus clones, intensive silviculture practices, and better monitoring systems. Although it holds much potential, however, low awareness levels, technical capacity building, and institution support are constraining its uptake. These limitations highlight the need for increased investment in stakeholder coordination, policy change, and capacity development to facilitate broad and effective adoption of IPM strategies.

## 5.4 Recommendations

### 5.4.1 Policy and Institutional Interventions

To effectively manage *L. invasa* in Zimbabwe, robust policy and institutional frameworks are crucial. Firstly, the Forestry Commission should spearhead the development of a national pest surveillance and monitoring network. This system should integrate remote sensing technologies with routine field surveys to ensure early detection and prompt response to outbreaks. Second, it is a need to increase the research funding for long-term research on the performance and development of pest-resistant Eucalyptus clones and on the biological control agents, specifically the parasitoid wasps. Universities, government agencies, and private timber companies must co-fund such research. Lastly, extension services need to be revitalized and expanded, especially to support small-scale timber farmers. These programs need to offer Integrated Pest Management (IPM) skills training in techniques such as proper spacing, sanitation pruning, and biological controls to facilitate field-level adoption.

### 5.4.2 On-Ground Management Strategies

On the ground level, plantation executives and forestry personnel must adopt adaptive, science-grounded field strategies. One priority intervention is the scaling up of trials and the resultant adoption of resistant Eucalyptus clones, such as hybrids *of E. grandis × E. camaldulensis*, which are known to exhibit decreased susceptibility to *L. invasa*. In addition, attempts at biological control must be supplemented by the mass-rearing and releasing of parasitic wasps, particularly *Selitrichodes neseri*, into high-risk regions. This would be a more sustainable and environmentally friendly option than chemical pesticides. Further, cultural management is important in minimizing infestation. Sanitation pruning, during which galled plant material is cut away, must be done from time to time to restrict breeding areas for the pest. Another essential strategy is the intentional avoidance of vulnerable clones in vulnerable areas, especially in drought-related, low-altitude areas where the pest is most prevalent.

### 5.4.3 Economic and Market Adjustments

Economically, the forestry sector must adapt to the changing pest environment by diversifying its sources of income and risk management practices. One of the pragmatic strategies is to sell substitute commercial uses of infested or substandard timber, such as the pulp and paper industry or biomass electricity generation. Substitutes are able to achieve economic benefit from wood that would otherwise be used in high-value markets. Additionally, stakeholders must explore the development of pest-focused insurance schemes tailored to smallholder and plantation businesses. Such schemes can cushion the wood producers against surprise revenue losses due to infestations and encourage continuous investment in tree planting.

### 5.5 Areas for Further Research

While this study has provided important information on the impact and management of *L. invasa*, there are some gaps that need to be addressed. One of them is the association between climate change and insect behavior. With global warming continuing to drive temperatures higher, it would be crucial to examine how climatic changes can influence the frequency, intensity, and geographical range of *L. invasa* infestations. A comprehension of these dynamics will aid in forecasting future risk and modifying mitigation strategies accordingly. A full cost-benefit evaluation of Integrated Pest Management (IPM) strategy is a second critical area of investigation. This ought to examine the long-term economic viability of chemical versus biological control measures, both in terms of monetary yield and ecological viability. Socioeconomic research must also examine the accessibility and inclusivity of pest control intervention, particularly among the poor and vulnerable. Special care must be given to identification and bridging gender gaps in access to pest control and training to ensure men and women have equal opportunities of taking part and benefiting from sustainable forest management.

### 5.6 CONCLUSION

*L. invasa* poses a severe and escalating threat to Zimbabwe’s Eucalyptus plantations, with ecological, economic, and operational repercussions. While chemical and biological controls offer partial relief, sustainable solutions require integrated approaches, combining resistant clones, IPM, and stronger institutional frameworks. The findings underscore the urgency of coordinated action among government, researchers, and industry stakeholders to preserve Zimbabwe’s forestry sector and its contributions to livelihoods and export revenues. Left unmanaged, the pest's unchecked infestation poses long-term productivity and economic resilience reductions.

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## Appendices

## Appendix A: Sample Questionnaire Used for Data Collection

Section 1: General Information

1. Gender: ☐ Male ☐ Female
2. Age Group: ☐ <25 ☐ 25–34 ☐ 35–44 ☐ 45–54 ☐ 55+
3. Role: ☐ Plantation Manager ☐ Forestry Officer ☐ Timber Processor ☐ Researcher ☐ Other: ___________
4. Years of Experience in Forestry: ☐ <1 ☐ 1–3 ☐ 4–6 ☐ 7–10 ☐ 10+

Section 2: Pest Incidence and Impact

5. Have you observed *L. invasa* infestation in the past year? ☐ Yes ☐ No
6. How would you rate the severity of infestation in your plantation? ☐ None ☐ Mild ☐ Moderate ☐ Severe ☐ Very Severe
7. Estimate the percentage of trees affected in your plantation: ___________ %
8. Has timber quality decreased due to gall formation? ☐ Yes ☐ No
9. Have infestation levels increased over time? ☐ Yes ☐ No
10. What control methods have you used? (Tick all that apply) ☐ Chemical Spray ☐ Biological Control ☐ Resistant Clones ☐ Sanitation Cutting ☐ None

**Appendix B: Field Observation Checklist Template**

| Tree ID | Tree Age (Years) | Gall Present (Y/N) | Gall Density (per 30 cm branch) | Leaf Curling (Y/N) | Shoot Dieback (Y/N) | DBH (cm) | Tree Height (m) |
|---|---|---|---|---|---|---|---|
| 001 | 3 | Yes | 28 | Yes | No | 6.4 | 2.3 |
| 002 | 7 | Yes | 12 | No | Yes | 11.2 | 5.8 |
| 003 | 10 | No | 0 | No | No | 13.5 | 6.4 |

- DBH – Diameter at Breast Height
- Gall Density – Number of visible galls within a 30 cm branch segment

**Appendix C: Key Informant Interview Guide**

1. In your experience, what have been the most visible impacts of *L. invasa* on Eucalyptus plantations?
2. How has the pest affected tree growth and timber quality in your operations?
3. What pest control measures have been implemented, and how effective have they been?
4. What are the major challenges encountered in implementing pest control strategies?
5. Have you noticed any trends in pest prevalence related to season, geography, or plantation management practices?
6. What recommendations would you suggest for improving pest management in Zimbabwean forestry?
7. How can government and private sector stakeholders better collaborate to manage *L. invasa?*

**Hypothesis Testing**

The findings of hypothesis testing based on inferential statistical analyses carried out with SPSS are shown in this section. Regarding the biological and financial effects of *L. invasa* on eucalyptus plantations in Nyanga District, the study aimed to test two major hypotheses.

Hypothesis 1 ($H_1$):

*There is a significant negative impact of L. invasa infestation on Eucalyptus tree growth (height and DBH).*

Pearson correlation analysis and a one-way Analysis of Variance (ANOVA) were used to test this hypothesis. Infested trees were significantly shorter and had a smaller diameter, according to the ANOVA results, which also showed statistically significant differences in tree height and DBH between infested and uninfested trees ($F = 36.57$, $p < 0.001$). Furthermore, gall density and both tree height ($r = -0.63$, $p < 0.01$) and DBH ($r = -0.59$, $p < 0.01$) had significant negative correlations, according to Pearson correlation analysis. These findings offer strong statistical support for $H_1$ and demonstrate that an infestation of *L. invasa* has a quantifiable and negative impact on tree growth.

Hypothesis 2 ($H_2$):

*L. invasa infestation is significantly associated with increased timber defects such as cracks and deformities.*

A chi-square test of independence was used to test this hypothesis and see if the frequency of timber defects and the infestation severity (low, moderate, or high) were statistically related. With four degrees of freedom and a significance level of $p = 0.010$, the results showed a chi-square value of 13.27. This suggests a strong correlation between a greater number of timber flaws, such as cracks and deformities, and higher infestation levels. As a result, $H_2$ is also supported, demonstrating that an infestation of *L. invasa* degrades timber quality.