EFFECTS OF EUCALYPTUS GALL WASP, *Leptocybe invasa* (HYMENOPTERA: EULOPHIDAE) ON GROWTH AND WOOD BASIC DENSITY OF SOME *EUCALYPTUS* SPECIES, TANZANIA

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A THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY OF SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

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EXTENDED ABSTRACT

Leptocybe invasa Fisher & La Salle (Hymenoptera: Eulophidae), also known as Blue Gum Chalcid (BGC) is native to Australia. The pest was first recorded in the Mediterranean region in 2000 causing severe injury to young foliage of *Eucalyptus camaldulensis* by inducing galls mainly on growing shoots. The pest was first reported in Tanzania in 2005 and has recently become a problem by infesting a range of commercially grown *Eucalyptus* species. The purpose of this study was to determine infestation density and assess the effects of *L. invasa* on growth, biomass production and wood basic density of some *Eucalyptus* species in Tanzania. Results showed that, trees in the Coastal were more infested, followed by Plateaux while trees in the Southern highlands agro-ecological zone were least infested. *Eucalyptus tereticornis* was more infested followed by *E. camaldulensis* while *E. saligna* was the least infested. *Eucalyptus citriodora* and *E. grandis* were not infested. The mean Dbh of infested trees were reduced by 7.8%, 2.1% and 13.6% and mean heights were reduced by 6.6%, 9.5% and 3.8% compared to uninfested ones for *E. camaldulensis, E. tereticornis* and *E. saligna* respectively. The mean basal area of infested trees were reduced by 16.4%, 17.1% and 24.5% and mean volume were reduced by 17.8%, 16.1% and 23.1% for *E. camaldulensis, E. tereticornis* and *E. saligna* respectively. The mean basic densities of infested eucalypt trees were higher than uninfested by 2.7%, 5.3% and 7.3% for *E. tereticornis, E. camaldulensis* and *E. saligna* respectively. Twenty two weeks after *L. invasa* infestation, the height and root collar diameter of infested seedlings were reduced by 39.6% and 11.3% for *E. grandis* and by 38.2% and 7.7% for *E. saligna* respectively. Dry weight biomass reduction in infested seedlings was significantly higher on stem and leaves than roots and branches of both *E. grandis* and *E. saligna*. It is recommended that, similar study on the impact of *L. invasa* on growth and biomass production should look into other commercially grown *Eucalyptus* species in Tanzania. Management efforts should

focus on controlling the spread of the pest using biological control, cultural techniques and planting resistant genotypes.

ORGANIZATION OF THE THESIS

This thesis is organised in to four chapters. The first chapter consists of the extended abstract and introduction of the overall theme studied; it offers a description of the commonality of concepts presented in separate papers. Chapter two contains main results and discussion. Chapter three presents series of originally published papers in different journals. Chapter four contains conclusion and recommendations.

DECLARATION

I, **REVOCATUS PETRO**, do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other institution.

______________________ ______________________

Revocatus Petro Date

(PhD. Candidate)

The above declaration is confirmed by:

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Professor S. S. Madoffe Date

(Supervisor)

______________________ ______________________

Professor S. Iddi Date

(Supervisor)

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DEDICATION

This work is dedicated to my both late father Deogratias Petro Muliro and mother Pelagia Issaya who laid the foundation of my education with a lot of sacrifice.

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LIST OF PAPERS

This thesis is based on the work contained in the following papers referred to by Roman numerals in the text:

I. Petro, R., Madoffe, S.S. & Iddi, S. (2014). Infestation density of Eucalyptus gall wasp, *Leptocybe invasa* Fisher & La Salle (Hymenoptera: Eulophidae) on five commercially grown Eucalyptus species in Tanzania. *Journal of Sustainable Forestry* 33:276 - 297.

II. Petro, R., Iddi, S. & Madoffe, S.S. Effects of Eucalyptus gall wasp, *Leptocybe invasa* Fisher & La Salle (Hymenoptera: Eulophidae) infestation on diameter and height growth and wood basic density of three Eucalyptus species in Tanzania. Manuscript submitted in the *Agricultural and Forest Entomology Journal.*

III. Petro, R., Madoffe, S.S., Iddi, S. & Mugasha, W. A. (2015). Impact of Eucalyptus gall wasp, *Leptocybe invasa* Fisher & La Salle (Hymenoptera: Eulophidae) infestation on growth and biomass production of *Eucalyptus grandis* and *E. saligna* seedlings in Tanzania. *International Journal of Pest Management* 61(3): 220 - 227.

DECLARATION

I, **REVOCATUS PETRO**, do hereby declare to the Senate of Sokoine University of Agriculture that the listed papers above that make this thesis summarize my independent efforts, it is my original work and will not be part of another thesis in the “published Papers” format in any other University.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
BGC	Blue Gum Chalcid
COSTECH	Tanzanian Commission for Science and Technology
Dbh	Diameter at breast height
DI	Damage Index
FAO	Food and Agriculture Organization of the United Nations
Ha	Hectare
m.a.s.l	metres above sea level
SAS	Statistical Analysis System
SE	Standard error
SUA	Sokoine University of Agriculture
TAFORI	Tanzania Forestry Research Institute
TTBP	Tanzania Tree Biotechnology Project

CHAPTER ONE

1.0 INTRODUCTION

1.1 Overview of Eucalypts in the World

Eucalyptus species, commonly referred to as eucalypts is a diverse genus of flowering trees (and a few shrubs) belonging to the family Myrtaceae (Ladiges *et al*., 2003). The genus *Eucalyptus* comprises more than 900 species and an unknown number of hybrids and varieties (Nair, 2001; Boland *et al.,* 2006; Oballa *et al*., 2010). Most of the eucalypts are native to Australia and few species are naturally found in Philippines, Papua New Guinea, Indonesia and Timor (FAO, 2000; Myburg *et al*., 2006). Eucalypts are among the most valuable and widely planted hardwood crop in the world due to their wide adaptability, extremely fast growth rate, good form and excellent wood and fibre properties (Myburg *et al*., 2006; Rockwood *et al.,* 2008). They are estimated to be planted in more than 22 million hectares (ha) in about 96 countries (Nichols *et al.,* 2010, Zheng *et al*., 2014). Eucalypts are grown extensively as exotic plantation species in tropical and subtropical regions throughout Africa, South America, Asia, and, in more temperate regions of Europe, South America and North America (Rockwood *et al.,* 2008). In 2000, India had 8 million ha of eucalypts followed by Brazil (3.7 million ha) and China (2.6 million ha) (Stape *et al.,* 2001; Stape, 2002; Liu and Li, 2010; Zheng *et al*., 2014). Eucalypts are also commercially planted in Indonesia, Malaysia, Thailand, Sri Lanka, Vietnam, France, Portugal, New Zealand, Chile and the United States of America. In Africa, eucalypts are widely planted in South Africa, Congo, Zimbabwe, Zambia, Kenya, Uganda, and Tanzania (Myburg *et al*., 2006; Rockwood *et al.,* 2008; Kilimo Trust, 2011). Most of the domesticated eucalypts are from the subgenus *Symphyomyrtus*, which is the largest of the 10 subgenera currently recognized within eucalypts, containing over 75% of the species. Four species and their hybrids from this subgenus are *Eucalyptus grandis* Hill ex Maiden, *E. urophylla* S.T. Blake*, E. camaldulensis* Dehnh and *E. globulus*

Labill account for about 80% of the eucalypt plantations worldwide (Myburg *et al*., 2006). However, Kilimo Trust (2011) reported that East Africa's plantations are dominated by *E. grandis,* which is suited to cooler and wetter areas, and *E. camaldulensis* which grows well in hotter and drier climates.

Eucalypts are utilized worldwide for a wide array of products including pulp for high quality paper (Tournier *et al*., 2003), lumber, plywood, veneer, solid and engineered flooring, fiberboard (Krzysik *et al*., 2001; Gorrini *et al.,* 2004), wood cement composites (Coutts, 2005), mine props, poles, firewood, charcoal, essential oils (Foley and Lassak, 2004; Ogunwande *et al.,* 2005), bee forage, tannin, and landscape mulch as well as for shade, windbreaks, shelter and soil reclamation (Eldridge *et al.,* 1993; Langholtz *et al*., 2005). Tanzania introduced eucalypts in the 1890s with the aim of supplementing wood supplies from natural forests (Schabel, 1990; Nshubemuki, 1998). The area under eucalypts in Tanzania is estimated to be 25 000 ha of plantations (Munishi, 2007) of which 4 665 ha are grown by government and the rest are grown by the private sector and small-scale farmers (Ngaga, 2011). *Eucalyptus* species planted in Tanzania include *E. saligna* Smith, *E. grandis, E. camaldulensis, E. globulus, E. citriodora* Hook*, E. regnans* F. Muell*, E. microtheca* F. Muell*, E. tereticornis* Smith*, E. maidenii* F. Muell*, E. urophylla, E. paniculata* Sm and *E. robusta* Smith (Nelson, 1974; Bryce, 2003; Munishi, 2007). In Tanzania, eucalypts are among the major species grown under small holder forestry and contribute significantly as a source of transmission poles, building material and fuel wood (Munishi *et al*., 2004; Munishi, 2007).

1.2 Status of Eucalypts Insect Pests in Southern and Eastern Africa

Until the recent expansion of forestry, exotic tree plantations including eucalypts were relatively free of insect pest problems. The situation however changed markedly from mid 1960s following accidental introduction of several insect pests originating from other countries (Ciesla, 1993). Paine *et al.* (2011) reported a biodiversity decline because of increase of the cultivated area of eucalypts. This has resulted in a sharp rise of eucalypts pests. Records indicate that species of eucalypts pests increased from 53 in 1980 to 282 in 2001 (Pang, 2001). A large number of pests seriously threaten the development of the eucalypt industry, farmer income and forest tenure reform (Zheng *et al*., 2014). The following is the review of some selected exotic and native pests which infest eucalypts plantations in some Southern and Eastern African countries. While the identification of these pests, major hosts and nature of the damage information are well known, little is known on the extent of their damage and impact. Most of eucalypt insect pests recorded in Southern and Eastern African countries have not been reported in Tanzania probably due to the lack of survey.

1.2.1 Eucalyptus bark beetles, *Phoracantha semipunctata* Fabricius (Coleoptera: Cerambycidae)

Phoracantha semipunctata is native to Australia and was accidentally introduced in many regions of the world including Southern and Eastern African countries where eucalypts are widely grown (Bubala *et al*., 1989; Nair, 2001). It attacks both growing trees and green logs (Annecke and Moran, 1998). Attacks can cause considerable damage to physiologically stressed trees, sometimes killing them. *Phoracantha semipunctata* is a serious pest in Zimbabwe, Malawi, Zambia and to a lesser extent in Southern part of Tanzania (Annecke and Moran, 1998). In 1989, all *Eucalyptus* species planted in Zambia were attacked by the pest while in South Africa, the most attacked species were *E.*

grandis, E. saligna, E. paniculata and *E. maculate* (Bubala *et al*., 1989). Control of these beetles includes stripping the bark and destroying the infested branches of felled trees. Trees felled for firewood should be similarly treated to prevent beetles from breeding and to stop them from being spread through firewood (Annecke and Moran, 1998). Stand vigour improvement by proper thinning and by other silvicultural means is a key to induce tree resistance against beetle attack (Madoffe and Petro, 2011).

1.2.2 Eucalyptus snout beetle, *Gonipterus scutellatus* Gyllenhal (Coleoptera: Curculionidae)

Gonipterus scutellatus is endemic to Australia where eucalypt trees are native. The pest is a major defoliator of the eucalypts and is commonly known as the eucalyptus snout beetle, the eucalyptus weevil or the gum tree weevil. Eucalypt trees are the only hosts for the gum tree weevil. Both the foliage and young shoots of eucalypt trees are eaten by *G. scutellatus.* The damage caused may result in stunted growth and even tree mortality in severe case. Both the adult and larval stage prefers new growth (FABI, 2010). The species most susceptible to attack include *E. camaldulensis*, *E. globulus*, *E. maidenii*, *E. punctata*, *E. robusta*, *E. smithii*, *E. viminalis* and a number of introduced *Eucalyptus* hybrids (Oballa *et al*., 2010). In Africa, the weevil has spread to Kenya, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, South Africa, Swaziland, Uganda and Zimbabwe (Nair, 2001). Biological control using the egg parasite, *Anaphes nitens* Siscaro successfully reduced attacks of snout beetles (Atkinson, 1999). Chemical treatment is not recommended because of the danger to honey bees attracted by the long flowering period of *Eucalyptus* (EPPO, 2005).

1.2.3 Australian psyllid, *Blastopsylla occidentalis* Taylor (Hemiptera: Psylloidea)

This is among the major pests of *Eucalyptus* species which is native to Australia (Taylor, 1985; Hollis, 2004). Up to now, it has been introduced in many countries in Africa including Kenya and South Africa where it has been noted attacking eucalypt seedlings (Tamesse *et al*., 2014). Adults and nymphs suck the young leaves, leaf stalks and shoots, causing significant deformations (Aytar *et al.,* 2011). The most affected species are *E. camauldulensis, E. urophylla, E. grands, E. nitens, E. teriticornis* (Hodkinson, 1991). The management strategies of this pest around the world are based on chemical control and no parasitoid has been identified until now (Tamesse *et al*., 2014).

1.2.4 Bronze bug, *Thaumastocoris peregrinus* Carpintero et Dellape (Hemiptera: Thaumastocoridae)

Thaumastocoris peregrinus is a sap-sucking insect that feeds on eucalypt leaves. It is native to Australia and is currently spreading through Africa, Europe and Latin America. In Africa, *T. peregrinus* was first reported in 2003 in South Africa, in 2007 in Zimbabwe, in 2008 in Malawi and 2009 in Kenya (Nair, 2001; Jacobs and Neser, 2005; Nadel *et al*., 2010). *Thaumastocoris peregrinus* has a wide host range, attacking at least thirty *Eucalyptus* species and common commercial hybrids. In South Africa, all commercially grown eucalypts are susceptible to attack (Nadel *et al.*, 2010). In severe *T. peregrinus* infestations, leaf loss leads to severe canopy thinning, and this sometimes results in branch dieback or tree mortality (Nadel *et al.,* 2010; Wylie and Speight, 2012). Systemic insecticides have been found to be an effective tool for the control of *T. peregrinus* but this approach is generally not feasible for large scale application such as in plantations. The Australian parasitic wasp, *Cleruchoides noackae* Lin and Huber (Mymaridae: Hymenoptera) has been identified as a potential biological control agent (Wilcken *et al*., 2010).

1.2.5 Wood-boring moth (Cossid moth), *Coryphodema tristis* Drury (Lepidoptera: Cossidae)

This insect is native to South Africa and is well known as a pest of fruit trees and vines as well as of a few native trees. In 2004, the pest was noted causing serious extensive tunneling in the wood of *E. nitens* in South Africa (Gebeyehu *et al.,* 2005). Its presence on *E. nitens* appears to represent a sudden new host association, which is of big concern to South African forestry. The pest was observed to infest eucalypts with the age range of 8 to 13 years (Gebeyehu *et al.,* 2005). Cossid moth was observed only on *E. nitens* and the extent of its distribution and whether or not it attacks other *Eucalyptus* species is still unknown (Adam *et al.*, 2013). Since the cossid moth is an indigenous insect, natural enemies of this pest are likely to be present. The identity of these natural enemies, their population and biology is not yet known. No insecticide is currently in use or registered for controlling the cossid moth (Boreham, 2006; Adam *et al.*, 2013).

1.2.6 Termites (Isoptera: Rhinotermitidae)

Termites are a group of insects (Isoptera) consisting of about 2 500 species of which 300 are considered pests (Su *et al.,* 1997). They are the most important damaging native insects to forests in Tanzania and the tropics at large. There are six families in the order Isoptera and in Southern and Eastern Africa, most species belong to termitidae (Browne, 1968). Termites nest underground, while others are found in the boles of trees, for example in hollow trees (Su *et al.,* 1997). Exotic hardwood plantation tree species are most susceptible to termite attack. *Eucalyptus* species are the most susceptible followed by *Tectona grandis* L.f and *Grevillea arborea* Roxb. Other hardwoods species attacked include *Senna siamea, Acacia species, G. arborea, Leucaena leucocephala* (Lam.) de Wit and *Terminalia* species (Madoffe and Petro, 2011). There are also some attacks in plantations/stands of indigenous tree species. In most cases, some species of termites can feed on live trees, causing damage to the root system of young trees resulting into mortality while other species feed on wood in contact with the soil but they can bridge gaps with foraging tubes to reach wood above ground level (John *et al.,* 2001). Termites are difficult to control because they live underground, so preventive rather than curative measures should be taken. The generally accepted method of termite control over the years has been chemical pesticides. However, chemicals are expensive and have many harmful effects. Cultural practices such as planting of resistant trees and protection from sun scorch damage, or shading and irrigating help to alleviate stress and thus reduce the likelihood of termite damage to the plant (TRIT, 2006; Madoffe and Petro, 2011).

1.3 Effects of Insect Infestation on Tree Biomass Production

Infestation of insects on trees has many and varied effects. These effects are direct on the trees themselves, effects on the other components of the forest ecosystem such as animals and other plants, and effects on people, both direct and indirect (Twery, 1990). The effects of insects on trees is due primarily to the reduction of carbohydrate production which results in increased vulnerability to pests that kill stressed trees, loss of growth, and subsequent indirect changes in the forest (Heichel and Turner, 1976). In a multi-layered, mixed-species forest stand, infestation/effect occurs first on understorey trees and later on overstorey trees. Similarly, trees in poor condition are often affected before other trees growing in good condition (Twery, 1990; Maddofe and Austarå, 1990). Losses resulting from mortality of trees are correlated with frequency and intensity of insect attack, which in turn are correlated with tree species according to insect feeding preferences. However, there are distinct differences among species in their ability to survive against infestation. The differences are due to many factors, including where the tree's reserve energy is stored, how much energy is required to recover after infestation, and how much energy is needed to maintain respiration during the refoliation process.

For example, hemlock's (*Tsuga canadensis*) reserves are stored in its needles, so after defoliation there is no available reserve energy, no refoliation occurs and the tree dies (Twery, 1990).

The standard approach to measuring growth loss for an individual tree has been to record changes in diameter growth at breast height and height. Twery (1990) found growth losses to be directly proportional to the extent of infestation and such losses are likely to be the most important component of forest productivity. Insects cause economic losses through lost forest production and reduced aesthetic qualities of the forest. Certainly, some of these effects are a result of reduced leaf area in recovering trees (Picolo and Terradas, 1989). However, it is difficult to separate pest infestation effects from other environmental factors such as drought or extreme temperatures.

1.4 Effects of Insect Infestation on Wood Quality

Wood quality can be considered as a concept that emphasizes particular wood properties (anatomical, chemical and physical) that individually, or in combination, have a positive influence on a specific wood product (Schimleck and Clark, 2008). Density of wood is directly related to other wood properties and is an important index of wood quality (Tsoumis, 1991; Walker, 1993). The density of wood is influenced by moisture, structure, extractives and chemical composition (Tsoumis, 2009). Various external factors like bacteria, fungi, insects, marine organisms, climatic, mechanical, chemical and thermal may cause degradation of appearance, structure or chemical composition of wood which have impact on wood density. Insects attack the wood of living trees, timber and products. In living trees, insects bore through the bark or enter through debarked areas. The attack may be confined to the region between bark and wood due to the abundance of nutritive substances in that region (Essiamah and Eschrich, 1985) or it may extend throughout the sapwood and heartwood. The damage is greater in trees with low vigour, logs and wood products. Insects attack wood for shelter, food and oviposition (Tsoumis, 2009). Insects open bore holes and galleries of varying size and some species change the interior of wood to dust, leaving a thin exterior layer (Tsoumis, 2009). All of these have an influence on wood quality depending on the extent of attack. The effects of defoliators and gall forming insects on wood density are described by Twery (1990) and Petro *et al*. (2014a).

1.5 Eucalyptus Gall Wasp, *Leptocybe invasa* Fisher & La Salle (Hymenoptera: Eulophidae)

1.5.1 Taxonomy and biology of *Leptocybe invasa*

Leptocybe invasa is a wasp that belongs to the gall forming hymenopterans commonly termed as BGC. It was identified as genus and species in the insect order Hymenoptera, and belongs to the sub-family Tetrastichinae, family Eulophidae in the super family Chalcidoidea in 2004 (Mendel *et al*., 2004). Adult female size ranges from 1.1 to 1.4 mm. *Leptocybe invasa* has a pathogenesis (thelytokous) form of reproduction. The adult female of *L. invasa* lays hundreds of eggs in the petiole and midrib of leaves and stems of young shoots. The larvae grow by feeding on the tender portion of the plant and releasing oxalic acid resulting in the formation of galls whose size is correlated to the number of wasps developing in the gall. Mature galls are usually deep pink in colour (Thu *et al.,* 2009). The larvae pupate within the galls and adults emerge through the holes that they cut on the surface. Adults lay eggs immediately after they emerge from host plant. The mean development time of *L. invasa* from oviposition to emergence at room temperature is 132.6 days (4.5 months) (Mendel *et al*., 2004; Protasov *et al*., 2007). Hesami *et al.* (2006) reported the developmental period to be 126.2 and 138.3 days in laboratory and field conditions respectively. The longevity of the adults depends on the type of food taken. For example, Mendel *et al*. (2004) reported that wasps fed with honey and water solution had the longest mean life span of 6.5 days, which was significantly longer than those supplied with flowers (4.7 days), water (3.7 days), fresh young foliage (3.5 days) or no food (3.0 days). Numbers of generations of *L. invasa* in one year are different in each climatic region. In the Mediterranean region, *L. invasa* produces two or three overlapping generations annually, and overwinters as larvae or pupae (Mendel *et al.,* 2004; Hesami *et al.,* 2006). In India, adult emergence was observed throughout the year with overlapping generations (Kulkarni, 2010). In China, *L. invasa* produced five overlapping generations in the south and west coastal regions, four or five overlapping generations in the middle and north regions and three overlapping generations in other invaded regions (Zhu *et al.,* 2013). Therefore, it is difficult to find the optimal time for control and to reach the large area with foliar sprays of pesticides in view of the overlapping generation (Qiu *et al.,* 2011; Zheng *et al*., 2014). The numbers of generations per year in Africa is still unknown.

1.5.2 Distribution and spread of *Leptocybe invasa* in the world

The wasp is believed to be a native of Australia, where its distribution is still unknown (Mendel *et al*., 2004; Thu, 2004; Branco *et al*., 2006; Protasov *et al*., 2008). *Leptocybe invasa* was first recorded on *E. camaldulensis* in the Middle East in 2000 (Mendel *et al.,* 2004; Nyeko, 2004). Currently, the wasp has spread throughout many countries in the Mediterranean basin, Africa, Asia, Europe, South America (Brazil), and North America (USA – Florida) (Mendel *et al*., 2004; Branco *et al*., 2006; Protasov *et al.,* 2007, 2008; Kim *et al.,* 2008; Costa *et al.,* 2008; Nyeko *et al*., 2009; Gaskill *et al*., 2009; Wylie and Speight 2012). In Asia, it is a threat in countries like China, Cambodia, Thailand, Vietnam, India, Iran, Iraq, Sri Lanka, Malaysia, Turkey and Syria (Aytar, 2003; Thu, 2004; Almatni and Mayhoob, 2004; Doğanlar, 2005; Hesami *et al.,* 2006; Xu *et al*., 2008; Kumari, 2009; Karunaratne *et al*., 2010; Hassan, 2012). In Europe, the wasp has been reported in Portugal, Greece, Italy, Spain and France (EPPO, 2006; Branco *et al*., 2006; 2009; Anagnou-Veroniki *et al*., 2009). In Africa, *L. invasa* was first reported in 2002 in Kenya, Uganda, Algeria and Ethiopia, in 2004 in Tunisia, in 2005 in Tanzania, in 2007 in South Africa and Zimbabwe, in 2008 in Malawi, in 2012 in Mozambique and in 2013 in Egypt (Mutitu, 2003; Nyeko, 2005; Neser *et al*., 2007; FAO, 2009; Petro, 2009; Dhahri *et al*., 2010; FRIM, 2010; MENRM, 2010; Tree Protection News, 2010; IPCC, 2012; Abd El-Raheem and Heikal, 2014). The most probable mode of spread is in the larval stage within infected plant material (Nadel and Slippers, 2011). Furthermore, FAO (2009) reported that adult wasps spread very quickly by flight and wind currents. The pest has a high rate of dispersal. For example, it has spread from the north (in Algeria) to the south of Africa (in South Africa) (about 7000 km) in less than a decade (Dittrich- Schröder *et al*., 2009). Its capability to have active and passive dispersal mechanisms plays a role in its fast spread within such a huge area. Its rapid population growth and spread in countries into which eucalypts have been introduced is attributed to the thelotokous parthenogenetic reproduction, multivoltine development and the absence of natural enemies (Mendel *et al.,* 2004). In Tanzania, the pest was first introduced through nursery planting stock (eucalypt clones) which were imported from Kenya in early 2005. Toward the end of 2005, the pest was reported in Tabora, Shinyanga and Coastal regions causing serious damage to young plantations and nursery seedlings (Roux, 2005; FAO, 2009; Petro, 2009). The attack appears to be spreading very fast and to date it is found in most *Eucalyptus* growing areas.

1.5.3 Effects of *Leptocybe invasa* on *Eucalyptus* species

In non-native eucalypt forests throughout the world, the wasp poses a serious threat by causing severe defoliation and degeneration of eucalypt seedlings, coppiced shoots and young trees induced by gall formation (Mendel *et al*., 2004; Protasov *et al*., 2008; Jacob and Kumar, 2009). Galling occurs on the petioles and leaves (mainly mid-ribs) of trees, causing leaf-curl and early senescence of the leaves (Mendel *et al*., 2004). Heavy galling causes malformation, stunted growth and in extreme cases, tree death (Mendel *et al*., 2004; Senthilkumar *et al.,* 2013). The effects have been reported to be most severe on eucalypt seedlings and trees of less than three years in age (Mendel *et al*., 2004; Thu *et al.,* 2009; Nyeko *et al.,* 2010; Petro *et al*., 2014b). Dittrich-Schröder *et al*. (2012) reported that infestations by *L. invasa* in its introduced range affect the productivity of commercial eucalypt plantations, ultimately adversely affecting the revenue generated from the forestry sector. In 2007, more than 20 000 ha of two year old eucalypts were reported to be affected by gall formation in the southern States of India (Jacob *et al.,* 2007). Kulkarni (2010) reported that in India, 2.5 million ha of eucalypts were expected to lose 25% of wood production annually resulting in an annual loss of US$ 20 million due to heavy damage of *L. invasa.* In Vietnam and India, it was reported that clones were seriously damaged by *L. invasa* in many nurseries and young plantations and it was becoming difficult to find seedlings to establish new plantations (Thu *et al.,* 2009; Javaregowda and Prabhu, 2010). In Israel, Thailand and China, planting of *E. camaldulensis* was stopped because of extensive attacks by the wasp (Thu *et al.,* 2009). In Sri Lanka, four ha of coppiced *E. camaldulensis* trees were damaged by *L. invasa* where the majority (62.5%) of the trees had low infestation while 10% had heavy infestation (Karunaratne *et al.,* 2010). In Kenya, 4% of trees under 5 years and 20% of seedlings were damaged by this pest (Anonymous, 2007).

1.5.4 Management of *Leptocybe invasa*

Various strategies are being pursued for the management of *L. invasa* in its introduced range. Chemical control of *L. invasa* includes foliar spray and spot application of insecticides (Zheng *et al.,* 2014). Among different insecticides tested, both under nursery and field conditions, acetamiprid (0.2 g/l) reduced adult emergence, whereas dimethoate (1.5 ml/l) and profenofos (2.0 ml/l) had no significant effect (Kumari, 2009; Javaregowda and Patil, 2010; Kulkarni *et al.,* 2010); spot application of carbofuran 10G at 0.5 g and 1.0 g per plant applied in the root zone were effective in reducing the number of fresh galls per 10 cm twig length and were superior to botanicals (Javaregowda and Patil, 2010); application of carbofuran 3G or phorate 10G at 1 g/plant in the soil, 45 days after transferring the seedlings to polyethylene bags followed by spray application of dimethoate at 0.03 % or phosphamidon at 0.04 % or oxydemeton-methyl at 0.025 % or acephate at 0.075 % at 15-day interval starting one month after granular application could be the effective strategy to check infestation by the pest in a eucalypts nursery (Jhala *et al.,* 2010). The application of Rogor or Metacid 50 (@ 2ml/1 litre water) on foliage at fortnightly intervals proved effective in Israel and Turkey (Protasov *et al*., 2008). Application of Imidacloprid (Confidor 350 sc) and Acephate 98% (Acephate) chemicals have been used in Tabora (Tanzania) and they appeared to be effective in nurseries (Madoffe and Petro, 2011). However, the larvae and pupae stay in gall for better protection and display overlapping generations, so that it is difficult to determine the optimum control period and obtain effective chemical control in the field (Zheng *et al.,* 2014). In view of the foregoing, using pesticides in controlling/mitigating *L. invasa* is not a sustainable strategy.

Biological control is a preferred strategy and it has been reported to show good promise. For example, the parasitic wasps, *Quadrastichus mendeli* Kim & La Salle (Hymenoptera: Eulophidae) and *Selitrichodes kryceri* Kim & La Salle (Hymenoptera: Eulophidae) have been introduced to Israel from Australia in an effort to control *L. invasa* in the Mediterranean region (Kim *et al*., 2008). Detailed work on the biology of *S. kryceri* and *Q. mendeli* has shown parasitism levels of 52 % and 73 %, respectively

(Kim *et al*., 2008). An Australian *Megastigmus* species (Hymenoptera: Torymidae) (Doğanlar and Hassan, 2010), two *Megastigmus* species native to Israel and Turkey (Protasov *et al*., 2008), and a range of parasitoids native to India (Kulkarni *et al.,* 2010), have also been used. A fifth species, *S. neseri* discovered in South Africa appears to hold good promise for control of *L. invasa* and is currently the main focus of study by the Tree Protection Co-operative Programme (TPCP) team in South Africa (Nadel and Slippers, 2011).

Breeding resistant varieties is another effective management option to prevent *L. invasa* from causing economic loss. Many countries and institutions such as Vietnam, Thailand, Laos, and the Forestry and Agricultural Biotechnology Institute (FABI) have paid attention to the development of resistant cultivars (Oates *et al.,* 2012). Many resistant varieties such as *E. henry*, *E. urophylla*, *E. torquata, E. citriodora,* and hybrid clones of *E. grandis* × *E. urophylla* (GU) 7, GU21 and GU609 have been found during field investigation (Mendel *et al.,* 2004; Nyeko and Nakabonge, 2008; Nyeko *et al.,* 2009; Petro *et al*., 2014b). Losses caused by *L. invasa* in eucalypt plantations may be reduced substantially through good silvicultural practices. Such practices include good site selection and preparation, planting healthy and vigorous seedlings, planting at the onset of the rainy season, proper weeding particularly in the first 1-2 years of planting or coppicing, and removal of severely infested seedlings or saplings. The rule of thumb should be not to plant any seedling having *L. invasa* galls (Nyeko and Nakabonge, 2008). Periodic monitoring of infested nurseries and plantations, mechanical removal, selective pruning or plucking of infested leaves or shoots and strict quarantine have been suggested (Jacob *et al.,* 2007; Kumari, 2009; Senthilkumar *et al*., 2013).

1.6 Problem Statement and Justification

The total gross area of forest plantations in Tanzania is estimated to be about 250 000 ha (Ngaga, 2011). Eucalypts occupy 25 000 ha or 10% of the total forest plantations in the country. These eucalypts provides goods and services which contributes to individual livelihoods and national economies in the tropics as well as to reduce pressure on natural forests. For several years, eucalypt trees have been pest free all over the world, until the year 2000 when *L. invasa* was reported for first time in history (Mendel *et al.,* 2004; Nyeko *et al*., 2009). Since 2005, when the pest was first reported in Tanzania, posing great threat of damage on young eucalypts particularly in Tabora, Shinyanga and Coastal regions, concern has been raised about its infestation on eucalypts in the country. Considering the rapid global spread of this introduced pest and the economic importance of eucalypts, very little has been done to avert the threats posed by the pest in the country. Little has been documented in Tanzania in terms of distribution, abundance, variability of attack on different germplasm and population dynamics. Nothing has also been documented on the effects posed by *L. invasa* on qualities of host trees, growth rates, mechanical properties of poles and timber and economic analysis of the implications of the pest infestation. Even after more than a decade of its existence, no specific recommendation for sustainable control of the pest has been documented. Information showing regular and prolonged monitoring of *L. invasa* populations and infestations on eucalypts under different management situations and seasons in East Africa is also lacking.

Therefore, knowledge on infestation density and effects of *L. invasa* on growth and on wood basic density of some widely commercially grown *Eucalyptus* species in Tanzania was required. The results from this study will be used to estimate the economic consequences and project future infestation levels of the pest. In addition, information generated on wood properties of infested and uninfested eucalypt wood will be used in making recommendations which will lead to efficient utilization of *L. invasa* infested and uninfested eucalypts. Furthermore, this study generated valuable information to forest managers, policy makers, plant protectionists, research and training institutions and individual's small eucalypt growers in the country to find ways of managing the pest situation accordingly.

1.7 Objective of the Study

1.7.1 Overall objective

The overall objective of this study was to provide information on the infestation density and the effects of Eucalyptus gall forming wasp, *Leptocybe invasa* Fisher & La Salle (Hymenoptera: Eulophidae) on growth, biomass production and on wood basic density of some widely commercially grown *Eucalyptus* species in Tanzania.

1.7.2 Specific objectives

i. To determine infestation density of *L. invasa* on five commercially grown *Eucalyptus* species (*E. camaldulensis, E. saligna*, *E. grandis, E. tereticornis* and *E. citriodora*) in three agro-ecological zones of Tanzania.

ii. To assess the effects of *L. invasa* infestation on diameter and height growth and wood basic density of *E. camaldulensis, E. saligna* and *E. tereticornis* species in Tanzania.

iii. To assess the impact of *L. invasa* infestation on growth and biomass production of *E. saligna* and *E. grandis* seedlings in Tanzania.

1.8 Hypotheses of the Study

This study was guided by two hypotheses

i. *Leptocybe invasa* is not widely distributed in Tanzania and has no serious effects on the health of the eucalypt trees.

ii. The abundance and intensity of damage of *Leptocybe invasa* to eucalypt trees is fairy low and has no serious effects on the health of the plantation and woodlots.

CHAPTER TWO

2.0 MAIN RESULTS AND DISCUSSION

2.1 Infestation Density of *L. invasa* on Five Commercially Grown *Eucalyptus* Species

2.1.1 Infestation density of *L. invasa* in different agro-ecological zones

The results from this study showed clearly that *L. invasa* was widespread in all areas of investigation. *Leptocybe invasa* infested about 60% of the 1 536 trees assessed with the most severe infestation occuring in the Coastal agro-ecological zone (Paper 1). The incidence, severity and damage index of *L. invasa* infestations was high in Coastal zone, followed by Plateaux and Southern Highlands being the least (Table 1). The Southern Highlands zone where infestation was relatively low is a low temperature zone (Paper I). Therefore, the results showed that there was a close relationship between temperature and *L. invasa* infestation. This is because optimal temperature is essential for the production and growth of new leaves of *Eucalyptus* species and speeding up metabolic activities within the wasp's body and consequently increase its rate of development ((Mendel *et al.*, 2004; Gullan and Cranston, 2005). Protasov *et al*. (2008) reported the emergence of gall wasp from eucalypt foliage throughout the year in greenhouse at a temperature range of 23–31^{o}C while Nyeko *et al.* (2009) did not record any *L. invasa* infestation in Kabale District with mean annual temperatures of 10 - 23^{o}C. In Israel, Mendel *et al.* (2004) indicated that the wasp oviposits only when the average maximum temperature has risen above 20^{o}C. The temperatures recorded in this study which ranged from 21^{o}C in the Southern highlands to 28^{o}C in the Coastal agro-ecological zones were within the range hence ensuring good survival of *L. invasa* in the studied sites.

Table 1: Mean Incidence, Severity and Damage Index of *Leptocybe invasa* in three Agro-ecological zones of Tanzania

Agro-ecological zone	Incidence (%)	Severity	Damage Index
Coastal	60^a	2.23^a	1.67^a
Plateaux	50^a	2.05^a	1.55^a
Southern Highlands	23^b	1.33^a	0.38^b

Note: Means followed by the same letters within a column are not significantly different at P = 0.05.

2.1.2 Infestation density of *L. invasa* on different *Eucalyptus* species

Overall, 1 536 trees were examined. The majority (47%) were *E. camaldulensis* followed by *E. saligna* (23%), *E. tereticornis* (16%), *E. grandis* (8%) and *E. citriodora* (6%) (Paper I). Results showed that *E. tereticornis* had highest mean incidence, severity and damage index (DI) of *L. invasa* followed by *E. camaldulensis* and *E. saligna* was the least while *E. citriodora* and *E. grandis* were not infested (Paper I). According to Nyeko *et al*. (2010), *Eucalyptus* species showing a damage index (DI) = 0 were considered to be resistant, 0 < DI < 0.1 (tolerant), 0.1 ≤ DI < 0.5 (moderately susceptible), and DI ≥ 0.5 (highly susceptible). Therefore, *E. grandis* and *E. citriodora* (with DI = 0.0) were classified as resistant, *E. saligna* (0.4) as moderately susceptible and *E. camaldulensis* (2.4) and *E. tereticornis* (3.0) as highly susceptible. This variation in infestation, to a large extent is genetically controlled (Nadel and Slippers, 2011). These findings are in line with Mendel *et al*. (2004). However, the absence of *L. invasa* on *E. grandis* contrasts with the report by the European and Mediterranean Plant Protection Organization (EPPO, 2006) that the species is host to *L. invasa*. This *L. invasa* infestation difference in the same species in different sites may be attributed to differences in climatic variables, provenances, soil factors, silvicultural practices, and crop type (coppice against first crop) (Nyeko *et al*., 2010). This susceptibility information of *L. invasa* can be used by stakeholders to promote what to plant in *L. invasa* infested areas. There was no evidence of preference of *L. invasa* infestation/damage in any particular level of the tree canopy (Paper I). Based on what has been observed in other species this could be due to relatively equal openness nature of the structure of the eucalypt tree crowns. This type of crown structure receives light, moisture and wind fairly equally in all parts, hence harbouring relatively equal number of gall wasps between crown parts. Madoffe (1989), Chilima and Leather (2001) and Petro (2009) found pine woolly aphid (PWA) settling and reproducing on the outer shoot-end sections of young *Pinus* trees and there was no evidence of preference for any particular levels of tree canopy.

2.1.3 Infestation density of *L. invasa* on different tree age groups

Results revealed that young (1-3 years) eucalypt trees were more preferred by gall wasps than middle aged (4-6 years) trees (Paper I). This is due to the fact that young eucalypt trees with thin bark require less energy to attack by the insect than mature trees. Similar results were reported by Kolb *et al*. (2006) that *Ips pini* selects stems of young *Pinus ponderosa* with thin bark which requires less expenditure of energy by the insect than an attack of stems of mature trees with thick bark. Results of this study are in keeping with those of Mendel *et al*. (2004), Nyeko (2005), Mutitu *et al.* (2010), Kumari *et al.* (2010). However, Dittrich- Schröder *et al.* (2012) reported that *L. invasa* attacks trees of all ages, from nursery stock to mature trees, but the damage is most severe on younger plants.

2.1.4 Relationship between *L. invasa* damage and stand altitude and age of eucalypts

Leptocybe invasa damage index showed a weak and non significant negative relationship with stand altitude (Paper I). There was a clear decrease in *L. invasa* damage with increase in stand altitude in Coast and Southern Highlands agro-ecological zones. This is due to the reason that an increase in altitude results in decrease in temperature which affects the development, survival and abundance of the insect (Gullan and

Cranston, 2005). The weak coefficient of determination observed implies that there are other factors than altitude that influence *L. invasa* damage. These factors may include tree phenology, tree secondary compounds, leaf traits, abundance of natural enemies, tree species, tree age, season, zone/site, soil, and climate (Kudo, 1996; Hodkinson, 1997; Petro, 2009). Similar relationships between altitude and *L. invasa* damage on eucalypts were observed by Nyeko *et al.* (2009). The contradicting results recorded in *E. camaldulensis* in Plateaux agro-ecological zone is due to an influence of higher relative humidity recorded in the zone (Paper I). Gullan and Cranston (2005) reported that low relative humidity affects the physiology and thus development, longevity and oviposition of many insects. The results showed that an increase in species age resulted in decrease of *L. invasa* damage (Paper I). The wasp prefers young trees, young coppice as well as nursery seedlings due to their softness compared to mature/old trees. Young eucalypt trees have low defence mechanism against pests. Rohfritch (1981) found that all secondary defence substances such as tannins, their phenolic precursors and lignin are considered to increase with tree age.

2.2 Effects of *L. invasa* Infestation on Diameter and Height Growth and Wood Basic Density of *Eucalyptus* Species

2.2.1 Diameter and height growth variation between infested and uninfested eucalypt trees

Results showed that the mean Dbh and height of all infested trees were relatively lower than uninfested ones although their differences were not statistically significant ($P>0.05$) (Paper II). The mean Dbh of infested *E. camaldulensis, E. tereticornis* and *E. saligna* were reduced by 7.8%, 2.1% and 13.6% respectively. Similarly, the heights of infested *E. camaldulensis, E. tereticornis* and *E. saligna* were reduced by 6.6%, 9.5% and 3.8% respectively. The recorded growth reduction for infested eucalypts is due to the fact that

L. invasa inflicts severe damage by inducing galls mainly on rapidly growing parts like shoots, young stems, petiole or midribs of leaves which form an ideal breeding site for the wasp (Thu *et al*., 2009). Severe damage of young stems and leaves caused by gall forming insects may cause loss of stored food in a tree and change production regulators, which would affect photosynthesis and hence cause growth loss in an infested plant (Dubt and Shurer, 1994; Mendel *et al*., 2004). The results of this study are relatively lower than that of Elek (1997) who reported a reduction of 53% and 25% of height and diameter respectively of *E. regnas* saplings when infested by *Chrysophtharta bimaculata* for a period of eight years.

2.2.2 Mean basal area and volume variation between infested and uninfested eucalypt trees

Results showed that the mean basal area and volume of all infested trees were relatively lower than uninfested ones although their differences were not statistically significant ($P>0.05$). The mean basal area of infested trees were reduced by 16.4%, 17.1% and 24.5% compared to uninfested *E. camaldulensis, E. tereticornis* and *E. saligna* trees respectively. Similarly, the mean volume of infested trees were reduced by 17.8%, 16.1% and 23.1% compared to uninfested *E. camaldulensis, E. tereticornis* and *E. saligna* trees respectively (Paper II). The reduction of basal area and volume in infested trees shows that *L. invasa* infestation results in loss in productivity. The results of this study are in keeping with those of Mendel *et al.* (2004) who reported that *L. invasa* infestation causes severe injury in young foliage of *Eucalyptus* species by inducing galls which become a major constraint in growth and wood production. In another study, Jordan *et al.* (2002) reported a reduction of 16% of basal area of *E. globulus* when mildly infested by *Perga affinis* (Sawfly) for a period of four years. They further reported a reduction of 31% of basal area of the same species when severely infested by *P. affinis*. Elek (1997) reported a reduction of 30% of wood volume of *E. regnans* saplings when infested by *Chrysophtharta bimaculata* for a period of eight years. Elliott *et al.* (1993) found that *E. regnans* trees repeatedly damaged by Chrysomelid leaf beetles lost about 45% and 52% of their potential height and basal area increment respectively, while both Candy *et al.* (1992) and Wills *et al.* (2004) observed, in defoliation trials running for more than 10 years, that repeated defoliation episodes significantly reduced diameter and height growth and overall economic viability of plantations.

Based on the reduction of basal area and volume of all three *Eucalyptus* species, it is clear that the effect of *L. invasa* on growth was higher in *E. saligna* than *E. camaldulensis* and *E. tereticornis.* This implies that *E. saligna* is more susceptible to *L. invasa* infestation than the other eucalypt species. The variation in effect on growth between the species was due to differences in susceptibility. This variation in susceptibility indicates an opportunity for selecting eucalypt germplasms for resistance against the pest. These results are contrary to those reported by Thu *et al.* (2009) and Petro *et al*. (2014b) who found that *E. saligna* were moderately infested while *E. tereticornis* and *E. camaldulensis* were severely infested by *L. invasa*. However, Nyeko *et al.* (2010) classified all *E. tereticornis, E. camaldulensis* and *E. saligna* as moderately susceptible to *L. invasa* infestation.

2.2.3 Wood basic density variation between infested and uninfested eucalypt trees

Results showed that infested wood had mean basic density which was 2.7%, 5.3%, and 7.3% higher than uninfested wood for *E. tereticornis, E. camaldulensis* and *E. saligna* respectively. However, there were no significant ($P > 0.05$) differences in mean basic densities between infested and uninfested trees (Paper II). The observed variations in wood basic density between infested and uninfested eucalypts were attributed by

L. invasa infestation intensity as severe infestation affects photosynthesis and hence growth retardation, stunting and loss of vigour (Mendel *et al.,* 2004; Nyeko, 2005; Protasov *et al.,* 2008; Kumari *et al.,* 2010; Karunaratne *et al*., 2010). Retardation and stunted growth of trees results in the formation of reaction wood (tension wood in hardwood) which influences density. Tension wood has higher density in comparison to normal wood. The results of this study are in agreement with those of Tsoumis (2009) that generally, the density of tension wood is 2-10% higher than normal wood. Batajas-Morales (1987) reported that in drier regions where trees become retarded in growth, such trees produce wood of higher density. Tsoumis and Panagiotidis (1980) reported that suppressed trees produce high proportion of latewood than unsuppressed trees, which could have also occurred in trees in this study. Latewood is made of cells which have thicker walls and small cavities in comparison to earlywood which results in latewood having higher density compared with earlywood (Tsoumis, 2009). *Leptocybe invasa* infestation might also results in the variation of chemical components of cell walls between infested and uninfested trees. Variation of chemical components of cell walls, for example cellulose and lignin contributes to wood density differences (Tsoumis, 2009).

2.2.4 Wood basic density variation between species and within trees

Results showed that the mean wood densities of both infested and uninfested *E. camaldulensis* and *E. tereticornis* were significantly higher than those of *E. saligna* (Table 2). The type of cells, their proportions and arrangements contributed to these differences (Panshin and De Zeeuw, 1970; Ishengoma *et al*., 2007). Axial and radial basic density variation of both infested and uninfested eucalypts showed different patterns of variation within each tree (Paper II). These results are in agreement with Panshin and De Zeeuw (1970) who noted that in hardwoods, basic density variations show very little consistency with no overall dominance of a single pattern. This is because of interaction of ring width and proportion of latewood, and effects of age (juvenile wood and heartwood) in different parts within a trunk results in a complex distribution of density (Tsoumis, 2009).

Table 2: Wood basic density variation between *Eucalyptus* species in Coastal agro-ecological zone of Tanzania

Eucalyptus species	Mean wood basic density (Kgm $^{-3}$)	
	infested	uninfested
E. camaldulensis	466.86^{a} (15.43)	442.09^{a} (11.11)
E. saligna	420.04^{b} (16.17	389.23^{b} (14.59)
E. tereticornis	466.01^{a} (12.54)	453.25^{c} (15.00)
p-value	0.047	0.004

Means followed by the same letters within a column are not significantly different at P = 0.05. Numbers in brackets are standard error.

2.3 Impact of *L. invasa* Infestation on Growth and Biomass Production of *E. grandis* and *E. saligna* Seedlings

2.3.1 Survival of *E. grandis* and *E. saligna* seedlings

The study revealed that 22 weeks after infestation, the survival of infested *E. grandis* seedlings was significantly lower (DF = 8, P = 0.0094) than the uninfested seedlings. The mean survival of infested *E. saligna* was relatively lower than that of uninfested ones though not statistically significant (DF = 8, P = 0.648) (Table 3) (Paper III). The mean survival of both uninfested *E. grandis* and *E. saligna* seedlings were higher than infested seedlings due to the fact that gall forming insects may cause loss of stored food in a seedling and change production regulators, which would affect photosynthesis and hence cause growth loss and subsequent death of the host (Dubt and Shurer, 1994).

Results further showed that both infested and uninfested *E. grandis* had higher survival than *E. saligna* seedlings (Paper III). This survival variation of seedlings between species is due to difference in susceptibility to various pests. Thu *et al*. (2009) recorded low survival rates of 37% and 44.4% of *L. invasa* infested *E. saligna* and *E. grandis* respectively of three months after planting in Vietnam (Thu *et al*., 2009). It is possible that the low survival recorded in that study was due to *L. invasa* and other pest attack.

Table 3: Mean survival (%) of *Eucalyptus* seedlings after 22 weeks of *L. invasa* infestation at Kwamarukanga, Tanzania

	E. grandis (Mean ±SE)	*E. saligna* (Mean ±SE)
Infested	81 ± 2.45	78 ± 5.15
Uninfested	93 ± 2.55	81 ± 3.67

2.3.2 Impact of *L. invasa* infestation on growth of *E. grandis* and *E. saligna* seedlings

Results showed that 22 weeks after infestation, heights of infested *E. grandis* seedlings were reduced by 39.6% while diameters were reduced by 11.3% compared to uninfested seedlings. Similarly, the heights of infested *E. saligna* seedlings were reduced by 38.2% while diameters were reduced by 7.7% compared to uninfested seedlings (Paper III). The wasp appeared to affect chiefly seedling height rather than diameter possibly due to the fact that it inflicts severe damage on rapidly growing parts like shoots, young stem, petiole or midribs of leaves than other parts (Mendel *et al.,* 2004; Thu *et al.,* 2009). The results are in agreement with Carter and Nichols (1985) who demonstrated that shoot infestation can seriously affect the overall height growth of a tree rather than growth of other parts. Elek (1997) reported a higher growth reduction of height (53%) than that of diameter (25%) of *E. regnans* saplings when infested by Eucalyptus leaf beetle, *Chrysophtharta bimaculata*. In another study, Prakash (2008) reported a reduction of

100% of height of Australian eucalyptus trees when infested by herbivorous insects for a period of three years after infestation. Likewise, Nadel *et al.* (2010) noted severe infestations of *Thaumastocoris peregrinus*, causing leaf loss leading to severe canopy thinning. This results in branch dieback, which generally has a very big impact on growth of eucalypts.

The reduction of heights and diameters of seedlings due to *L. invasa* infestation was higher in *E. grandis* than *E. saligna* implying that *E. grandis* is more susceptible to *L. invasa* infestation than *E. saligna*. These results concur with Thu *et al.* (2009) who reported that three month old nursery stock of *E. grandis* and *E. saligna* were severely and moderately damaged by *L. invasa* respectively. However, Nyeko *et al.* (2010) classified both *E. grandis* and *E. saligna* as moderately susceptible to *L. invasa* infestation although *E. grandis* had a higher DI than *E. saligna.*

2.3.3 Impact of *L. invasa* infestation on biomass production of *E. grandis* and *E. saligna* seedlings

Results showed that 22 weeks after *L. invasa* infestation, the biomass was reduced by 28.2% (roots), 61.2% (stem), 5.6% (branches), 62.0% (leaves), and 52.1% (whole plant biomass) in *E. grandis.* Similarly, the biomass was reduced by 18.0% (roots), 67.9% (stem), 7.9% (branches), 21.3% (leaves) and 44.5% (whole plant biomass) in *E. saligna* (Paper III). Yield losses due to *L. invasa* infestation shown by whole seedlings and their components for eucalypt seedlings imply that the pest has a substantial impact on biomass production. The large recorded loss in dry weight of stems and leaves is possibly due to the fact that *L. invasa* inflicts severe damage by inducing galls mainly on rapidly growing parts like shoots, young stem, petiole or midribs of leaves which form an ideal breeding site for the wasp (Thu *et al.,* 2009). Severe damage of stems and leaves, which are photosynthetic parts of the plant, results in reduced stored food reserves and hence growth decline of the whole plant. Madoffe and Austarå (1990) reported that Pine Woolly Aphid (PWA) caused reduction of root, stem and shoot and total plant dry weight biomass production by 27.8%, 20.9% and 22.4% on *P. patula* seedlings respectively. In another study, Madoffe *et al.* (2001) found that *Heteropsylla cubana* caused a reduction of shoot dry weight biomass production of 20.1%, 6.1% and 9.1% for *Leucaena leucocephala* seedlings at 10%, 25% and 50% shade respectively. Further, they found 15.9%, 4.8% and 7.0% reduction of whole plant dry weight biomass production for seedlings in 10%, 25% and 50% shade respectively. This implies that the largest reduction occurred at the lowest shading. The higher dry biomass reduction of whole seedling of *E. grandis* is an indication that the species is more susceptible to the pest than *E. saligna*. Such variations in host susceptibility indicate an opportunity for selecting *Eucalyptus* species for resistance against the pest. Stakeholders can be able to use less susceptible eucalypt species to determine the planting species in areas with *L. invasa* infestation.

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CHAPTER THREE

PAPER I

Infestation Density of Eucalyptus Gall Wasp, *Leptocybe invasa* Fisher and La Salle (Hymenoptera: Eulophidae) on Five Commercially Grown Eucalyptus Species in Tanzania

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PAPER II

Effects of Eucalyptus gall wasp, *Leptocybe invasa* Fisher and La Salle infestation on diameter and height growth and wood basic density of three *Eucalyptus* species in Tanzania

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PAPER III

Impact of Eucalyptus gall wasp, *Leptocybe invasa* infestation on growth and biomass production of *Eucalyptus grandis* and *E. saligna* seedlings in Tanzania

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CHAPTER FOUR

4.0 CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

4.1.1 Infestation density of *L. invasa* on five commercially grown *Eucalyptus* species

Results showed that *L. invasa* was widespread in all studied agro-ecological zones although at different intensities. The infestation was more prevalent and severe in Coastal agro-ecological zone which is hotter than Plateaux and Southern highlands agro-ecological zones which are relatively cooler. The trend showed that *E. tereticornis* was more infested followed by *E. camaldulensis* and *E. saligna* was the least while *E. grandis* and *E. citriodora* were not infested. The young age group (1-3 years) of trees was more damaged by pest than the middle age group (4-6 years). Pest infestation increased with increase in temperature but decreased with increasing altitude.

4.1.2 Effects of *L. invasa* infestation on diameter and height growth and wood basic density of *Eucalyptus* species

The mean Dbh of infested trees with the age of 6 years were reduced by 7.8%, 2.1% and 13.6% and mean heights were reduced by 6.6%, 9.5% and 3.8% compared to uninfested ones for *E. camaldulensis, E. tereticornis* and *E. saligna* respectively. The mean basal area of infested trees were reduced by 16.4%, 17.1% and 24.5% and mean volume were reduced by 17.8%, 16.1% and 23.1% for *E. camaldulensis, E. tereticornis* and *E. saligna* respectively. The mean wood basic densities of infested eucalypt trees were higher than uninfested eucalypts. The reduction of height, diameter, biomass, basal area and volume of eucalypt trees due to *L. invasa* infestation showed that the pest affects the productivity of commercial eucalypt trees which may affect the revenue generated from the forestry sector.

4.1.3 Impact of *L. invasa* infestation on growth and biomass production of *E. grandis* and *E. saligna* seedlings

Leptocybe invasa infestation had a significant impact on growth and biomass production of *E. grandis* and *E. saligna* seedlings. Twenty two weeks after infestation, the pest appeared to affect chiefly seedling height rather than diameter. Height and diameter were reduced by 39.6% and 11.3% for *E. grandis* and by 38.2% and 7.7% for *E. saligna* respectively compared to uninfested seedlings. There was a large biomass reduction in stem and leaves than other components in both *E. grandis* and *E. saligna* seedlings. The impact of *L. invasa* infestation on growth and biomass production was higher in *E. grandis* than *E. saligna* seedlings.

4.2 Recommendations

Based on the results from this study and experiences from other studies, it is recommended that;

- Further study is recommended to assess the magnitude of damage and extent of spread across the country.
- Similar study on impact of *L. invasa* infestation on growth and biomass production should look into other commercially grown *Eucalyptus* species in Tanzania.
- Further research is also needed to better understand the mechanisms governing resistance to *L. invasa* and thus be able to better predict the susceptibility of new genotypes or current genotypes planted in new areas.
- *Leptocybe invasa* infested and uninfested wood of eucalypts trees can be assigned similar uses although more and detailed studies are required on fibre properties in order to arrive at recommendations on specific uses of infested and uninfested wood.

- Management efforts need to focus on controlling the spread of the pest using biological control, cultural techniques and planting resistant / less susceptible genotypes.