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THESIS

DISTRIBUTION OF THE YELLOW CRAZY ANT (*Anoplolepis gracilipes* Smith, 1857; HYMENOPTERA: FORMICIDAE) IN THAILAND AND ITS ECOLOGICAL IMPACT AT SAKAERAT BIOSPHERE RESERVE

SASITORN HASIN

A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
Doctor of Philosophy (Forestry)
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Sasitorn Hasin 2015: Distribution of the Yellow Crazy Ant (*Anoplolepis gracilipes* Smith, 1857; Hymenoptera: Formicidae) in Thailand and Its Ecological Impact at Sakaerat Biosphere Reserve. Doctor of Philosophy (Forestry), Major Field: Forestry, Faculty of Forestry. Thesis Advisor: Assistant Professor Wattanachai Tasen, Ph.D. 149 pages.

Anoplolepis gracilipes is a widespread, tropical ant species in Asia and can cause considerable damage to natural ecosystems. Recent information on this ant has shown that it has caused the reduction of native animal communities in island ecosystems. *A. gracilipes* is currently formally classified as an invasive ant species which is threatening the biodiversity of fauna and flora in Thailand, However, in Thailand, there is a little information concerning its distribution, and its impact on forest ecosystems is uncertain. This study focused on the distribution of *A. gracilipes* in Thailand and its impact on forest ecosystems in the Sakaerat Biosphere Reserve (SERS). The sampling distribution of *A. gracilipes* in Thailand was investigated in 2011, 2012, and 2013, and its ecological impact was assessed during November, 2011 to October, 2012, in a dry evergreen forest in SERS. Based on the sampling distribution, *A. gracilipes* had the highest frequency (82 % of the total study sites) and currently inhabits almost all habitats-types in Thailand including forest areas, plantation, agricultural and urban areas, with the exception of hill evergreen forest, and these data provide strong evidence that *A. gracilipes* is the most common invasive species in Thailand. The study documents that *A. gracilipes* has a negative ecological impact on the diversity of non-ant arthropods and communities resulting in the potential loss of six groups of non-ant arthropods—isopods, cockroaches, termites, centipedes, millipedes, and spiders. Similar results were also found for ants, with the study providing evidence that invasion by *A. gracilipes* has resulted in losses of native ant diversity and communities and has altered the nest abundance of ants and especially ant nest soil and litter. The CO_2 measurements indicated that supercolonies of *A. gracilipes* can have direct and indirect effects on soil CO_2 efflux. There is a direct effect on soil CO_2 efflux values from its subterranean nests from which the CO_2 efflux was significantly higher than from surrounding nest soil. Thus, it is possible that the reduction of ant diversity and community composition, and nest abundance caused by the invasion of *A. gracilipes* could be the causes of a decrease in the CO_2 efflux from the soil in dry evergreen forest.

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Student's signature Thesis Advisor's signature

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LIST OF ABBREVIATIONS

DNP	=	Departments of National Park, Wildlife and Plant Conservation
ONEP	=	Office of Natural Resources and Environmental Policy and Planning
UNEP	=	United Nations Environment Programme-Asia Pacific
ACB	=	ASEAN Centre for biodiversity
IUCN	=	International Union for Conservation of Nature
CBD	=	Conversation Biological Diversity
GISP	=	Global Invasive Species Programme
SERS	=	Sakaerat Environmental Research Station
US	=	United States of America
T	=	Tramp ant
N	=	Native ant
I	=	Invasive ant
UVS	=	Uninvaded site
IVS	=	Invaded site
ha	=	Hectare
v/v	=	Volume/Volume
g	=	Gram
m	=	Meter
m^2	=	Square meter
cm	=	Centimeter
masl	=	Meters above sea level
CO_2	=	Carbon dioxide
μmol CO_2 m^{-2} s^{-1}	=	Micromoles carbon dioxide per square meter per second

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DISTRIBUTION OF THE YELLOW CRAZY ANT (*Anoplolepis gracilipes* Smith, 1857; HYMENOPTERA: FORMICIDAE) IN THAILAND AND ITS ECOLOGICAL IMPACT AT SAKAERAT BIOSPHERE RESERVE

INTRODUCTION

Invasive species are considered as the most important threat to the biodiversity of fauna and flora in ecosystems. Ants are considered among the most successful invaders (Holway *et al*., 2002). They can easily hide in cargo, infest mail parcels, and be transported to new ecosystems by human activities. The impact of invasive ant species can be measured in natural ecosystems. Previous studies have attempted to quantify the impact of an invader by comparing one site before and after an invasion (McNeely *et al*., 2001), and by comparing different sites of invaded and uninvaded patterns with detailed experiments to elucidate the mechanisms involved. The impact of an invader is well studied through the community effects on native species in term of species richness, diversity, and trophic structure (Holway *et al*., 1998; 1999; 2002). Invasive ant species have high populations and can have a negative effect on native communities and ecosystems. For example, invasive ants disrupt: arthropods which play an important ecological role in the decomposition process such as the carrion decomposers (6 families) (Stoker *et al*., 1995), insect herbivores (Eubanks, 2001) and ant seed dispersal (Rodriguez-Cabal *et al.*, 2009; Gómez *et al.*, 2003).

Ants have been defined as ecosystem engineers, because they affect ecosystem processes and soil function by their nesting and foraging activities (Lavelle and Spain, 2003). In their nests, ants alter their physical and chemical environments by constructing tunnels and chambers, accumulating soil particles, and storing litter and food above and below the tunnels in the ground nests (Folgarait, 1998). Studies have reported that mound-type nests made from soil and/or litter have nutrient profiles that differ from those of the surrounding soil or forest floor (Domisch *et al*., 2008; Ohashi

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et al., 2007a). Moreover, subterranean ant nests can affect water infiltration rates (Lavelle and Spain, 2003) and soil erosion (Cerdà and Jurgensen, 2008) by decreasing the soil bulk density and increasing the soil porosity. The alteration of soil chemical properties, such as nutrient concentrations (Wagner *et al.*, 2004), can result in different vegetation types and biodiversity in areas around subterranean nests (Wagner *et al.*, 1997; Whitford *et al*., 2008). Some recent studies have suggested that the high CO_2 efflux from ant mounds increases the spatial variability in total CO_2 efflux from the forest floor (Domisch *et al.*, 2006; Ohashi *et al*., 2005), and ant nests can affect variations in the C balance in ecosystems (Ohashi *et al*., 2012).

Thailand is located in the tropical region and is one of the important ecosystems on Earth in terms of its high species diversity of plants and animals (Myers *et al*., 2000). Unfortunately, increasing human population growth and deforestation, resulting in growing urbanization and industrialization, have been implicated not only in reducing biodiversity (CBD, 2004) but also in decreasing natural and ecological barriers to invasion processes (Davis, 2009). It might be possible that as a consequence, biological invasion by invasive ant species can occur in various ecosystems in Thailand.

Anoplolepis gracilipes was first reported in Thailand in 1930 (ISSG, 2011). ONEP (2009) described the status of *A. gracilipes* as an invasive ant species in Thailand and also concluded that this species was having a negative effect on the species diversity and population of native animals in forest ecosystems including arthropods. Previous studies have reported lower species diversity and abundance of arthropods in the infestation areas of invasive species such as spiders, beetles, and ants (Morrison, 2002; Krushelnycky and Gillespie, 2008). Other research has documented that *A. gracilipes* acts as a predator of keystone species, such as the land crab, and that declines in the abundance of these communities results in forest ecosystems change (Abbott and Green, 2007; O′Dowd *et al*., 2003; Vanderwoude *et al*., 2000).

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The present study aimed to answer basic scientific questions regarding the diversity of invasive ant species in Thailand. Also, this study attempted to clarify the distribution and ecological impact of invasive ant species by focusing on only one invasive species—*A. gracilipes*—because this invasive ant species was considered to be a serious threat to ecosystems and biodiversity in tropical forest and is one of the world's worst invasive species (Lowe *et al.*, 2000) and an invasive alien ant species in Thailand (ONEP, 2009). In turn, *A. gracilipes* has been introduced in Asia and has had huge impacts on ecosystems and biodiversity, particularly on forest ecosystems on islands; thus, I would expect that *A. gracilipes* can be found in many areas and its ecological impact would also be evident in the forest ecosystems of Thailand. *A. gracilipes* is distributed throughout Thailand. To investigate its impact on ecosystems, the general aim of this study was to document the impact of *A. gracilipes* on the biodiversity of ground-dwelling arthropods and on the CO_2 efflux from soils within forest ecosystems. Therefore, I concentrated my sampling effort in the dry evergreen forest in the Sakaerat Biosphere Reserve because this site has areas recorded as having the presence and absence of *A. gracilipes* in recent history.

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OBJECTIVES

The objectives of this study are divided into two main parts:

Part 1: The diversity of ant and distribution of the invasive ant, *Anoplolepis gracilipes*, in Thailand

Objectives:

1. To study the diversity of an invasive ant species.
2. To examine the distribution of *Anoplolepis gracilipes.*

Part 2: Ecological impact of the yellow crazy ant (*Anoplolepis gracilipes* Smith, 1857; Hymenoptera: Formicidae) in dry evergreen forest in the Sakaerat Biosphere Reserve

Objectives:

1. To investigate the impact of *Anoplolepis gracilipes* on the diversity and community compositions of arthropods.
2. To investigate the impact of *Anoplolepis gracilipes* on the nesting abundance of ants.
3. To compare the CO_2 efflux of the nest and the surrounding soil
4. To investigate the variation in the CO_2 efflux from subterranean nests among ant species.
5. To examine the impact of ants on the CO_2 efflux from soil.

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LITERATURE REVIEW

1. Biological invasions

1.1 Overview

Biological invasion is defined by Vermeij (1996) as "a comparative and systematic approach in which invasion (the extension of species ranges to areas not previously occupied by that species) is studied from the perspective of individual species as well as of the regions and biotas that export and receive invaders". Several definitions is defined by Davis (2011a) biological invasion is a scientific discipline that studies the human transport and introduction of species throughout the world, as well as the subsequent spread of these species and their health, economic and environmental impacts (McNeely *et al*., 2001). Biological invasions have increasingly become intensive research topic in the past decade which leading to conservation concern (e.g. Nentwig, 2007; Davis, 2009; Davis, 2011b; DIVERSITAS, 2011). Biological invasions can transform the ecosystem, exterminate native species, reduce global biodiversity, and threaten human and animal health, and the total cost to control. Consequently, the topic issue on biological invasion has to required international cooperation supplement with the actions of governments, economic sectors and individuals at national and local levels (McNeely *et al*., 2001). Lowry *et al.*, (2013) summarised the literature on the biological invasion, published between 1966 and 2011, with 2398 relevant studies in a field synopsis of the biological invasions. A majority of those studies were concerned with hypotheses for the causes of biological invasions (1405 publications), and the next most common studies were the impacts of invasions (761 publications).

Since major research topics in ecology of invasion by invader such as the competitive abilities of invaders, environmental disturbance, interaction between invader and other organisms (e.g. replacing and changing the roles of native animal species in natural ecosystems (Holway *et al*., 2002; Devis, 2006; Devis, 2011b; Lowry

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et al., 2013), and causing in the occurrence, abundance and extinction of species by invasive species have been examined (Davis, 2011b). Impacts on ecosystems structure and function have also been measured, including on the change and decline in species diversity and community composition, soil nutrient loss and it cycling process, and energy budgets (Mack *et al*., 2000). The ecological explanation and prediction on invasions are most common aims of ecological research nowadays. There are important to examine the impacts of invasion on biodiversity and ecosystem functions (Davis, 2011b; Mack *et al*., 2000). In practice, the explanations of the invasive responses to controlling factors have provided excellent suggestions for invasive species management plans. Standard methods for action plans to control and prevention of invasion or re-invasion have been established which is a key for future management.

1.2 Biological invasion process

The invasion process can be listed as a multi-step of process that is occurred when non-native species are transported to new area range until they become invasive species (Mack *et al.*, 2000).The conceptualization of invasion process was proposed by Richardson *et al.* (2000), as shown in Figure 1. The major barriers in scheme includes (A) geographical barrier (i.e. intercontinental and/or infra-continental), (B) Environmental barriers (i.e. abiotic and biotic) at the new ecosystems, (C) Reproduction barriers (e.g. prevention of consistent and long-term vegetative and generative production of offspring), (D) Local and regional dispersal barriers, (E) Environmental barriers in human-modified or alien-dominated vegetation, and (F) Environmental barriers in natural ecosystems. Following this scheme, Richardson *et al.*, (2000) and McNeeley *et al.*, (2001) documented that invasion is a process requiring an alien species to overcome various abiotic and biotic barriers. Introduction means that the species (or its propagule) has overcome, through human agency, a major geographic barrier A. Establishment step begins when non-native species has overcoming geographic (A) and environmental (B) barriers. They can survive and regular reproduction (C) within new areas (Richardson *et al*., 2000).

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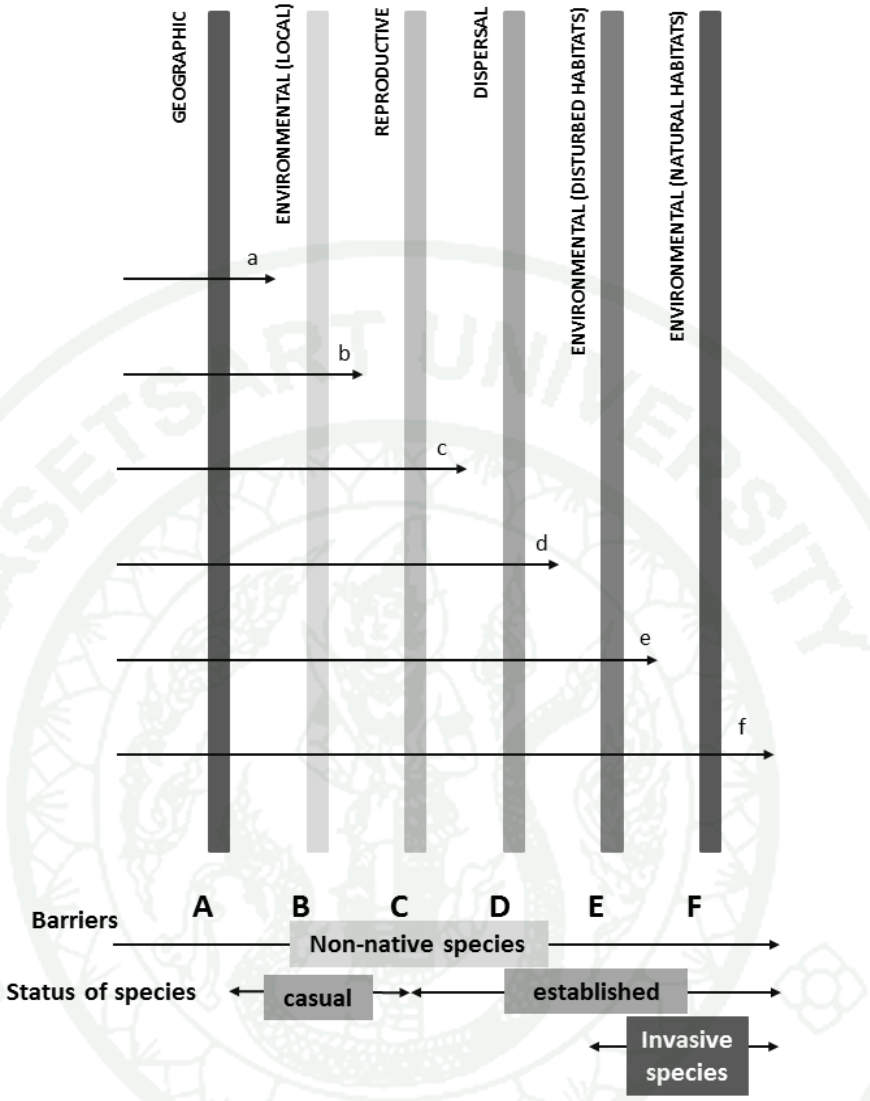

Figure 1 Invasion process diagram of invasive species (slightly modified from Richardson *et al*. (2000) and McNeeley *et al.* (2001)). Arrows indicates the paths followed by taxa to reach different states from introduced to invasive species in natural vegetation.

At this stage, populations are sufficiently large that the probability of local extinction due to the change in environmental events is low. Spreading of a species into areas away from initial sites of introduction requires the non-native species to also overcome barriers to disperse within the new region (D) and cope with the abiotic environment and biota in the general area (E). An invasion success usually

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requires that the non-native species overcomes resistance posed by a different category of environmental factors in both disturbed (E) and natural (F) habitats. In order to become invasive species, a non-native species must be able to reproduce, established and spread within new habitats. Then, their colonization appears to disturb the native fauna and flora communities within habitats. Invasion process can be summarized as a complex phenomenon including introduction and established of non-native species, the ecological appropriateness of new areas, and further spread across these areas (Peterson, 2003)

Invasions by invasive species have been introduced by both intentional and unintentional to new areas (Nentwig, 2007). For example, intentional introductions, in the aquarium trade, a fish caught from its native river and transported from their native range into new ecosystems unintentional introduction, e.g. in the woody biomass trade, some invasive plants having its seeds bundled with a shipment of wheat, and an invasive insect burrowed into a tree, stowed away in a shipment of lumber (Lowe *et al.*, 2000).

Most of a series of invasions process has occurred due to human activities (Williamson, 1996), and humans is likely recognized that they are "one of the factors in invasion successfulness of invading species" (Mack *et al*., 2000). For example, human population growth is associated with long-distance transport and commerce networks which can increase the survival chance of invasive species to establish and spread into new areas. Increasing human activities (i.e. agro-forestry, animal husbandry practices) are provided effective support to the introduction of invasive species, establishment and spreading to new habitats (Mack *et al*., 2000; Nentwig, 2007).

1.3 Impact of biological invasion

Biological invasion can have a serious consequence on biodiversity losses. There are many scientific literatures that provide varies in evidences and case

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studies of negative impacts of invasion on biodiversity (McNeely *et al*., 2001). Invasive species affect biodiversity in all ecosystems on the earth, freshwater and marine, above and belowground (Williamson, 1996; Mack *et al*., 2000).

Invasive ant species are a main cause of native species extinctions and threaten numerous species of animal such as amphibians, birds and mammals. They are also cause of alteration of soil properties, nutrient cycling and productivity patterns (Belnap and Phillips, 2001; Ehrenfeld, 2003), alteration of disturbance regimes (Mack and D'Antonio, 1998; Brooks *et al*., 2004), decrease agricultural productivity and disruption human health concerns; and enormous economic costs (Davis, 2006; Mack *et al*., 2000). Many invasive species account for a large cost of control and management program and the estimates of total yearly costs at least US$ 2 billion (Table 1).

Table 1 Indicative costs of some alien invasive species (slightly modified from McNeely (2001)

Species	Economic variable	Economic impact ($ costs in US)	Reference
Invasive rabbits (*Oryctolagus* sp.)	Damages to agroecosystems in Australia	373 million per year	Wilson, 1995 cited in White and Newton-Cross, 2000
Invasive plant (Water hyacinth)	Costs in 7 African countries	20–50 million/year	Joffe-Cook, 1997, cited in Kasulo, 2000
The parasitic mite (*Varroa sp.*)	Economic cost to beekeeping in New Zealand	267–602 million	Wittenberg *et al*, 2001
Invasive weed (6 sp.)	Damages to agroecosystems in Australia	105 million per year	CSIRO, 1997 cited in Watkinson *et al.*, 2000
Golden apple snail (*Pomacea canaliculata*)	Damages to rice in the Philippines	28–45 million per year	Naylor, 1996

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Table 1 (Continued)

Species	Economic variable	Economic impact($)	Reference
Disease organisms	Annual cost to human, plant, animal health in USA	41 billion per year	Daszac *et al*., 2000
Alien species of plants and animals	Economic costs of damage in USA	137 billion per year	Pimentel *et al*., 2000
Invasive plant (*Tamarix* spp.)	Economic lost in western USA	7–16 billion over 55 years	Zavaleta, 2000
Invasive plant (*Centaurea* spp. and *Euphorbia escula*)	Economic costs of damage in three US states	Approximately 40.5 to 89 million per year	Bangsund, 1999; Hirsch and Leitch, 1996
Zebra mussels	Damages to industrial plants in US and European	750 million to 1 billion between 1989 and 2000	O'Neil, cited in Carlton, 2001
Invasive plant (12 sp.)	Costs of control in Britain, 1983 to 1992	344 million per year	Williamson, 1998

2. Invasive ant species

2.1 Ecological role of ant

The ant plays an important role in variety of topic, and their function to directly or indirectly positive in forest ecosystem such as dispersing plant seeds (Hölldobler and Wilson, 1990; Gómez *et al*., 2003), soil modification (De Bruyn and Conacher, 1990), bioindicator (Chen *et al*., 2011) and nutrient cycling (Folgarait, 1998). Ant has been commonly adopted as bio-indicator in land management and ecosystems health (Andersen, 1997). Most studies focus on the relationship between

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diversity and abundance of ant species with ecosystem health and change of other land-use situations (Schultz and McGlynn, 2000; Phipott and Armrecht, 2006). Due to the sensitivity of ants to environmental disturbance, it makes them readily practical and powerful bio-indicators in varieties of ecosystem disturbance and health (Andersen 1997, Schultz and McGlynn, 2000). A bioindicator can defined as a species, functional group and communities that reflects in environment change such as off-site mining impacts (Andersen *et al*., 2002), forest management or deforestation and logging (Floren *et al*., 2001; Suarez *et al*., 1999), and agricultural intensification (Amador and Gorres, 2007). Yamamoto *et al*., (1994) have been reported that some ant species, *Cryptopone sauteri,* are easily found in old-grown native forest, while *Brachyponera chinensis* and *Pristomyrmex pungens* are indicator species for converted forest.

Ant as ecosystem engineers, many studies have investigated the roles of ants in creating nutrients and also modifying chemical and physical properties of soil (Folgarait, 1998). Decomposition processes are mainly first stages of mineralization. The fungi and ammonifying bacteria are very active and more represented in ant mounds in comparison to adjacent soils due to the relationship and evaluation between ants and fungi. The humification process is delayed due to the decrease of Actinomycetes in ant nests, and the effect of anthills on humus fraction composition seems to be ant-species dependent (Czerwinski *et al*., 1971). Bolton *et al*. (2003) studied the effect of *Messor andei* nests and non-ant area soil, on major soil organism groups (bacteria, fungi, nematodes, miscellaneous and micro-arthropods) from a grassland in California. They found that all soil organism groups were more abundant and diverse in ant nests that in non-ant soil. Moreover, all soil nutrients were similarly enriched inside ant's nests, suggesting that these ant nests exert significant effects on the resident soil biota through the movement of nutrients to the soil surface.

Ants also alter soil chemistry and affect nutrient immobilization, indirectly affecting plant and microbial communities. Most studies revealed an increase of organic matter and N, P, and K within the nest of *Formica* sp. and *Atta* sp. and

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compared it to adjacent soil samples (Lugo *et al*., 1973; Risch *et al*., 2005). Decomposition processes by fungi and ammonifying bacteria increase, while humification is delayed due to declines in Actinobacteria abundance in *Atta* mounds as compared to adjacent soils (Folgarait, 1998). In Panama, *Atta columbica* increases the flux of 13 chemical elements when compared to surrounding areas (Haines and Haines, 1978) In Puerto Rico, leaf-cutting ant activity associates with higher plant productivity, presumably because of an increase in phosphorous availability (Lugo *et al*., 1973). In Finland, Formica ants have been increasing C and N to the soil of the subalpine forests (Risch *et al*., 2005). As referred herein above on the ant has positive effects of their roles with other function on ecosystem where they are present. On the other hand, some ant species play act as invader which it has negative impacts in biodiversity and ecosystems health (Hölldobler and Wilson, 1990).

2.2 Invasive ant species

Ants are one group of the world's worst invasive species (ISSG, 2011). It can produce highly population, and have invaded native ecosystems and caused environmental change (Holway *et al*., 2002). Many scientists use the term 'invasive' with the ant species when they are introduced, established and spread, which can cause negative effects on ecological and economic. Indeed, Williams (1994) used the phases of "invasive" for the Argentine ant that 'cause harm' to the environments that they invade according to literature by Woodworth (1908). Since, the term of "invasive ant" have been used to describe the non-native ant species that become increasingly evidence of economic and agricultural impacts, health effects on humans, and disruption to natural ecosystems (Holway *et al*., 2002).

Invasive ants are a subset of introduced or exotic ant (non-native) (Abbott, 2004; Abbott *et al*., 2007; Colautti and Richardson, 2009; Krushelnycky *et al*., 2010). Approximately 150 ant species indicated into exotic ant species, when they established the colony outside of their native ranges. However, not all of them have become invasive ants, but after establishment, they appear to disrupt the native ecosystem

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outside of their native range (Drescher *et al*., 2007; Holway *et al*., 2002; McGlynn, 1999). The successes of the ant invasion in ecosystems depend on invasive ant characteristic regarding to their share some ecological and biological traits, and also the competition hierarchy of ants is based on differences in their colony structure and number of foragers (Passera, 1994; McGlynn, 1999).

Generally, colony structure of invasive ant is separated into two types by the number of ant queen in their colony. The one type is the polygynous that they have many queens and nests per colony, and another type is the monogynous that have only one queen in their colony. Both of them can from Supercolonies (Krushelnycky *et al*., 2010). Supercolonies consist of interrelated nest but not clear of the colony boundaries (Drescher *et al.* 2007; Holway *et al.*, 2002; Krushelnycky *et al.*, 2010; O′Dowd *et al*., 2003). After the supercolonies of invasive ant species establish and develop dense population consisting and a large network of cooperating nests, they may become ecologically dominant (Passera, 1994). Thus, trade routes associated with specific geographic regions represent an important filter and where climate conditions that is suitable for the transfer and arrival of specific invasive ant species. Climatic variables including temperature, rainfall and humidity play a large role for determining the diversity and spread of invasive species in new areas or regions, and they can also be limiting factors to the opportunity of ant invasion (Holway *et al*., 2002; Kaspari *et al*., 2000). Moreover, the opportunity to be invasive does not only rely on an ability of establishing and expanding of their colony within new ecosystem of invasive ants but also depends on a dispersal opportunity, the suitable environmental conditions (Hoffman and Saul, 2010), consisting of competition to the native ant communities (Passera, 1994; Vanderwoude *et al.*, 2000), highs biotic and abiotic resistance (Hoffman and Saul, 2010; O′Dowd *et al.*, 2003). For example, thedistribution borders of *Solenopsis* sp. populations are rarely within undisturbed habitat (Epperson and Allen, 2010; Morrison, 2002).

For the purposes of this thesis, the term “invasive ant species” is referred as the non-native species which they has negatively impact at the invaded habitats in

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economic, environmental, ecological and health terms. Native species is referred as the species originally belong to an area. Tramp ant specie is referred as small subset of non-native species that have been successfully established in new areas but they are no harm (Holway *et al*., 2002).

2.3 Five ant species on the world's worst invasive species

Ants are on a list of "100 of the world's worst invasive species". Five invasive ant species were listed in Table 2 which formulated by International Union for Conservation of Nature (IUCN) (Lowe *et al*., 2002).

Table 2 Geographical range of the five major invasive ants in the world (modified from Holway *et al*. (2002))

Species (Common name)	Geographical Range	
	Native	Introduced
Anoplolepis gracilipes (Yellow crazy ant)	Africa? , Asia? (Wilson and Taylor, 1967)	Africa, Asia, Australia, Caribbean, Indian Ocean, Indian Ocean, Pacific Ocean (McGlynn, 1999)
Linepithema humile (Argentine ants)	South America (Suarez *et al*., 2001), (Tsutsui *et al*., 2001)	Africa, Atlantic Ocean, Asia, North America, Pacific Ocean (Suarez *et al*., 2001)
Pheidole megacephala (Big-headed ant)	Africa (Wilson and Taylor 1967)	Australia, North and south America, Indian Ocean, Pacific Ocean, Mediterranean, (McGlynn, 1999)
Solenopsis invicta (Fire ant)	South America (Ross and Trager, 1990)	Caribbean, North America (Williams *et al*., 1998)
Wasmannia auropunctata (Little fire ant)	Central and south America (McGlynn 1999)	Africa, Caribbean, Pacific Ocean, South and North America (McGlynn 1999)

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Invasive ants originate in both the New and Old Worlds, however, it can occur in many areas outside their original ranges where are the climate of the introduced range approximately matches that of the native range. For example, *Solenopsis invicta*, from central South America, is an invader primarily in areas of the south-eastern United States with mild-temperate or subtropical climates (Korzukhin *et al*., 2001). The remaining invasive ants are from the tropics or subtropics and have primarily invaded regions with similar climates. They are considered a major threat to global biodiversity due to the displacement and reduction of animal richness and populations by threating and competing with the native species for the foods and nesting habitat (Krushelnycky *et al*., 2010; Passera, 1994).

2.4 Invasive ant species in Thailand

Ants are on a list of invasive species in Thailand formulated by the Office of Natural Resources Environmental Policy and Planning; ONEP (2009). They are also separated invasive ant species into two groups based on literature review and public consultation on the invasive alien species, and the list of invasive ant species in each group as followed:

Group I: Alien ant species are invading species and its can have devastating on native fauna and flora in ecosystems, which include two species, *Anoplolepis gracilipes* and *Solenopsis geminata.*

Group II: Alien ant species with a history of negative impact on the diversely organisms in the other countries, but its impact have not found in Thailand at certain times throughout history, which include two species, *Pheidole megacephala*, *Tapinoma melanocephalum.*

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3. Impact of invasive ant

Invasive ant has negatively impact in various ecosystems such as island ecosystem (Abbott and Green, 2007; O'Dowd *et al*., 2003; Vanderwoude *et al*., 2000) forest ecosystems (Hoffman and Saul, 2010), urban ecosystem (Dejean *et al.*, 2008; Tanaka *et al*., 2011) and agroecosystems (Bos *et al*., 2008; Bruhl and Eltz, 2009; Campbell, 1994; Powell and Silverman, 2010; Wielgoss *et al*., 2010). They are cause of reduction in diversity and populations of native ants and other arthropods. In some case, single invasive species has effects on population of invertebrates, vertebrates, and plants by their invasion and displacement (Hölldobler and Wilson, 1990; Holway, 2002; Krushelnycky *et al*. 2010).

3.1 Impact on native animals

Invasions by invasive ant result in declining of native animal as demonstrated in a large-scale field where native animal present. This evidence is also consistent with competitive dynamics. The interaction between invasive ants and other animals has been demonstrated as the competition relationship. Invasive ants could cause of declines and change in diversity, community and populations of various animals from invertebrates to vertebrates (Holway *et al.*, 2002), including birds (Matsui *et al.*, 2009; Schultz and McGlynn, 2000), amphibian and reptile and mammal fauna (Schultz and McGlynn, 2000), invertebrates including red crap (Abbott and Green 2007; O'Dowd *et al.*, 2003) and other soil arthropod (Holway *et al*., 2002; O'Dowd *et al.*, 2003; Lester and Tavite, 2004). For example, Fire ants have a painful nuisance and serious medical risk to hypersensitive individuals, possibly resulting in death. Further, they have an effect on the arthropod community (Epperson and Allen, 2010). Yellow crazy ants have been recorded to be preyed of blind snakes, turtle hatchlings and fairy tern chicks (Feare, 1999).

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3.2 Impact on native plants

Invasive ants can have crucial effects on plants. The effects have been divided into two indirect impacts by the characteristic of each invasive ant species and their relationship with other functions in ecosystem. First impact is the relationship of invasive ants with herbivorous insects and the second effect is in seed-dispersal activity. Invasive species have a strongly relationship with herbivorous insects such as Argentine ants and Ghost ant (Powell and Silverman, 2010), and Yellow crazy ants (Abbott and Green, 2007; O′Dowd *et al.,* 2003), Big-headed ants (Campbell, 1994). A number of publications described the benefits of ant to plants and other insects in ecosystem (Stadler and Dixon, 2005; Way, 1963). The invasive ant limits in insect herbivores dispersal and can directly regulate on the population size of Hemipterans (Abbott and Green, 2007; Campbell, 1994; Powell and Silverman, 2010). The hemipterans feed on the plant and renewable source of carbohydrates and amino acids processed from plant phloem. The ants protect the hemipterans from parasites and predator and the hemipterans provide ants with honeydew (Ness and Bronstein, 2004; Stadler and Dixon, 2005). Consequently, its cause of high mortality and populations of hemipterans, and these interactions can have a negative impact on biological control of insect pest on the plants.

Hemipterans could be the pest insect when they are fed in large aggregations and their predators are low densities, because they are at outbreak densities and damage plants while provide no beneficially biological control (Krushelnycky *et al*. 2010; Ness and Bronstein, 2004; O′Dowd *et al.,* 2003). For example, In the Seychelles, yellow crazy ants have been reported to cause the die-back in *Pisonia grandis* R.Br. woodland caused by coccoid bugs (*Pulvinaria urbicola* Cockerell) cultured by Yellow crazy ants (Hill *et al.,* 2003). As the results in dense outbreaks of the honeydew producer, the consequences of ant invasion can therefore be extensive by indirectly damaging vegetation and altering local ecosystem (Dunham and Mikheyev, 2009; O′Dowd *et al.,* 2003).

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The invasive ants are not only having relationship with other insect but also they have relations with plants, particular in ant seed-dispersal activity (Sender *et al*., 2003). Seed dispersal mutualisms involve with many dispersers. Seed dispersal can result in an alteration of species, diversity and community structure of plants (Lessard *et al.*, 2009). Invasive ants have an effect within tropic process when they disrupt the diversity and structure of the native ants as they play an important role as seed-dispersal (McGlynn, 1999; Holway *et al*., 2002; Traveset and Richardson, 2006; Rodriguez-Cabal *et al*., 2009). Most studies have focused on the impact of two invasive ant species; Asian needle ant (Rodriguez-Cabal *et al*., 2009; 2012), and Argentine ants (Gómez *et al*., 2003; Gómez *et al*, 2003; Rodriguez-Cabal *et al*., 2009).

Asian needle ant and Argentine ant have been recorded of their disruption on an ant-plant seed dispersal mutualism, and are considered to potentially reduce an abundant of plant seeds seeds (Rodriguez-Cabal *et al*., 2009). This result are similar as reported by Rodriguez-Cabal *et al*. (2012) which suggested that the presence of the argentine ant led to a 92% reduction in the abundance of native ant seed dispersers whereas the presence of the Asian needle ant led to a 96% reduction. Studies on argentine ant and fire ants generally indicate strong negative effects on seed dispersal mutualisms. After displacing populations of native seed dispersers, argentine ant and fire ants often fail to disperse seeds effectively (Gómez and Oliveras, 2003).

Moreover, in case of Christmas Island clearly exhibited indirect impacts of invasive ant on plant community. Native land crab (*Gecaroidea natalis)* population and habitat suitable for foraging and nesting were decreased by invasion of Yellow crazy ants. The reduction of the crab population resulted in muti-trophic level distortions in the ecosystem causing an invasion breakdown with changes in forest structure and tree composition (Abbott and Green, 2007; O'Dowd *et al.,* 2003). The result of both mutualisms showed that the invasion by single invasive ant interferes with mutualism in plant community (McGlynn, 1999; Holway *et al*., 2002: Gómez *et al*., 2003; Hill *et al*., 2003; O'Dowd *et al*., 2003; Dunham and Mikheyev, 2009), and

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preservation of such mutualistic interactions are necessary for maintaining natural communities (Gómez *et al*., 2003).

3.3. Impact on native ants

Invasive ants become established in new areas after being transported by human activity and changed in environment conditions. Invasive ants not only eliminate native ant species, but also disassemble their communities where each invasive species occupies in position after achieve to the invasion process (McGlynn, 1999; Holway *et al*., 2002; Gerlace, 2004). Native ant species are ecological resistance by putting up strong resistance to the raid of invasive ant workers. Those competitions may help explain the success of colony establishment and invasion of invasive ants in areas where they has been introduced. Furthermore, the occurrence of ecologically dominant species is major factors predicting species diversity in ecosystem (Wielgoss *et al.*, 2010).

Consequently, the ability to compete, execute, discharge and raid other ants constitutes a prerequisite for the success of invasive ant to becoming an ecologically dominant species in areas where it is introduced (Holway *et al*., 2002; Passera, 1994). For example, Dejean *et al*. (2008) studied impacts of Big-head ant in Mexico and Cameroon and concluded that Big-head ant heightened its ability to successfully raid the nests of the other ants in both sites. Moreover, the colonies of eight species out of 11 nests were often killed by big head ant which three species colonies of fire ant could resist these raids. Similar results provided by Wielgoss *et al*. (2010) who suggested that the abundance and aggression of *Philidris* species reduced arboreal ant species richness. Moreover, many species of invasive ants have been introduced that cause the decline of ground-dwelling ant diversity and community in varieties of ecosystem (Bos *et al*., 2008; Brühl and Eltz, 2009).

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4. Yellow Crazy Ant (*Anoplolepis gracilipes* Smith, 1857)

4.1 Taxonomy category

Anoplolepis gracilipes (Smith, 1857) belong to subfamily Formicinae, Family Formicidae, Order Hymenoptera.

Order Hymenoptera
Family: Formicidae
Subfamily: Formicinae
Genus: *Anoplolepis*
Species: *gracilipes*

Synonyms: *Anoplolepis longipes* Emery 1925, *Formica longipes* Jerdon 1851, *Plagiolepis longipes* Emery 1887, *Prenolepis gracilipes* (Smith), and *Plagiolepis gracilipes* (Smith)

Common names: Yellow crazy ant (English), crazy ant (English), long-legged ant (English), Maldive ant (English-Seychelles), Gelbe Spinnerameise (German), gramang ant (Indonesian Bahasa) and ashinaga-ki-ari (Japanese) (AntWeb, 2013), and Mod Num Pheng (Thai).

4.2 Description

A. gracilipes is typically medium sized ant and ranges from 4-6 mm with very long legs and antennal scapes (first antennal segment attached to the head) that extend far past the top of the head (Figure 2). The body colors are yellow-brownish or reddish brown and the gaster usually darker than the head and thorax. There is only a single waist segment (petiole), no spines or protrusions, and all workers are the same size (monomorphic) (AntWeb, 2013). *A. gracilipes* lacks a sting; thus, it kills a prey by spraying formic acid (DEH, 2004).

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Figure 2 An external morphology of Yellow Crazy Ant (*Anoplolepis gracilipes* Smith, 1857)

4.3 Geographical range and dispersal

The native range of *Anoplolepis gracilipes* is not clear, with the likely possibilities originated in West Africa, India, or China (Wilson and Taylor, 1967). *A. gracilipes* has been found widely throughout the moist tropical lowlands of Asia, the Indian Ocean and the Pacific Ocean (Harris *et al*., 2005: CABI, 2014: Table 3). *A. gracilipes* has been found in some parts of Africa, Central and South America, Panama and Mexico and Australia in Northern Territory (Wetterer, 2005), Papua New Guinea (Baker, 1976; Young, 1996) and Queensland (Csurhes, 2012). It are also recorded from including Malaysia, Brunei Darussalam, Viet Nam, Thailand Cambodia, Indonesia, Myanmar, Singapore and Philippines (CABI, 2014). *A. gracilipes* often found widely across the Islands on the Caribbean and Indian Ocean, (Abbott, 2006; Devis *et al*., 2010; Boland *et al*., 2011, Haines and Haines, 1978a, b; Hill *et al*., 2003, Gerlach, 2004, Fluker and Beardsley, 1970), and some Pacific Islands, such as Okinawa (Suwabe *et al*., 2009; Tanaka *et al*., 2011), Minami-Daito islands (Matsui *et al*., 2009) and Ryukyu Islands (Yamaguchi and Ogata, 1995).

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Table 3 Distribution of *Anoplolepis gracilipes* (modified from CABI (2014))

Country	Distribution	Origin	First Reported	Status
Asia				
Brunei Darussalam	Present	Native	1975	
Cambodia	Present	Native	1928	
China	Present	Native	1859	
-Fujian	Present	Introduced	<1927	
-Hong Kong	Present	Introduced		Invasive
-Tibet	Present	Introduced	1935	
-Yunnan	Present	Introduced	1994	
Christmas Island (Indian Ocean)	Present		<1934	Invasive
Cocos Islands	Present	Introduced	<1999	
India	Present	Native	<1851	
-Andaman and Nicobar Islands	Present		<1903	
-Assam	Present	Introduced	1944	
-Goa	Present	Introduced	after 1980	
-Karnataka	Present	Introduced	after 1980	
-Kerala	Present	Introduced	after 1980	
-West Bengal	Present	Introduced	<1925	
Indonesia	Present	Introduced		Invasive
-Irian Jaya	Present	Introduced		Invasive
-Java	Present	Introduced		Invasive
-Kalimantan	Present	Introduced		Invasive
-Sulawesi	Present	Introduced		Invasive
-Sumatra	Present	Introduced		Invasive
Japan	Present	Introduced	1930	
-Bonin Island	Present	Introduced		Invasive
-Ryukyu Archipelago	Present	Introduced	1930	Invasive

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Table 3 (Continued)

Country	Distribution	Origin	First Reported	Status
Malaysia	Present	Native	1854	
-Sabah	Present			Invasive
- Malaya	Present			
-Sarawak	Present			Invasive
Myanmar	Present	Native	1887	
Philippines	Present	Native	1890	
Singapore	Present		1854	
South East Asia	Present	Introduced		Invasive
Sri Lanka	Present	Native	<1887	
Taiwan	Present	Introduced	1992	
Thailand	Present	Native	1930	
Vietnam	Present	Native	<1894	
Africa				
Mauritius	Present	Introduced	1942	
Réunion	Present	Introduced	<1895	
Rodriguez Island	Present	Introduced	<1954	
Seychelles	Present	Introduced	1962	Invasive
South Africa	Present	Introduced	<1980	
Tanzania (i.e. Zanzibar)	Present	Introduced	<1893	
North america				
Mexico	Widespread	Introduced	1893	
USA (i.e. Hawaii)	Present	Introduced	1950	Invasive
Central America and Caribbean				
Panama	Present	Introduced	1964	
South america				
Bolivia	Present	Introduced	1978	
Chile	Present	Introduced	1859	
Oceania				
American Samoa	Present	Introduced		Invasive

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Table 3 (Continued)

Country	Distribution	Origin	First Reported	Status
Australia				
- New South Wales	Eradicated	Introduced	2004	Invasive
- Northern Territory	Restricted	Introduced		Invasive
-Queensland	Restricted	Introduced	2001	Invasive
Caroline Islands	Present		1936	
Cook Islands	Restricted	Introduced	1937	Invasive
Fiji	Present	Introduced	1876	
Frenc h Polynesia	Present	Introduced	1934	
-Marquesas	Present	Introduced	1925	
Guam	Present	Introduced		Invasive
Kiribati	Present	Introduced		Invasive
Marshall Islands	Present	Introduced		Invasive
Micronesia, Federated states of	Present	Introduced		Invasive
New Caledonia	Present		<1882	
New Zealand	Absent, intercepted	Introduced		Invasive
Niue	Present	Introduced	<1967	
Northern Mariana Islands	Present	Introduced		Invasive
Palau	Present		1936	
Papua New Guinea	Present		1896	
Samoa	Present	Introduced		Invasive
Solomon Islands	Present		1916	
Tokelau	Present	Introduced	1934	Invasive
Tonga	Present		<1870	
Tuvalu	Present		<1870	
Vanuatu	Present		1929	
Wallis and Futuna Islands	Present		1913	

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4.4 Habitat and nesting requirements

Anoplolepis gracilipes has been reported from a wide range of areas, including agricultural areas containing many types of crops, disturbed areas, natural and planted forests, riparian and coastal areas, rangeland and grasslands (Wetterer, 2005). Due to a tropical species, therefore *A. gracilipes* habits are moist, warm and shaded areas. It is rarely to find them in hot areas such as on the beach, inhabits buildings and human-frequented areas such as industrial zones. *A. gracilipes* has very general nesting requirements, and can be found within trees, in cracks and crevices, under the ground. They are also build nest in the ground which has no piled soil surround the nest entrance hole, which have a single entrance (Csurhes and Hankamer, 2012).

4.5 Colony organization and reproduction

Anoplolepis gracilipes' colonies occurs in polygynous from and by many queens. No aggression was observed between workers from different nests of different supercolonies (Abbott, 2005). It supercolonies can contain up to 300 queens (Williams, 2011). *A. gracilipes*' super-colonies can from extending continuously over larger areas between 10 to 10,000 ha and have high density of ant workers up to 2254 individuals per m^2 and biomass of 1.85 g per m^2 (Abbott, 2005). The dispersal mechanism of new colonies is most likely colony budding. While, the aerial dispersal by mating flights has not been reported yet in the literature and that by winged queens is also still unclear.

5. General impacts

Anoplolepis gracilipes is a generalist diet foraging, with broad diets, including plant seeds, arboreal and terrestrial invertebrate, crustacean, bird, reptile and mammals (O'Dowd *et al*., 1999, O'Dowd, 2003). They are also feed on the carbohydrates and amino acids from plant nectarines, especially from honeydew excreted by Homoptera

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(Haines and Haines, 1978b). High densities of *A. gracilipes* have the potential to devastate and replace native species, and request more food preys than native ones, It has been documented that the *A. gracilipes* invasion is a cause of an alteration of ecosystem processes and reduction in number of species and population of native species (O′Dowd *et al*., 2003).

On Christmas Island, a territory of Australia in the Indian Ocean, *A. gracilipes* causes an increase in population of insect pest species of plant. These results in an increased level of carbohydrate-rich honeydew on plant surface, causing leaf and needle stunting and yellowing, twig and branch dieback as well as dead of some rainforest canopy tree species (*Inocarpus fagifer*), resulting in the alteration of the species composition of the primary rainforest (Parks Australia, 2013; O′Dowd *et al*., 2003). *A. gracilipes* threatens many endemic, endangered and keystone species especially on island. For example, on the Christmas Island, *A. gracilipes* super-colonies reduced the populations of native land crabs (*Gecarcoidea natalis* up to 20 million as *A. gracilipes'* preys (O′Dowd *et al*., 1999). Land crab is one of the endemic species, and also island's keystone species that plays many important roles within the forest ecosystem, including recycling nutrients by degrading leaf litter, maintaining the structure of the rainforests by reducing new seedling recruitment (Parks Australia, 2013). Invasion by *A. gracilipes* also leads on to increasing numbers of secondary invasions by the Giant African Landsnail and some woody weeds in invaded sites in forest ecosystems on the Island (O′Dowd *et al*., 1999). The abundance and species richness of native fauna and flora were lower in the *A. gracilipes* invaded area. There have been reported that *A. gracilipes* are caused the decrease in the abundance and species richness of native ants species (Sarty *et al*., 2007; Hoffman and Saul, 2010), native reptiles (O′Dowd *et al*., 2003; Abbott, 2004), and native small mammal and birds (Feare, 1999; Abbott, 2004).

In Seychelles, *Anoplolepis gracilipes* has been recorded as pest insect in the household, because it crawled all over people and food (Haines and Haines, 1978a; Haines *et al*., 1994). It is also, considered as a medical problem that caused acute

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distress by entering ears, nose, eyes and open wounds, especially in the young and old ages (Abbott *et al*., 2005). Similar observations were reported in Tokelau indicated that *A. gracilipes* can be increase population rapidly and becomes an agricultural and household pest (Lester and Tavite, 2004). On Mahé, *A. gracilipes* has been recorded that their invasion significant declines in the abundance of the other ant species, several insect groups, millipedes and spider (Haines and Haines, 1978a).

In Thailand, Thai Government's Biodiversity Policy had focused on the conversation research to measure biosafety impact migration and regulation on invasive species (ONEP, 2009). Most of studies on diversity and distribution were focused on mammals, fishes and plants, while a very few research data in insects particularly in the ants. As *Anoplolepis gracilipes* have been described into invasive ant species which have negatively impact on diversity and population of fauna and flora in ecosystems in Thailand. However, distribution of *A. gracilipes* is virtually unknown and tits ecological impact in more generally poorly documented

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MATERIALS AND METHODS

Part 1: The diversity and distribution of invasive ants in Thailand

1. Study sites

Surveys of ant diversity were conducted from thirty-five study sites at 30 provinces in Thailand (Figure 3). The detail information of study sites are shown in the Table 4. Thailand is situated in the Indochina Peninsula of Southeast Asia. It is bounded between 5° 40′ and 20° 30′ North latitudes, 90° 70′ and 105° 45′ East longitudes. Total land area of the country is 513,115 km^2. The country is neighbor to Laos and Burma on the North, to Laos and Cambodia on the East, to Laos on the Northeast. It is surrounded by the Andaman Sea and the southern extremity of Burma on the West and by the Gulf of Thailand and Malaysia on the South (UNEP, 1997). The study sites were classified into four types including forest areas, plantation, agricultural area and urban (Figure 3). The detail information of the habitat types are shown in the Table 5.

1.1 Forests area were classified into nine sub-types comprising hill evergreen forest, dry dipterocarp forest, dry evergreen forest, mixed deciduous forest, tropical rain forest, grassland, peat swamp forest, secondary forest and tourist zone.

1.2 Plantations included three sub-types according to the planted essences: rubber, teak and eucalyptus.

1.3 Agricultural areas has many annual crops, both short- and long-day lived plant species, but were not categorized into any particular sub-type.

1.4 Urban areas referred to commercial areas in various cities. At each site, the ants were sampled at the sample plots at least 50 m × 50 m in areas. All ant collections were conducted during the period in 2011, 2012 and 2013.

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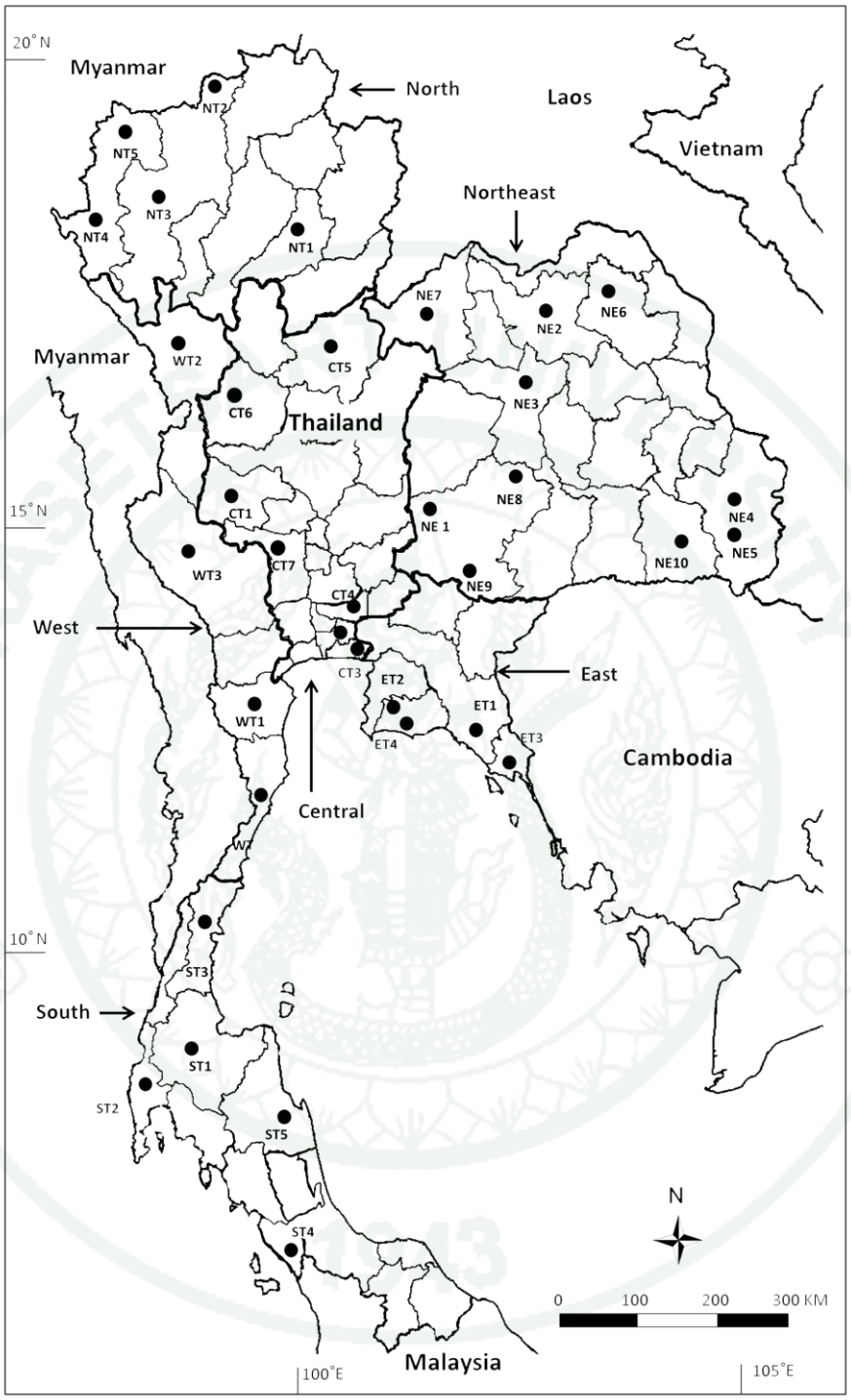

Figure 3 Study sites of ant survey in Thailand. Abbreviation of study sites present in the Table 4

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Table 4 The study sites in each region and distributed forest from the northern to southern region of Thailand

	Site	Site Abbr.	Province	Region	Altitude (m a.s.l)	Coordinates	Habitat type	Total number	
								sample plot	pitfall trap
1	Huai Kha Khaeng Wildlife Preserve Area	CT1	Uthai Thani	Central	800	15°25′05″N 99°13′57″E	DEF	2	30(15*2)
2	Mo Chit BTS skytrain station	CT2	Bangkok	Central	200	13°44′44″N 100°32′3″E	UCA	4	80 (4*20)
3	Suvarnabhumi Airport	CT3	Samut Phakarn	Central	200	13°41′33″N 100°45′0″E	UCA	4	80 (4*20)
4	Agricultural wholesale market	CT4	Phatumthani	Central	150	14°4′54″N 100°37'17″E	UCA	4	80 (4*20)
5	Thung Salaeng Luang National Park	CT5	Phitsanulok	Central	900	16°49′40″N 100°52′12″E	GRL FAT	1 1	20 (1*20) 20 (1*20)
6	Paddy and Sugarcane fields	CT6	Kamphaeng Phet	Central	200	16°15′0″N 99°30′0″E	ATA	2	30(2*15)
7	Paddy and Sugarcane fields	CT7	Suphanburi	Central	200	14°44′31″N 100°5′43″E	ATA	7	70(7*10)
8	Khao Khitchakut National Park	ET1	Chaunthaburi	East	700	12°50′44″N 102°9′35″E	DEF FAT	1 1	20 (1*20) 20 (1*20)
9	Khao Cha Mao National Park	ET2	Rayong	East	1000	12°55′6″N10 1°44′36″E	TRF FAT	1 1	20 (1*20) 20 (1*20)

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Table 4 (Continued)

	Site	Site Abbr.	Province	Region	Altitude (masl)	Coordinates	Habitat type	Total number	
								sample plot	pitfall trap
10	Namtok Khlong Kaeo National Park	ET3	Trat	East	600	12°34′26″N 102°32′41″E	DEF FAT	1 1	20 (1*20) 20 (1*20)
11	Industrial Estate Authority of Rayong	ET4	Rayong	East	150	12°43′7″N 101°20′41″E	SDF RTP	2 2	30(2*15) 30(2*15)
12	Mae Yom National Park	NT1	Phare	North	500	18°44′45″N 100°11′45″E	MDF FAT	1 1	20 (1*20) 20 (1*20)
13	Doi Pha Hom Pok National Park	NT2	Chaingmai	North	2000	19°59′16″N 99°08′47″E	HEF FAT	1 1	20 (1*20) 20 (1*20)
14	Mae hor Phra Plantation	NT3	Chaingmai	North	600	19°6′55″N 99°0′18″E	DDF MDF SDF TGP	2 2 1 6	30(2*15) 30(2*15) 15(1*15) 90(6*15)
15	Khun Korn Waterfalls Forest Park	NT4	Mae Hong Son	North	1970	19°18′14″N 97°58′38″E	HEF FAT	1 1	20 (1*20) 20 (1*20)
16	Namtok Mae Surin National Park	NT5	Mae Hong Son	North	1700	19°8′26" N 98°1′58″E	HEF FAT	1 1	20 (1*20) 20 (1*20)

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Table 4 (Continued)

	Site	Site Abbr.	Province	Region	Altitude (masl)	Coordinates	Habitat type	Total number	
								sample plot	pit fall trap
17	Khao Yai National Park	NE1	Nakhon Ratchasima	Northeast	300	14°26′29"N 101°22′11″E	DEF FAT	1 1	20 (1*20) 20 (1*20)
18	Na Yung - Nam Som National Park	NE2	Udon Thani	Northeast	750	17°55′30″N 102°15′30″E	DDF FAT	1 1	20 (1*20) 20 (1*20)
19	Phu Wiang National Park	NE3	Khon Khan	Northeast	600	16°40′42″N 102°21′13″E	DDF FAT	1 1	20 (1*20) 20 (1*20)
20	Phu Chong–Na Yoi National Park	NE4	Ubon Ratchathani	Northeast	500	14°32′0″N 105°23′9″E	DEF FAT	1 1	20 (1*20) 20 (1*20)
21	Piboon Plantation	NE5	Ubon Ratchathani	Northeast	200	15°14′ 40′′ N 105°13′44″E	DDF DEF GRL MDF ETP RTP	3 1 1 1 1 1	45(3*15) 15(1*15) 15(1*15) 15(1*15) 15(1*15) 15(1*15)
22	Phu Phan National Park	NE6	Sakol Na Khon	Northeast	400	17°3′45″N 103°58′22″E	DDF FAT	1 1	20 (1*20) 20 (1*20)
23	Phu Ruea National Park	NE7	Loei	Northeast	1000	17°30′53″N 101°20′41″E	MDF FAT	1 1	20 (1*20) 20 (1*20)

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Table 4 (Continued)

	Site	Site Abbr.	Province	Region	Altitude (masl)	Coordinates	Habitat type	Total number	
								sample plot	pit fall trap
24	Sakaerat Biosphere Reserve	NE8	Nakhon Ratchasima	Northeast	300-800	14°30′30″N 101°56′18″E	DEF	8	120 (8*15)
							DDF	2	30 (2*15)
							MDF	2	30 (2*15)
25	Wang Nam Khieo Agricultural Areas	NE9	Nakhon Ratchasima	Northeast	200	14°25′6″N 101°51′0″E	ATA	6	120 (6*20)
26	Khun Han Plantation	NE10	Sisaket	Northeast	600	14°37′2″N 104°25′28″E	SDF	3	60 (3*20)
							ETP	7	140 (7*20)
							RTP	2	40 (2*20)
27	Kaeng Krung National Park	ST1	Surat Thani	South	930	9°18′0″N 98°52′0″E	TRF	1	20 (1*20)
							FAT	1	20 (1*20)
28	Khaolak Lamru National Park	ST2	Phang Nga	South	600	8°41′54″N 98°16′49″E	TRF	1	20 (1*20)
							FAT	1	20 (1*20)
29	Mu Ko Chumphon National Park	ST3	Chumphon	South	500	10°2′18″N 99°7′42″E	TRF	1	20 (1*20)
							FAT	1	20 (1*20)

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Table 4 (Continued)

	Site	Site Abbr.	Province	Region	Altitude (masl)	Coordinates	Habitat type	Total number	
								Sample	pit fall trap
30	Thale Ban National Park	ST4	Stun	South	1000	6°28′22″N	TRF	1	20 (1*20)
						100°8′2″E	FAT	1	20 (1*20)
31	Khuan Khreng swamp forest	ST5	Nakhon Sri Thammarat	South	150	7°54′38″N 100°6′40″E	PSF	5	100 (5*20)
32	Kaeng Krachan National Park	WT1	Phetchaburi	West	400	12°45′0″N	DEF	1	20 (1*20)
						99°36′0″E	FAT	1	20 (1*20)
33	Lan Sang National Park	WT2	Tak	West	500	16°47′0″N	DEF	1	20 (1*20)
						99°1′0″E	FAT	1	20 (1*20)
34	Sai Yok National Park	WT3	Khanchanaburi	West	250	14°25′4″N	DEF	1	20 (1*20)
						98°44′50″E	FAT	1	20 (1*20)
35	Khao Sam Roi Yot National Park	WT4	Prachuap Khiri Khan	West	200	12°10′57″N	MDF	1	20 (1*20)
						99°56′54″E	FAT	1	20 (1*20)
	Total							129	2205

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Table 5 The habitat types and its dominant vegetation

Habitat type		Abrr.	Sampling point	Altitude (masl)	Dominant species
Forest areas	Hill evergreen forest	HEF	3	1000-1600	*Castanopsis* spp., *Lithocarpus* spp., *Quercus* spp., *Michelia* spp. *Caryota* spp., *Cephalotaxus mannii* , *Podocarpus neriifolius* and *Nageia wallichianus*
	Dry evergreen forest	DEF	17	500-900	*Dipterocarpus alatus, D. turbinatus, Hopea* spp., *Erythrina subumbrans, Toona ciliate, Tetrameles nudiflora, Pterocymbium tinctorium* and *Gmelina arborea,*
	Tropical rain forest	TRF	5	900-1000	*Dipterocarpus* spp., *Anisoptera curtisii, Neobalanocarpus heimii, Cotylelobium lanceolatum, Parashorea stellata, Hopea* spp., *Shorea* spp. , *Vatica* spp., *Calamus* spp.,*Daemonorops* spp. and *Korthalsia* spp.
	Swamp forest	PSF	7	200	*Calophyllum inophylloides, Baccaurea bracteata, Blumeodendron kurzii, Stemonurus malaccensis, Eleiodoxa conferta, Licuala paludosa, Korthalsia lacinosa, Neesia altissima, Xylopia fusca, Dialium patens* and *Horsfieldia* sp.
	Dry dipterocarp forest	DDF	10	200-600	*Dipterocarpus* spp., *Anisoptera curtisii, Cotylelobium lanceolatum*, Hopea spp., *Parashorea stellata, Shorea* spp. , *Vatica* spp., *Calamus* spp. *Daemonorops* spp. and *Korthalsia* spp.
	Mixed deciduous forest	MDF	8	300-600	*Tectona grandis, Afzelia xylocarpa, Xylia xylocarpa, Dalbergia* spp., *Pterocarpus* spp., *Largerstroemia calyculata* and various bamboo

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Table 5 (Continued)

	Habitat type	Abrr.	Sampling point	Altitude (masl)	Dominant species
	Grassland	GRL	2	900	tall grass such as *Imperata cylindrica*, *Saccharum* spp. and herbaceous species
	Secondary forest	SDF	6	300-800	*Dipterocarpus alatus, D. turbinatus, Hopea odorata, Haldina cordifolia, Albizia odoratissima* and *Lagerstroemia duperreana*
	Tourist zone	FAT	28	100- 1200	*Dalbergia cochinchinensis, Hopea odorata, Diospyros decandra , Cananga odorata, Cerbera odollam, Milletia brandisiana , Milletia brandisiana, Tabebuia chrysantha, Radermachera hainanensis,* flower gardens and herbaceous .
Plantation	Rubber Tree Plantation	RTP	6	200-900	*Hevea brasiliensis*
	Teak plantation	TGP	6	300-600	*Tectona grandis*
	Eucalyptus Plantation	ETP	8	200-500	*Eucalyptus* spp.
Agricultural areas	Agriculture	ATA	15	200-300	*Allium porrum, Brassica oleracea , Lactuca sativa, Cucurbita pepo, Brassica* spp.and *Impomoea aquatic.*
Urban areas	Commercial Zone	UCA	13	150-200	*Swietenia macrophylla, Pterocarpus indicus, Peltophorum pterocarpum, Lagerstroemia floribunda,* flower gardens and herbaceous
Total			134		

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2. Sampling methods

Ground-dwelling ants were sampled by pitfall trapping. Pitfall trapping is one effective method to estimate the diversity and composition of surface active ants (Bestelmayer *et al.*, 2000). Twenty or thirty pitfall traps were used per study site. Each trap consists of a 70 ml plastic glass (7 cm in diameter) buried in the ground and half-filled with a mixture of soapy water and ethyl-alcohol 30%. All pitfall traps were placed 5 m away from each other and left for 24 hours. All ant individuals were sorted from the traps and preserved in 95% ethyl alcohol then brought back to laboratory for identification.

3. Ant identification

All ants were identified to genus level using identification guides of Bolton, (1994; 2003). Species level identification was made using taxonomic papers written by the specialists of each ant group, and was also confirmed by using the reference collection of ant species in Ant museum at Kasetsart University and in the Forest Insect Collection at the Departments of National Park, Wildlife and Plant Conservation (DNP). Bio-status are given as following; invasive ant, native ant and tramp ant. This research is conformed to previous publications and databases, e.g. Ward (2007), Sarnat (2008), ACB (2014a; b) and ONEP (2009).

4. Data analysis

A frequency of occurrence was used to quantify the probability of finding a species in any sampling point in each site. The proportional frequency of the species is often used as an indicator of abundance (McCune and Grace, 2002). It is an efficient index technique for ants, because of their sociality procures (Romero and Jaffe, 1989).
It was calculated by:

$$\text{Frequency; F (\%)} = \frac{\text{Number of occupied study sites}}{\text{Total number of study sites}} \times 100 \qquad (1)$$

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Part 2: Ecological impact of the yellow crazy ant (*Anoplolepis gracilipes* smith, 1857; Hymenoptera: Formicidae) in dry evergreen forest at Sakaerat Biosphere Reserve

1. Study sites

The study on ecological impact of *Anoplolepis gracilipes* on ecosystems were conducted in a dry evergreen forest (DEF) at Sakaerat Biosphere Reserve (SERS; 14°30'N, 101°56' E, 500 masl) in northeastern Thailand (Figure 4a). The DEF covers 64% of the natural forest area at the SERS (Trisurat, 2009). The study area had a gentle slope of less than 10° (Figure 4b). The forest site consisted of *Hopea ferrea* and *H. odorata*, forming a closed canopy with heights ranging from 23 to 40 m.

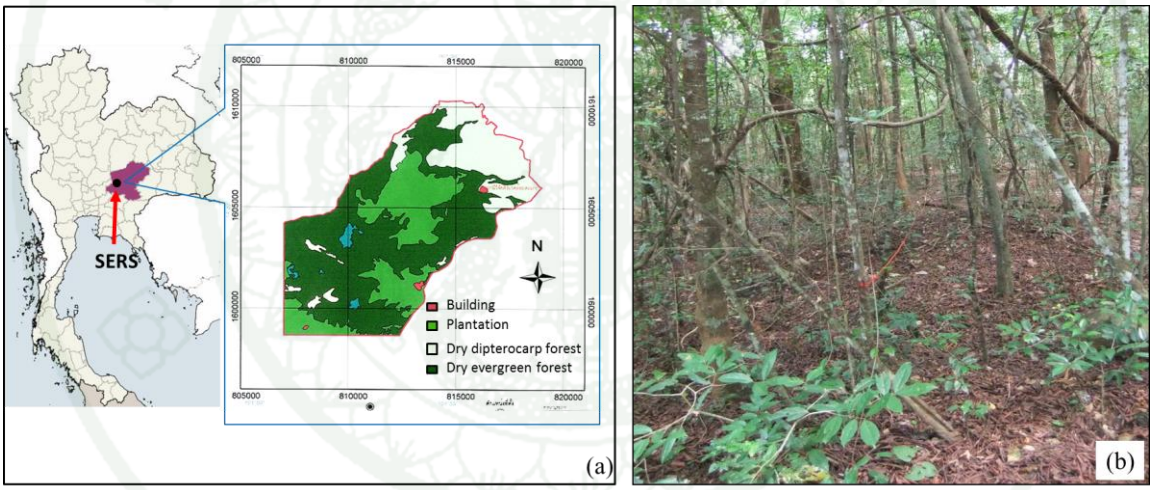

Figure 4 Study site at Sakaerat Biosphere Reserve (SERS), Nakorn Ratchasima, Thailand; (a) the geological location and (b) dry evergreen forest within SERS

The mid-layer comprised *Hydnocarpus ilicifolius*, *Aglaia pirifera*, *Walsura trichostenon* and *Memecylon caeruleum*, which formed a canopy at a height of 16–22 m. The lower canopy, which was 4–14 m in height, consisted of *M. ovatum*, *Ixora barbata* and *Randia wittii* (Lamotte *et al*., 1998). The forest floor was covered with a thin layer of undergrowth containing seedlings from the three different forest canopy species.

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The mean litter mass accumulated on the forest floor (A0-layer) was 25 t ha^{-1} (dry weight) and included leaves, twigs, and dead wood (Yamada *et al.*, 2003). The thickness of litter layer was 2–5 cm. The soil texture was loam and clay loam, derived from sandstone (Lamotte *et al.*, 1998), classified as ultisols soil (USDA classification). The soil porosity and available water capacity in the 0–50 cm depth layer were in the range of 50%–67% and 6–24 mm, respectively (Murata *et al.*, 2009). The mean annual precipitation, temperature, and relative humidity at the SERS meteorological station were 978 mm, 26.3°C, and 88.3%, respectively, from 2000 and 2009. The climate is characterized by a dry season from November to May, (< 50 mm rainfall per month) and a wet season from June to October (Sakurai *et al.*, 1998). I conducted the research from October, 2010 to September, 2011. During the measurement period, the mean monthly precipitation, temperature, and relative humidity was 43.5 mm, 25.5°C, and 76%, respectively, in the dry season (November–May) and 159.7 mm, 27.1°C, and 82.3%, respectively, in the wet season (June–October). The annual precipitation, temperature, and relative humidity during this period were 1237 mm, 25.8°C, and 81.7%, respectively.

2. Sample Plots

To investigate the ecological impact of *Anoplolepis gracilipes* on ecosystems are divided into two main parts:

2.1 Study on impact of *Anoplolepis gracilipes* on the diversity and community compositions of arthropods

Six sample plots, 40×40 m, were established in a dry evergreen forest (Figure 5a). Each plot was divided in to 10×10 m quadrat and 5×5 m subquadrat. At each sample plot, the diversity and composition of arthropod were conducted in the sixteen subplots, 10×10 m, and the nesting site of ant were observed in the sixty-two subplots, 5×5 m (Figure 6).

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Sample plots were separated into two groups based on the presence data of *A. gracilipes* individuals and supercolonies. Three plots is 'invaded site (IVS)' which it refers as the area where supercolonies of *A. gracilipes* (Figure 5b). Nothing is unknown of the distribution history of *A. gracilipes* in the SERS, but it is believed to have arrived here at least 3 year prior to the study (Yotin, 2003; Hasin, 2008). At the time of this study, three was *A. gracilipes* population large and higher nest abundance enough at least 30 nests per each site. Three plots is 'uninvaded site (UVS)' which it refers as the areas where not /never been found *A. gracilipes* individuals and supercolonies least 8 year prior to the study (Hasin, 2008). All sample plots were established throughout the accessible area of invaded site, and it is also a nearby invaded site. The plant community of all sites appeared comparable to most vegetation covering in dry evergreen forest in SERS (pers. Obs.).

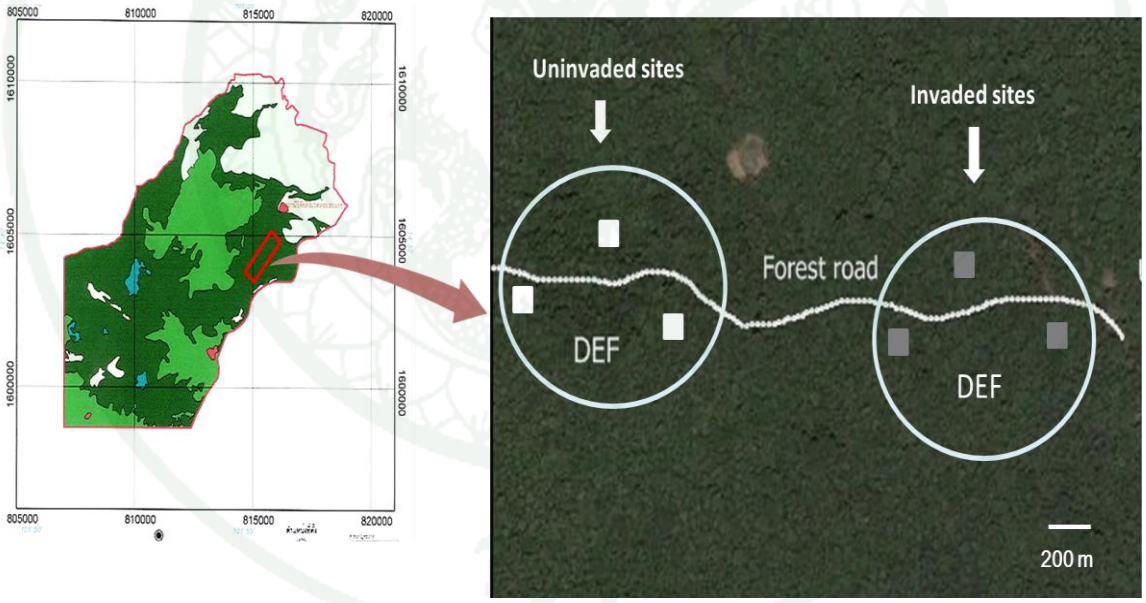

Figure 5 Sample plots in Dry evergreen forest (DEF) at SERS (a) , and the location of all sample plots in DEF (b)

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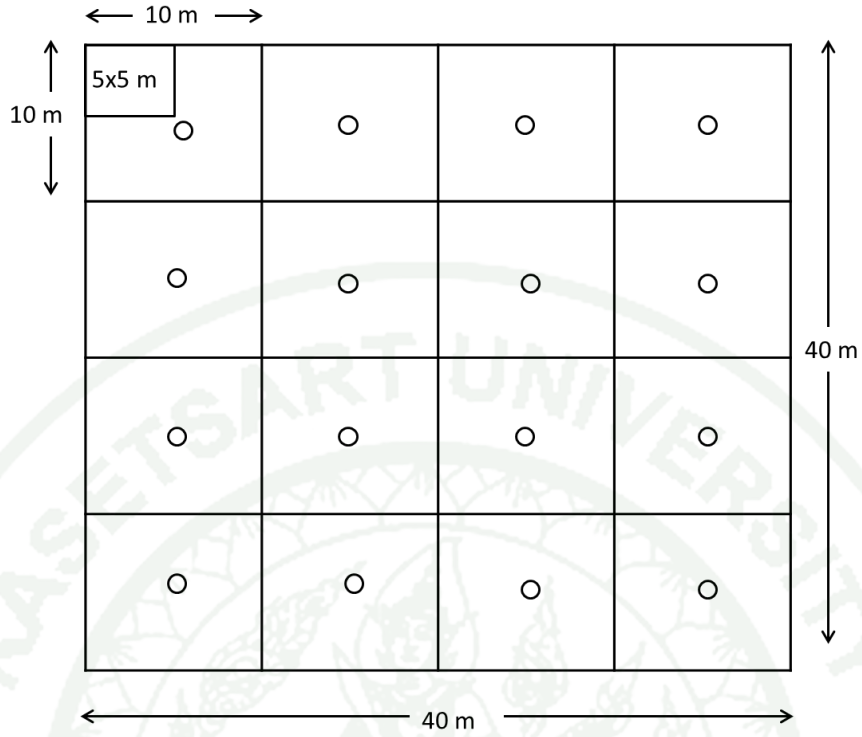

Figure 6 Sample plots and subplots used to sample ground dwelling arthropods and nesting sites of ants. White circle represented grid points where pitfall traps were installed

2.2 Impact of subterranean nests of ant on CO_2 efflux from soil

For CO_2 efflux measurements were conducted at all sample plots and surrounding plot areas. Subterranean nest of different kinds of ants were used as a main point for set up experimental plots for CO_2 efflux measurements. Subterranean nest of 13 dominant ant species with high abundances and activity based on preliminary observations were chosen for CO_2 efflux measurements. Among the 13 ant species, the ant worker body length ranged from 1.5 to 17 mm (Table 6). We identified the entrance holes of potential nests by using the food-baiting method. We did not select nests close to large trees, rotten logs, or stones, to decrease variations in CO_2 efflux due to CO_2 production from other sources.

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Table 6 Ant species, number and characteristics of the ant nests examined in this study. The mean ant body size and hole diameter are shown with the standard error in parentheses. Range is shown for the number of entrance holes

Species	Species Code	Number of ant nests [1]	Ant body size [2] (mm)	Number of nest holes	Hole diameter [3] (mm)
Anochetus graeffei Mayr, 1870	A1	4 [1,3]	4.27 (0.03)	1	4.1 (0.3)
Anochetus sp.2 of AMK	A2	4 [1,3]	4.93 (0.02)	1	4.5 (0.2)
Anoplolepis gracilipes (F. Smith, 1857)	AG	5 [2,3]	4.83 (0.03)	1-3	37.3 (1.0)
Aphaenogaster sp.1 of AMK	AP	6 [3,3]	5.41 (0.04)	1	9.9 (0.4)
Diacamma cf. *vagans* (F. Smith, 1860)	DV	5 [2,3]	9.82 (0.11)	1	12.8 (0.8)
Ectomomyrmex astuta (F. Smith, 1858)	EA	4 [1,3]	16.34 (0.28)	1-2	4.9 (0.1)
Harpegnathos venator (F. Smith, 1858)	HV	3 [3,0]	12.80 (0.11)	1	18.3 (0.9)
Odontoponera denticulata (F. Smith, 1858)	OD	6 [3,3]	9.51 (0.08)	1-3	3.6 (0.2)
Odontomachus rixosus F. Smith,1857	OR	6 [3,3]	10.85 (0.05)	1-2	43.5 (6.4)
Pheidole hongkongensis Wheeler, 1928	PH	4 [1,3]	2.50 (0.00)	1-2	1.6 (0.1)
Pheidole plagiaria F. Smith, 1860	PP	5 [2,3]	3.49 (0.01)	1	48.8 (1.6)
Pheidole parva Mayr, 1865	PV	4 [1,3]	1.70 (0.03)	1	1.3 (0.2)
Tetramorium lanuginosum Mayr, 1870	TL	5 [2,3]	2.47 (0.03)	1	1.9 (0.1)
Total		61			

[1] The number in square brackets means number of nests in wet and dry season.

[2] 15–30 individuals from the nests and the length from head to last section of abdomen was measured using microscope

[3] The number of replicates was the number of ant nests

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` I ensured that the sampled ant nests were constructed from soil, to ensure that the soil characteristics at the nest were comparable to those of surrounding soil. Ant workers were collected from the entrance holes of each nest for identification. Ants were identified to the subfamily and genus level according to Bolton, (1994) and to the species level by comparisons with the ant collections in the Ant Museum at Kasetsart University (AMK), Thailand. After identifying each species, we selected the main entrance hole of each nest by observing worker traffic intensity

To identify nest-hole type (single-hole or multiple-hole types) we searched for other entrance holes around the main entrance hole, collecting ants from the adjacent and main entrance holes, and allowing them to fight each other in a chamber to determine whether they were from the same nest (Heller, Sanders and Gordon, 2006). We selected three to six independent nests for each of the 13 species, making a total of 61 nests (Table 5). An experimental plot, 2 × 2 m, were established in the area of each nest. The plot centered the main entrance hole and included all of the other entrance holes (Figure 7).

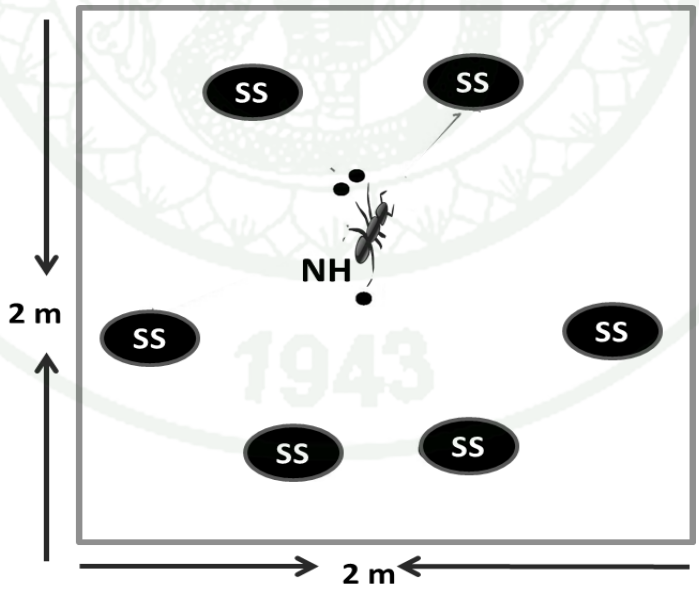

Figure 7 Experimental plot for each nest with the entrance hole in center (NH) and SS was the surrounding nest soils

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3 Ground dwelling arthropods sampling

The impact of *A. gracilipes* on ground dwelling arthropod community were examined by using pitfall traps. Pitfall traps were plastic containers with 10 cm in height, 7 cm in diameter. The traps were placed into the soil and the rim traps was level with the ground surface. Each trap consists of a 70 ml plastic glass and half-filled with a mixture of soapy water and ethyl-alcohol 30%.

Sixteen pitfall traps were set up in each 10×10 subplots. All pitfall traps were placed at the center point of each subplot (Figure 6), and left for 24 hours. All ant individuals were sorted from the traps and preserved in 95% ethyl alcohol then brought back to laboratory for identification. I separated data collection from pitfall trap into two different sets for analysis. First set is arthropod group, and it refers as the all arthropod diversity which found in pit fall traps. They were identified at coarser levels of taxonomic resolution (e.g. ant, beetle, bug, centipede, isopoda and spider). For this data collection sets, non-ant arthropod refer is data collection of regroup exclude ant. Second set is ant group, and they were described to species level. Data on the number of species and individuals for each species from sixteen pitfall trap in each sampling sites were pooled for analysis.

4 Ant nest sampling

Ant nest was sampled from sixty four, 5×5 m, subplots in the sample plot. Ant nets were surveys within subplots by combine methods with food baiting and direct sampling. Food bait consisted of three types of foods, including canned tuna, peanut butter and honey solutions diluted to concentrations 30 % v/v. Mixed food approximately 3 g were placed on 10×10 cm white cottons (Figure 8).

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Figure 8 Mixed food on white cottons above the soil surface

Within each subplot, I placed the three bait card randomly with each bait was approximately 2 m apart. The bait was laid out for 45 minute, and then we looked for ant trails starting at each bait station and followed ant worker carrying food back to their nest (Baccaro and Ferraz, 2013). Colony direct sampling: Ant nest were searched directly on forest floor to tree trunk at high level 0-120 cm by one collector in five minute per each subplots. All surveys were done between 8:00 to 17:00. Ten to twenty individuals from each nest found were collected and were preserved in 95% ethylene alcohol for ant identification. The number of ant nest for each ant species within subplot were counted for analysis. Nesting sites for ant species were recorded.

5 Measurements of CO_2 efflux and environmental factors

Nest CO_2 efflux was measured from the soil surface at the entrance hole of the nests, using a commercial respiration chamber (SRC-1, PP-system; Amesbury, MA, USA) and infrared gas analyzer (EGM-4, PP-systems) following methods in Ohashi *et al.*, (2007c) (Figure 9). Additionally, I selected five to six soil control points surrounding the nest entrance holes in each experimental plot for the soil CO_2 efflux measurement. The presence/absence of ant nests and/or other ants and termites were examined by digging up the soil under the control points to a depth of 10–30 cm, following the completion of all measurements to confirm there was no influence from

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the ant nest. The absence of nest was used as the criterion to define where there is no impact of ant nest. Commercial respiration chamber (SRC-1, PP-system; Amesbury, MA, USA) and infrared gas analyzer (EGM-4, PP-systems).



Figure 9 Experimental plot with the size of 2 × 2 m in the area of each nest. MH was the PVC collars at the ant nests, and SS was the PVC collars at the surrounding ant nest soils

CO_2 efflux measurement has done by using a closed- chamber method. The PVC collars (height 3-4 cm, diameter 10 cm) were inserted into the soil at least 0.5 cm deep to mount the commercial respiration chamber and put plasticine sealing between the collars and soils to make them air-tight during the measurement (a, b). The collars were set up 1 day before the CO_2 measurement, and left in the place throughout the experiment. To minimize ant activity disturbance, CO_2 measurements were started at the main entrance hole. We then measured the other entrance holes and controls in the same plot and averaged the nest and soil CO_2 efflux, respectively. Measurements were repeated three times at each entrance hole and twice for the controls and then averaged for each measurement point. It took around 15 minutes for a nest and 10 minutes for a control point to finish the repetition and get a data of CO_2 efflux. We measured the diameter of each entrance, and then calculated the average entrance hole diameter for

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each nest. The nest structure of subterranean ants is characterized by the size and number of tunnels and chambers (Tschinkel, 2003). Therefore, it is possible that the size and number of entrance holes is related to the nest structure characteristics. In this study, the mean diameter and number of the nest entrance holes per plot was used to calculate a nest structure index.

After CO_2 measurements, soil temperature and moisture content were measured at three locations around each collar. We measured the soil temperature at a depth of 10 cm with a Drip-Proof Type Digital Thermometer (MODEL PC-9215; SATO, Tokyo, Japan), and from ground level to 6 cm with a moisture sensor (ThetaProbe type ML2x; Delta-T Devices Ltd., Cambridge, UK) .

The series of measurements were conducted during the day, between 09:00 and 16:00 h, with measurements at each plot taking approximately 2 h, resulting in two to three plots measured daily. We measured at least three nests randomly for each species. The measurements of most ant species occurred during the wet and dry seasons, except for *Harpegnathos venator* (Table 5).

6. Arthropod Identification

All ground dwelling arthropods from pitfall trap were classified into two groups, ants and non-ant arthropods. Ants were identified to species/ morphospecies by reference to the ant collection in Ant Museum at Kasetsart University and the Insect collection at Department of National Parks, Wildlife and Plant Conservation (DNP, systematic keys of Bolton (1994), Eguchi (2001) and reliable digital resources (http: //www.antweb.org and http://www.antbase.de).Some ant specimens were identified to species with help of ant experts, Prof. Seiki Yamane (Japan). For non-ant arthropods, as arthropods are extremely high diversity in the tropics and the fact that species richness to date remains undescribed by taxonomist (Basset, 2001). Therefore, all individuals of non-ant arthropods were identified at least family by using systematic keys of Triplehorn and Johnson, (2005).

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7. Data analysis

7.1 Impact of *Anoplolepis gracilipes* on the diversity and community compositions of arthropods

Impact of sampling sites on arthropods and nesting habitat of native ants species were determined by difference in diversity and compositions. There are six general types of variables used to represent ground dwelling arthropod diversity and communities: (1) number of species and individuals in sampling sites, (2) frequency of occurrence across samples, (3) abundance, (4) Shannon diversity index (*H'*), (5) Evenness index (*E*) and (6) Bray-Curtis similarity indices. Frequency and abundance were calculated by:

$$\text{Frequency; } F(\%) = \frac{\text{Number of occupied pitfall traps/ study sites}}{\text{Total number of pitfall traps}} \times 100 \quad \ldots.(1)$$

$$\text{Abundance; } A(\%) = \frac{\text{Number of individuals of species A}}{\text{Number of occupied pitfall traps}} \times 100 \quad \ldots\ldots..(2)$$

Diversity indices for each study area types were estimated using the Shannon diversity index (*H'*) and Evenness index (*E*). Bray-Curtis similarity indices were evaluated for both uninvaded and invaded. All indices were performed with the PAST software package (version 2.16, Hammer *et al*., 2001). For comparison of average number of species and individual, frequency and abundance, and diversity indices was divided into four parts. First a test was used to examine if all indices of non-ant arthropod was a difference between sites (i.e. uninvaded and invaded sites), and between seasons (i.e. wet and dry seasons) respectively. Ant data collection was excluded from this analysis. The second test was used to determine the difference in all indices of ant species between sites, and between seasons. The third test was used to examine the difference in number of nest conducted in nesting types, frequency and abundance of nest between sites, and between seasons. The last test was used to

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examine the difference in number of ant species detected in nest surveys between sites. A comparison in all statistical tests was performed using a univariate analysis of variance (ANOVA). Whenever significant results (at the level of $P < 0.05$) occurred in ANOVA, a post-hoc test was done using Bonferroni pairwise comparisons. Normality and homogeneity of data were confirmed prior to the analyses using Shapiro-Wilk's and Levene's tests, respectively. Non-distributed variables were transformed through log10(x+1) for attain to improving normality before analysis. These statistical analyses were performed with SPSS ver. 20.0.0 for Windows (SPSS Inc., Chicago, IL, USA).

7.2 Impact of subterranean nests of ant on CO_2 efflux from soil

The differences in CO_2 effluxes among ant nests and the control soils, season and ant species were examined using a General Linear Model (GLM) analysis with the sampling location (ant hole and surrounding soil) as within-subject factor, and season (wet and dry) and ant species as between-subject factors. Raw data were natural log-transformed to decrease heteroscedasticity, after checking for normality and homogeneity using Shapiro-Wilk's and Levene's tests, respectively. Whenever significant results (at the level of $P<0.05$) occurred in the GLM, a post-hoc test was done using Bonferroni pairwise comparisons. To compare the relationship between CO_2 efflux and environmental factors (i.e., soil temperature and soil moisture content) we used linear regression analyses for the ant nest and the control data separately.

We used the number of entrances and the diameter of entrance holes as an index of nest structure. The number of entrance holes were classified into two groups, single-(only one) and multiple (greater than one) hole types. The effect of the different hole type on the CO_2 efflux from ant nests was determined using a two-way ANOVA with the hole types and season as explanatory variables. Nest CO_2 efflux data were natural log transformed to meet the assumptions of normality. The relationship between the mean diameter of entrance holes per nest and nest CO_2 efflux was tested using linear regression analysis. All statistical analyses were performed with SPSS ver. 20.0.0 for Windows (SPSS Inc., Chicago, IL, USA).

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RESULTS AND DISCUSSION

Part 1: The diversity and distribution of invasive ants in Thailand

1. Diversity of ant in Thailand

A total of 6448 individual ants comprised 2205 from pitfall traps. I identified a total of 220 ant species and 52 genera belonging in 10 subfamilies (Table 7; Appendix Figure 1-5). The subfamilies Aenictinae, Amblyoponinae, Cerapachyinae, Dolichoderinae, Dorylinae, Ectatomminae, Formicinae, Myrmicinae, Ponerinae and Pseudomyrmecinae collected were. The greatest number of ant species were found in the subfamily Myrmicinae (110 species) followed by Ponerinae (42 species) and Formicinae (34 species) respectively, and the lowest in the Dorylinae, Cerapachyinae, Amblyoponinae and Ectatomminae.

Table 7 The total numbers of ant genera and species in each subfamily collected from the pitfall traps

Subfamily	Genera	species
Aenictinae	1	9
Amblyoponinae	1	2
Cerapachyinae	1	3
Dolichoderinae	6	12
Dorylinae	1	1
Ectatomminae	1	2
Formicinae	10	34
Myrmicinae	21	110
Ponerinae	9	42
Pseudomyrmecinae	1	5
Total	52	220

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The most common genus of ant is *Pheidole* (29 species), *Leptogeys* (16) and *Camponotus* (14). The genera with the lowest species numbers include *Acropyga, Anoplolepis, Cataulacus, Dorylus, Iridomyrmex, Myrmecaria, Ochetellus, Oecophylla, Paratopula, Paratrechina, Philidris, Plathytyrea, Ponera, Prenolepis, Proatta, Pseudolasius, Recurvidris, Rhoptromyrmex and Solenopsis* which have only one species in each genus.

In terms of ant diversity among habitat types, the richest habitat was the forest areas with 212 species followed by agricultural areas, plantation and the urban areas with 75, 62 and 36 species respectively. For the forest areas, there were more ant species in the dry evergreen forests (128 species) than the dry dipterocarp forest (91 species) and mixed deciduous forest (90 species) respectively. The numbers of ant species among habitat types of plantation are quite similar with a range between 48 to 50 species (Table 8). The six most abundant species were *Odontoponera denticulata* (100%), *Pheidologeton diversus* (85%), *Anoplolepis gracilipes* (82%), *Tetramorium lanuginosum* (74%), *Nylanderia* sp.2 n. *N. fulva* (65%) and *Paratrechina longicornis* (65%). The lowest abundances were found in 138 species, which have smaller frequency value with approximately 3 % per study sites (Table 8).

This study of ant species diversity is the first inventory of ant biodiversity on terrestrial ecosystems in Thailand. Overall, 220 species of ants belonging to 53 genera and 10 subfamilies were found. These values were higher than previous survey of ant diversity in specific areas in Thailand (Watanasit *et al*., 2000; Sakchoowong *et al*., 2008; 2009), and in the other countries of Asia such as India (Chavhan and Pawar, 2011), and Indonesia (Asfiya *et al.*, 2008).

Myrmicinae has the largest number of species and the lowest were found in Dorylinae, Cerapachyinae, Amblyoponinae and Ectatomminae. These results are similar to previous studies (Yotin, 2003; Hasin, 2008; Senthong, 2003) and could be explained by the fact that Myrmicinae is the greatest subfamily with high number of genera and species. In contrast, Dorylinae, Cerapachyinae, Amblyoponinae and Ectatomminae contain few genera and species (Bolton, 1994; 2006).

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Table 8 List of ant species recorded, their biostatus and frequency of occurrence (%) in Thailand

Species	Biostatus[1]	Frequency[2]
Aenictinae		
Aenictus binghami Forel, 1900	N	8.8
Aenictus dentatus Forel, 1911	N	2.9
Aenictus hottai Terayama&Yamane,1989	N	2.9
Aenictus javanus Emery, 1896	N	11.8
Aenictus laeviceps (Smith, 1857)	N	2.9
Aenictus sp.1	N	2.9
Aenictus sp.2	N	2.9
Aenictus sp.3	N	5.9
Aenictus sp.4	N	5.9
Amblyoponinae		
Amblyopone reclinata Mayr, 1879	N	17.6
Amblyopone sp.2	N	5.9
Cerapachyinae		
Cerapachys sulcinodis Emery, 1889	T	2.9
Cerapachys sp.1	T	2.9
Cerapachys sp.2	T	8.8
Dolichoderinae		
Dolichoderus thoracicus (Smith, 1860)	T	38.2
Dolichoderus sp.1	T	2.9
Iridomyrmex anceps (Roger, 1863)	I	32.4
Ochetellus glaber (Mayr, 1862)	I	8.8
Philidris sp.1	N	8.8
Tapinoma indicum Forel, 1895	T	2.9
Tapinoma melanocephalum (Fabricius, 1793)	I	55.9
Tapinoma sp.1	T	5.9
Technomyrmex albipes (Smith, 1861)	T	17.6
Technomyrmex kraepelini Forel, 1905	N	14.7
Technomyrmex sp.1	N	5.9
Technomyrmex sp.2	N	8.8

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Table 8 (Continued)

Invasive Species	Biostatus[1]	Frequency[2]
Dorylinae		
Dorylus oreientalis Westwood, 1835	N	11.8
Ectatomminae		
Gnamptogenys bicolor Emery,1889	N	20.6
Gnamptogenys binghami (Forel,1900)	N	23.5
Formicinae		
Acropyga acutiventris Roger, 1862	N	5.9
Anoplolepis gracilipes Smith, 1857	I	82.4
Camponotus arrogans (Smith, 1858)	N	2.9
Camponotus gigas (Latreille, 1802)	N	2.9
Camponotus leonardi Emery, 1889	N	5.9
Camponotus rufoglaucus (Jerdon, 1851)	N	41.2
Camponotus selene (Emery, 1889)	N	2.9
Camponotus singularis Smith, 1858	N	2.9
Camponotus sp.1	N	35.3
Camponotus sp.2	N	23.5
Camponotus sp.3	N	8.8
Camponotus sp.4	N	5.9
Camponotus sp.5	N	8.8
Camponotus sp.6	N	2.9
Camponotus sp.7	N	38.2
Camponotus sp.8	N	2.9
Nylanderia sp.1	T	44.1
Nylanderia sp.2 near *N. fulva*	I	64.7
Nylanderia sp.3	T	29.4
Nylanderia sp.4	T	11.8
Oecophylla smaragdina Fabricius, 1775	N	50.0
Paratrechina longicornis Latreille, 1802	N	64.7
Plagilepis sp.1	N	50.0
Plagilepis sp.2	N	26.5
Polyrachis sp.1	N	5.9

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Table 8 (Continued)

Invasive Species	Biostatus[1]	Frequency[2]
Polyrhachis armata (Le Guillou, 1842)	N	2.9
Polyrhachis dives Smith, 1857	N	5.9
Polyrhachis hippomanes Smith, 1861	N	2.9
Polyrhachis illaudata Walker, 1859	N	2.9
Polyrhachis laevissima Smith, 1858	N	8.8
Polyrhachis proxima Roger, 1863	N	20.6
Polyrhachis(Campomyrma) sp.1	N	11.8
Prenolepis sp.1	N	2.9
Pseudolasius sp. 1	N	26.5
Myrmicinae		
Aphaenogaster sp. 1	N	2.9
Aphaenogaster sp.2	N	17.6
Aphaenogaster sp.3	N	2.9
Aphaenogaster sp.4	N	2.9
Aphaenogaster sp.5	N	2.9
Aphaenogaster sp.6	N	2.9
Cardiocondyla emeryi Forel, 1881	I	32.4
Cardiocondyla nuda (Mayr, 1866)	T	47.1
Cardiocondyla wroughtoni Forel, 1890	I	11.8
Cataulacus granulatus Latreille, 1802	T	8.8
Crematogaster aurita Karavaiev, 1935	N	14.7
Crematogaster rogenhoferi Mayr, 1879	N	35.3
Crematogaster sp.1	N	5.9
Crematogaster sp.2	N	5.9
Crematogaster sp.3	N	2.9
Crematogaster sp.4	N	8.8
Crematogaster sp.5	N	14.7
Crematogaster sp.6	N	11.8
Crematogaster sp.7	N	11.8
Crematogaster sp.8	N	2.9

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Table 8 (Continued)

Invasive Species	Biostatus[1]	Frequency[2]
Crematogaster sp.9	N	5.9
Lophomyrmex sp.1	N	2.9
Lophomyrmex sp.2	N	8.8
Lophomyrmex sp.3	N	8.8
Meranoplus bicolor Guérin-Méneville, 1844	T	26.5
Meranoplus sp.1	N	8.8
Meranoplus sp.3	N	2.9
Meranoplus sp.4	N	2.9
Monomorium sp.1	N	47.1
Monomorium australicum Forel, 1907	N	47.1
Monomorium chinense Santschi, 1925	I	35.3
Monomorium destructor (Jerdon, 1851)	I	26.5
Monomorium floricola (Jerdon, 1851)	I	2.9
Monomorium latinoda Mayr, 1872	N	50.0
Monomorium pharaonis (Linnaeus, 1757)	I	8.8
Myrmecaria sp.1	N	2.9
Myrmicina sp.1	N	2.9
Myrmicina sp.2	N	2.9
Myrmicina sp.3	N	5.9
Myrmicina sp.4	N	2.9
Oligomyrmex sp.1	N	2.9
Oligomyrmex sp.2	N	2.9
Oligomyrmex sp.3	N	2.9
Oligomyrmex sp.4	N	2.9
Oligomyrmex sp.5	N	2.9
Oligomyrmex sp.6	N	2.9
Oligomyrmex sp.7	N	2.9
Oligomyrmex sp.8	N	5.9
*Paratopula m*acta Bolton, 1988	N	5.9
Pheidole bugi Wheeler, 1919	N	29.4

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Table 8 (Continued)

Invasive Species	Biostatus[1]	Frequency[2]
Pheidole butteli Forel, 1913	N	55.9
Pheidole fervens Smith, 1858	I	5.9
Pheidole hongkongensis Wheeler, 1928	N	2.9
Pheidole inornata Eguchi, 2001	N	20.6
Pheidole longipes Smith, 1857	N	20.6
Pheidole nodifera (Smith, 1858)	N	26.5
Pheidole megacephala (Fabricius 1793)	I	2.9
Pheidole parva Mayr, 1865	N	14.7
Pheidole plagiaria Smith, 1860	N	61.8
Pheidole tjibodana Forel, 1905	N	11.8
Pheidole sp.1	N	44.1
Pheidole sp.2	N	29.4
Pheidole sp.3	N	11.8
Pheidole sp.4	N	11.8
Pheidole sp.5	N	23.5
Pheidole sp.6	N	5.9
Pheidole sp.7	N	8.8
Pheidole sp.8	N	2.9
Pheidole sp.9	N	5.9
Pheidole sp.10	N	5.9
Pheidole sp.11	N	8.8
Pheidole sp.12	N	14.7
Pheidole sp.13	N	5.9
Pheidole sp.14	N	2.9
Pheidole sp.15	N	2.9
Pheidole sp.16	N	5.9
Pheidole sp.17	N	8.8
Pheidole sp.18	N	20.6
Pheidologeton affinis (Jerdon, 1851)	N	52.9
Pheidologeton diversus Jerdon, 1851	N	85.3

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Table 8 (Continued)

Invasive Species	Biostatus[1]	Frequency[2]
Pheidologeton pygmaeus (Emery, 1893)	N	8.8
Pheidologeton silenus Smith,1858	N	5.9
Proatta butteli Forel,1912	N	8.8
Pyramica sp.1	N	2.9
Pyramica sp.2	N	5.9
Pyramica sp.3	N	2.9
Pyramica sp.4	N	5.9
Pyramica sp.5	N	2.9
Pyramica sp.6	N	2.9
Pyramica sp.7	N	2.9
Pyramica sp.8	N	2.9
Recurvidris recurvispinosa (Forel, 1890)	N	8.8
Rhoptromyrmex wroughtonii Forel, 1902	N	5.9
Solenopsis geminata Fabricius, 1804	I	41.2
Strumigenys sp.1	N	8.8
Strumigenys sp.2	N	5.9
Strumigenys sp.3	N	5.9
Strumigenys sp.4	N	2.9
Tetramorium bicarinatum Nylander,1846	I	8.8
Tetramorium lanuginosum Mayr, 1870	I	73.5
Tetramorium parvum Bolton, 1977	T	5.9
Tetramorium polymorphum Yamane & Jaitrong, 2011	T	29.4
Tetramorium simillimum Smith, 1851	I	32.4
Tetramorium smithi Mayr, 1879	I	44.1
Tetramorium pacificum Mayr, 1870	I	17.6
Tetramorium sp.2	T	8.8
Tetramorium sp.3	T	8.8
Tetramorium walshi (Forel, 1890)	T	58.8
Vollenhovia sp.1	N	5.9
Vollenhovia sp.2	N	2.9

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Table 8 (Continued)

Invasive Species	Biostatus[1]	Frequency[2]
Ponerinae		
Anochetus graeffei Mayr, 1870	N	23.5
Anochetus sp.1	N	5.9
Anochetus sp.2	N	2.9
Anochetus sp.3	N	11.8
Anochetus sp.4	N	2.9
Diacamma rugosum LeGuillou, 1842	N	41.2
Diacamma vagans Smith, 1860	N	52.9
Diacamma sp.1	N	8.8
Diacamma sp.2	N	5.9
Hypoponera sp.1	T	8.8
Hypoponera sp.2	T	5.9
Leptogenys birmana Forel, 1900	N	26.5
Leptogenys diminuta Smith, 1857	N	52.9
Leptogenys kitteli (Mayr, 1870)	N	20.6
Leptogenys sp.1	N	11.8
Leptogenys sp.2	N	5.9
Leptogenys sp.3	N	5.9
Leptogenys sp.4	N	14.7
Leptogenys sp.5	N	2.9
Leptogenys sp.6	N	8.8
Leptogenys sp.7	N	2.9
Leptogenys sp.8	N	2.9
Leptogenys sp.9	N	8.8
Leptogenys sp.10	N	8.8
Leptogenys sp.11	N	5.9
Leptogenys sp.12	N	2.9
Leptogenys sp.13	N	2.9
Odontomachus rixosus Smith,1857	N	29.4
Odontomachus simillimus Smith, 1858	T	20.6

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Table 8 (Continued)

Invasive Species	Biostatus[1]	Frequency[2]
Odontoponera denticulata F. Smith 1858	N	100.0
Odontoponera transversa (F. Smith, 1857)	N	2.9
Pachycondyla amblyops (Emery, 1887)	N	2.9
Pachycondyla astuta Smith, 1858	N	35.3
Pachycondyla chinensis (Emery)	I	11.8
Pachycondyla leeuwenhoeki Forel, 1886	N	17.6
Pachycondyla luteipes (Mayr, 1862)	I	50.0
Pachycondyla rufipes (Jerdon, 1851)	N	11.8
Pachycondyla sp.1	N	14.7
Pachycondyla sp.2	N	8.8
Pachycondyla sp.3	N	2.9
Platythyrea sp.1	N	2.9
Ponera sp.1	N	8.8
Pseudomyrmecinae		
Tetraponera attenuata Smith, 1877	N	14.7
Tetraponera nigra (Jerdon, 1851)	N	17.6
Tetraponera rufonigra Jerdon, 1851	N	17.6
Tetraponera sp.1	N	5.9
Tetraponera sp.2	N	2.9

[1] T = Tramp ant,
N = Native ant
I = Invasive ant

[2] Frequency (%) = Num. of sites where the species found / Num. of total sites, n=34.

The most species-rich genera are *Pheidole*, *Leptogeys* and *Camponotus*. The results indicate that those ant species are the most common ground dwelling ants in Thailand, in agreement with previous studies that identified these genera as the most prevalent in various regions of the world such as in Eastern Madagascar (Fisher, 2000), in Brazil (Vasconcelos and Delabie, 2000), and even in the world (Hölldobler and Wilson, 1990).

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Some of these ant genera, such as *Oecophylla*, *Anoplolepis*, *Cataulacus*, *Proatta* and *Ochetellus*, actually have the lowest numbers of species in the world (between 1 to 3 species) (AntWeb, 2013). Considering the results of abundance, I suggest that six ant species are the dominant ground dwelling ant species in Thailand: *O. denticulata*, *P. diversus*, *A. gracilipes*, *T. lanuginosum*, *Nylanderia* sp.2 n. N. *fulva* and *P. longicornis*. They can often be found across the country, (Appendix Table 1). Difference in ant composition was related to the difference in habitat type. The highest number of native ant species was collected at some forest areas: the dry evergreen forest (111 species), dry dipterocarp forest (76 species) and mixed deciduous forest (72 species). The lowest numbers of native ant species were found in the urban area and also in some natural forests (18 species), and also at natural forest in the peat swarm forest (25 species) and hill evergreen forest (30 species). The highest number of invasive ant species was found in the tourist zone within forest areas with 22 species, (Figure 10).

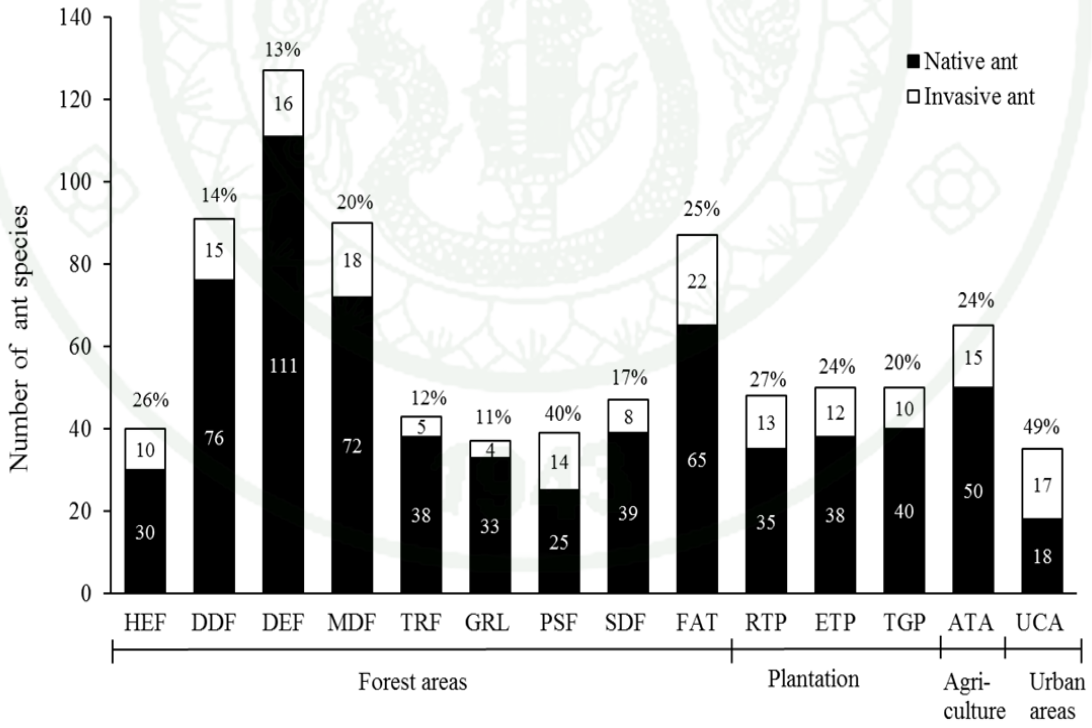

Figure 10 The number of invasive and other ant species in each habitat. The proportion of invasive ant species in parentheses had shown above each bar.

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2. Diversity of invasive ants in Thailand

A total of 24 invasive ant species and 22 tramp ant species were found (Table 9), There was greater value of frequency for seven invasive ant species, *A. gracilipes* with 51 % per habitat types followed by *T. lanuginosum* (38%), *M. pharaonis* (38%), *Nylanderia* sp.2 n. *N. fulva* (37%), *T. melanocephalum* (36%) and *P. longicornis* (35%). The lower value was found in *Pheidole megacephala* (1%), *Technomyrmex albipes* (2%), *Tetramorium bicarinatum* (2%) and *Ochetellus glaber* (2%). High frequency of each species was related to habitat types. *T. lanuginosum*, *T. melanocephalum* and *Nylanderia* sp.2 n. *N. fulva* have high frequently abundance in forest areas, *M. pharaonis* and *P. longicornis* in agricultural areas and *A. gracilipes* in the plantation. For seven dominant invasive species, the most frequently abundance of *A. gracilipes* was found in the eucalyptus plantation (88%), and *T. lanuginosum* in hill evergreen forest (100%), *M. pharaonis* in agricultural areas (73%), *and Nylanderia* sp.2n. *N. fulva* in peat swarm forest (86%), *T. melanocephalum* peat swarm forest (100%) and *P. longicornis* in agriculture areas (80%).

This observations showed that eight species of invasive ants, *A. gracilipes*, *M. pharaonis*, *M. destructor*, *S. geminata*, *P. longicornis*, *T. simillimum*, *T. smithi* and *T. lanuginosum*, have high frequency not only in human habitat (plantation, agricultural and urban areas) , which was similar reported by the other studies (Haines *et al.*, 1994; Sarnet, 2008; Rust and Choe, 2012; Figure 11;12).

3. Distribution of the *Anoplolepis gracilipes* in Thailand

For the distribution of *A. gracilipes*, it can found in 32 studies sites in Thailand with 94 % of total of study sites (Figure 13). In this study, *A. gracilipes* can not found at the hill evergreen forest.

This results clearly showed that *A. gracilipes* can be easily found in Thailand. Its distribution is below 1700 masl, which was also supported by the study of Wetterer, (2005). in the range of the lowlands tropical rainforest to the tropical moist rainforest.

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Table 9 List of invasive ant species and frequency of occurrence it in Thailand

Invasive Species	Frequency [2]														
	HEF (3)	DDF (10)	DEF (17)	MDF (8)	TRF (5)	PSF (7)	GRL (2)	SDF (6)	FAT (28)	ETP (8)	RTP (6)	TGP (6)	ATA (15)	UCA (13)	Total (134)
Anoplolepis gracilipes Smith, 1857 [1]	-	60	53	38	40	57	50	50	61	88	83	17	47	23	51
Cardiocondyla emeryi Forel, 1881	-	30	12	13	-	-	-	-	32	-	-	-	27	8	15
Cardiocondyla wroughtoni Forel, 1890	-	-	-	13	-	86	-	-	7	-	-	17	-	-	7
Iridomyrmex anceps (Roger, 1863)	-	20	-	13	-	71	50	33	14	50	50	33	27	15	22
Monomorium chinense Santschi, 1925	33	30	12	25	-	29	-	-	39	25	17	-	-	23	20
Monomorium destructor (Jerdon, 1851)	-	30	12	13	-	-	50	17	29	63	67	-	47	31	27
Monomorium floricola (Jerdon, 1851)	-	10	6	-	-	71	-	-	14	13	-	-	27	31	15
Monomorium pharaonis (Linnaeus, 1757)	33	50	53	63	-	-	-	17	39	25	-	33	73	31	38
Nylanderia sp.2 near *N. fulva*	33	20	29	50	-	86	-	33	46	25	33	50	33	31	37
Ochetellus glaber (Mayr, 1862)	-	-	-	-	-	14	--	-		13	17	-	-	-	2
Odontomachus simillimus Smith, 1858	-	10	12	13	-	71	-	-	11	-	17	-	-	8	10
Pachycondyla chinensis (Emery)	-	-	6	13	40	-	-	-	4	-	-	-	-	-	4
Pachycondyla luteipes (Mayr, 1862)	67	30	29	13	20	-	-	-	29	38	-	17	20	-	20
Paratrechina longicornis Latreille, 1802	67	20	18	38	20	29	-	-	57	-	50	-	80	23	35
Pheidole fervens Smith, 1858	-	-	-	-	-	-	-	-	11	-	-	-	-	15	4
Pheidole megacephala (Fabricius 1793)	-	-	-	-	-	-	-	-	4	-	-	-	-	8	1

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Table 9 (Continued)

Invasive Species	Frequency [2]														
	HEF (3)	DDF (10)	DEF (17)	MDF (8)	TRF (5)	PSF (7)	GRL (2)	SDF (6)	FAT (28)	ETP (8)	RTP (6)	TGP (6)	ATA (15)	UCA (13)	Total (134)
Solenopsis geminata Fabricius, 1804 [1]	33	-	-	13	-	-	-	33	29	13	67	-	73	23	23
Tapinoma melanocephalum (Fabricius, 1793)	-	50	12	63	-	100	-	17	32	13	67	33	47	38	36
Technomyrmex albipes (Smith, 1861)	-	-	6	-	-	-	-	-	7	-	-	-	-	-	2
Tetramorium bicarinatum Nylander,1846	-	10	-	-	-	-	-	-	7	-	-	-	-	-	2
Tetramorium lanuginosum Mayr, 1870	100	20	53	50	20	57	50	33	57	13	50	17	67	31	46
Tetramorium simillimum Smith, 1851	33	-	12	13	-	29	-	-	18	-	33	33	20	8	14
Tetramorium smithi Mayr, 1879	33	10	-	25	-	-	-	-	39	-	17	17	53	23	21
Tetramorium pacificum Mayr, 1870	33	-	-	-	-	43	-	-	-	-	-	-	7	-	5

[1] Invasive ant species were indicated in Thailand

[2] Frequency of occurrence of species (%) per habitat type was calculated as [Num. of sites where the species found] / [Num. of total sites, n=3-28]. Number in parentheses is number of replicate

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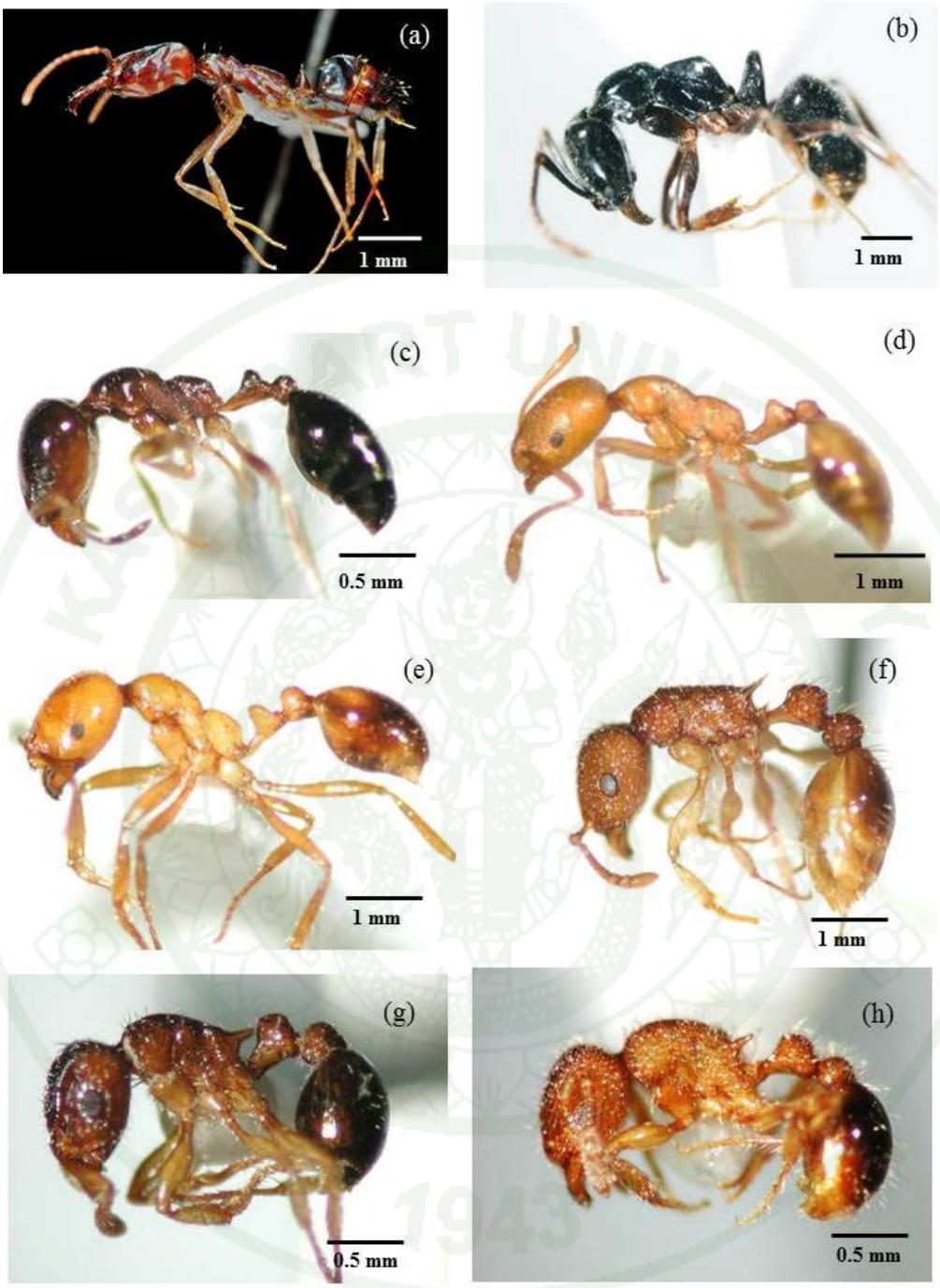

Figure 11 The sample of invasive ant species found in this study area, (a) *Odontomachus simillimus* Smith,1858 , (b) *Pachycondyla luteipes* (Mayr, 1862), (c) *Monomorium destructor* (Jerdon, 1851), (d) *Monomorium pharaonis* (Linnaeus, 1757), (e) *Solenopsis geminata* Fabricius, 1804, (f), *Tetramorium bicarinatum* (Nylander, 1846) (g) *T. smithi* Mayr, 1879 and (h) *T. lanuginosum* Mayr, 1870

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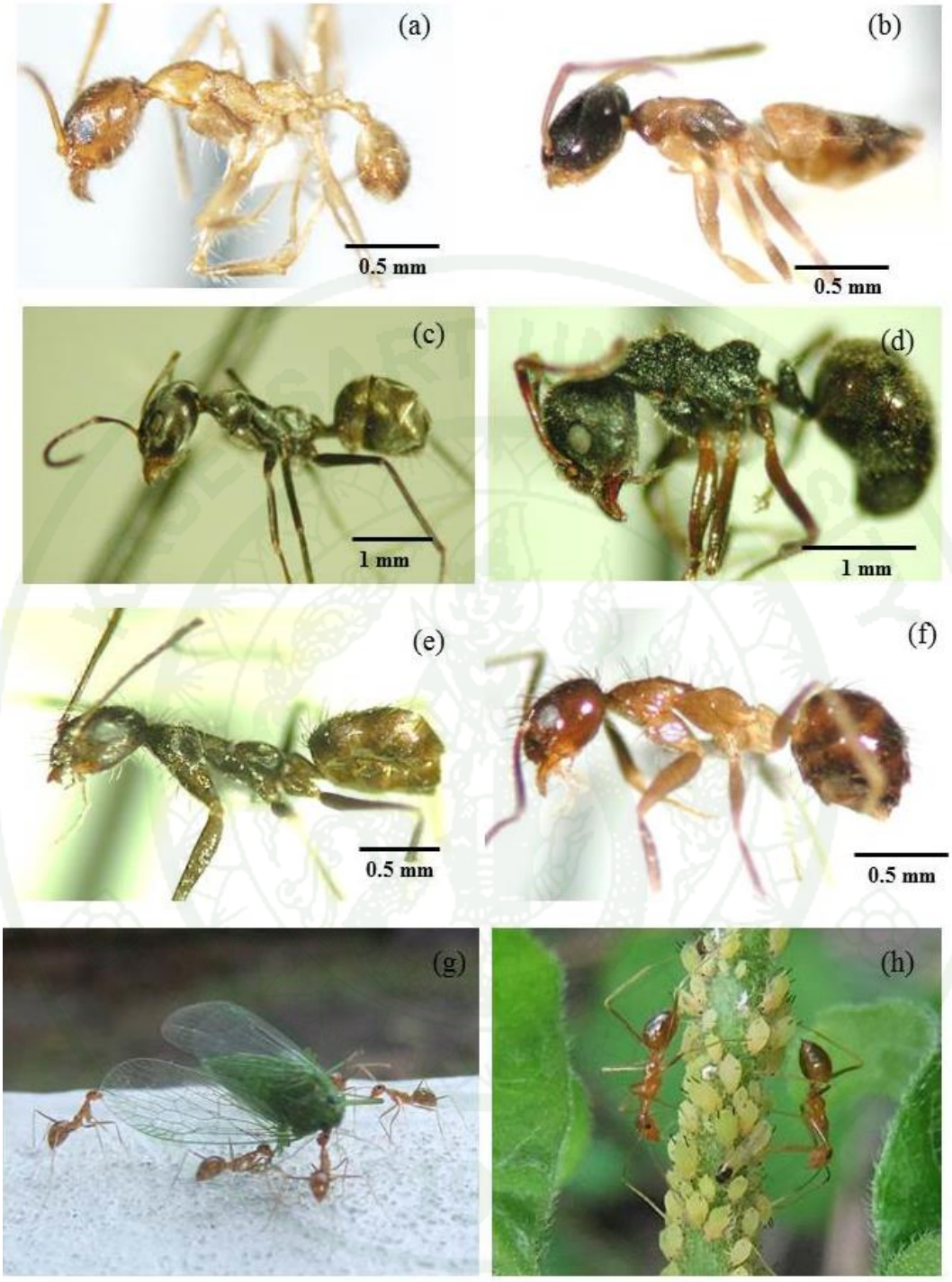

Figure 12 The sample of invasive ant species found in this study area, (a) *Pheidole fervens*, (b) *Tapinoma melanocephalum* (Fabricius, *1*793), (c) *Iridomyrmex anceps* (Roger, 1863), (d) *Dolichoderus thoracicus* (Smith, 1860), (e) *Paratrechina longicornis* Latreille, 1802, (f) *Nylanderia* sp.2 n. N. *fulva* , (h) and (g) the foraging workers of *Anoplolepis gracilipes*

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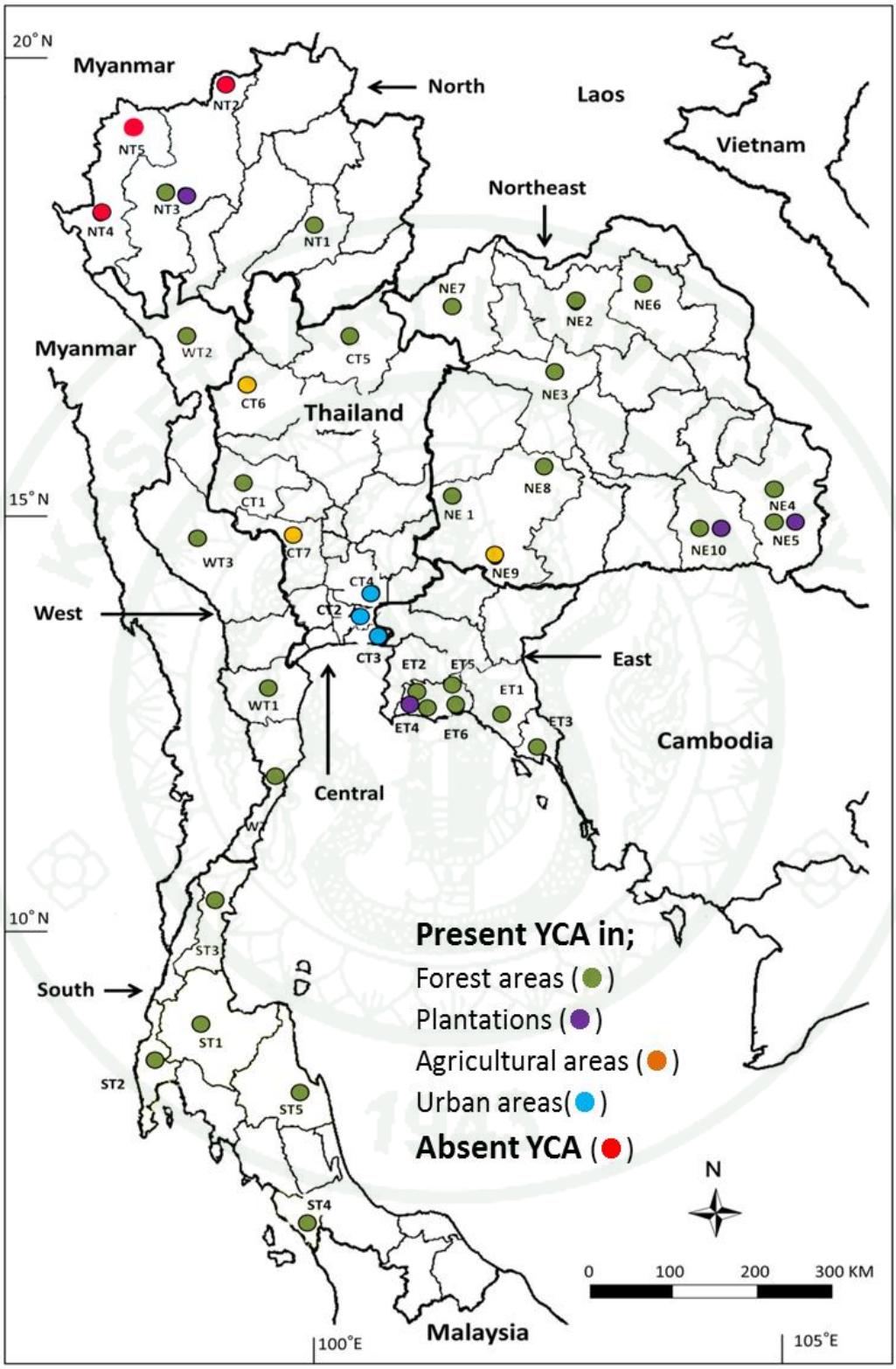

Figure 13 Distribution map of *Anoplolepis gracilipes* Smith, 1857 in Thailand

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Part 2: Ecological impact of the yellow crazy ant (*Anoplolepis gracilipes* smith, 1857; Hymenoptera: Formicidae) in dry evergreen forest at Sakaerat Biosphere Reserve

1. Impact on arthropods

A total 12 orders of arthropods (excluding ant data) were collected from both studies (Table 10). The effect of three main factors (i.e. arthropod group, seasons and sampling sites) and their interaction were shown in Table 12. The results showed that arthropod individuals, frequency of occurrence and abundance varied among arthropod groups (P<0.001), and arthropod individuals and frequency of occurrence levels varied with sites and seasons (P<0.05). Arthropods individuals and frequencies of occurrence had highly significant interaction between arthropod group and sampling sites (P<0.05), which average numbers of individuals and frequency of occurrence in arthropod groups at invaded sites were significantly lower than those in un-invaded sites(P<0.05, Figure 14a, 14b), however, the difference was not found in the abundance (Figure 14c). By using Bonfrroni post hoc test for pairwise comparison between invaded and un-invaded sites, we found that five groups of arthropod, including beetle, cockroach, termite, centipedes, and spider, had lower individuals in invaded site when compared to un-invaded sites (P<0.001). Frequency of occurrence showed the similar trend as the individuals in six groups including cockroach, termite, centipede, millipede, isopod, and spider.

There was no statically significant difference in the Shannon diversity index (H') and Evenness (E) between sites and season (P>0.05; Figure 15a; 15b).However, both H' and E at uninvaded site were greater in value when compared to with invaded site. For the similarity index, the similarity of non-arthropod between sites and seasons was more than 70 %, suggesting the strong overlap of arthropod community in the study sites (table 13).

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Table 10 Numbers of individual arthropods in 16 pitfall traps at uninvaded (UVS) and invaded site (IVS). Values were averaged per site (Ave. ± SE) with 3 replicates at each site. Different lower case letters indicated a significant difference between the UVS and IVS within the season (P< 0.05)

Arthropods group	Total number of non-ant arthropods individuals				Number of non-ant arthropods individuals			
	Dry season		Wet season		Dry season		Wet season	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Beetle; Coleoptera	351	146	369	221	117±16.5a	49±8.1b	123±14.4	74±5.0
Bug; Hemiptera	0	2	0	10	0	1±0	0	4±3
Cricket:Orthoptera	39	38	58	39	13±4	13±2.7	20±4.2	13±2.6
Cockroach; Blattodae	39	16	74	20	20±10a	6±2b	25±4a	7±2b
Earwig; Demaptera	0	4	0	3	0	2 ± 1	0	1 ± 1
Termites; Termitidae	41	13	111	8	14±8a	5±2b	37±22a	3±2b
Centipede; Chilopoda	6	2	24	3	2 ± 2	1 ± 0	8±5a	1±1b
Isopods; Isopoda	15	2	31	12	5 ± 3	1 ± 0	11±8	4 ± 4
Millepede; Diplopoda	16	0	15	2	6 ± 3	0	5 ± 3	1±1
Harvestmen; Opiliones	0	37	0	32	0	13 ± 6	0	11±7
Pseudoscorpion; Pseudoscorpionida	15	6	23	7	5 ± 2	2 ± 2	8±2	3±2
Spider; Araneae	48	38	83	32	16 ± 2	13 ± 4	27±4a	11±2b
Total	2310	1171	2943	1634	770±76 a	391±40.2 b	981±60 a	545±21 b

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Table 11 Frequency and abundance of arthropods in 16 pitfall traps at UVS and IVS. Values are averaged per site (Ave. ± SE) and n=3 for each site. Difference lower case letters indicate a significant difference between the UVS and IVS within the season ($P < 0.05$)

Arthropods	Frequency (%)				Abundance (%)			
	Dry season		Wet season		Dry season		Wet season	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Beetle; Coleoptera	95.8±2.1	81.3±9.5	89.6±5.5	91.7±5.5	15.8±3.4	12.3±1.2	12.6 ± 1.6	13.6±1.0
Bug; Hemiptera	0	2.1±2.1	0	6.3±6.3	0	0.1±0.1	0	0.7 ± 0.7
Cricket; Orthoptera	39.6±9.1	43.8±3.6	52.1 ± 9.1	39.6 ± 9.1	1.6 ± 0.3	3.2±0.4	1.9 ± 0.3	2.4 ± 0.4
Cockroach; Blattodae	27.1±13.6	22.9 ± 4.2	68.8±15.7a	27.1 ±4.2b	1.8 ± 1.3	1.5 ± 0.6	3.0 ± 0.5	1.4 ± 0.4
Earwig; Demaptera	0	6.3 ± 3.6	0	4.2 ±4.2	0	0.4 ± 0.2	0	0.2 ± 0.2
Termites; Termitidae	16.7±9.1	12.5 ± 6.3	33.3±9.8a	8.3±5.5b	1.9 ± 1.1	1.5 ± 0.9	4.4±2.5	0.6±0.3
Centipede; Chilopoda	8.3 ± 8.3	4.2 ± 4.2	35.4±21.7a	6.3±3.6b	0.3 ± 0.3	0.2 ± 0.2	1.0 ± 0.5	0.2 ± 0.1
Isopods; Isopoda	14.6±9.a	2.1 ± 2.1 b	10.4 ± 5.5	2.1 ± 2.1	0.9 ± 0.7	0.2 ± 0.2	1.2 ± 0.9	0.9 ± 0.7
Millepede; Diplopoda	16.7±4.1	0	22.9±10.4a	2.1±2.1b	1.0 ± 0.7	0	0.6 ± 0.3	0.1 ± 0.1
Harvestmen; Opiliones	0	31.3 ±15.7	0	27.1 ± 16.3	0	3.9 ± 2.1	0	2.2 ± 1.4
Pseudoscorpion; Pseudoscorpionida	20.8±5.5	10.4 ±10.4	31.3 ± 9.5	10.4 ± 10.4	0.8 ± 0.2	0.7 ± 0.7	0.9 ± 0.3	0.5 ± 0.5
Spider; Araneae	37.5±3.6	39.6 ± 7.5	62.5±14.4a	35.4±8.3 b	2.6 ± 0.4	3.7 ± 0.9	3.4 ± 0.7	2.3 ± 0.5
Total					100	100	100	100

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Table 12 Results from the GLM univariate anlysis showing *F* values and levels of significance for each source of variation and each dependent variable

Source of variation	Dependent Variable [1]								
	Number of individuals (N per plots)			Frequency (%)			Abundance (%)		
	d.f.n.	*d.f.d.*	*F*	*d.f.n.*	*d.f.d.*	*F*	*d.f.n.*	*d.f.d.*	*F*
arthropod groups	12	60	63.96***	12	60	27.48***	12	60	102.66***
season	1	60	7.92**	1	60	4.46*	1	60	0.01
sites	1	60	40.04***	1	60	23.56***	1	60	1.08
season*site	1	60	1.17	1	60	2.68	1	60	2.26
arthropods group*season	12	60	0.70	12	60	0.60	12	60	0.64
arthropods group*site	9	60	2.86 *	9	60	2.55*	9	60	1.81
arthropods group*season*site	8	60	0.41	8	60	0.95	8	60	0.60

[1] *, ** and *** ($P<0.05$, $P<0.01$ and $P< 0.001$, respectively) indicate significant differences with the 95% confidence interval

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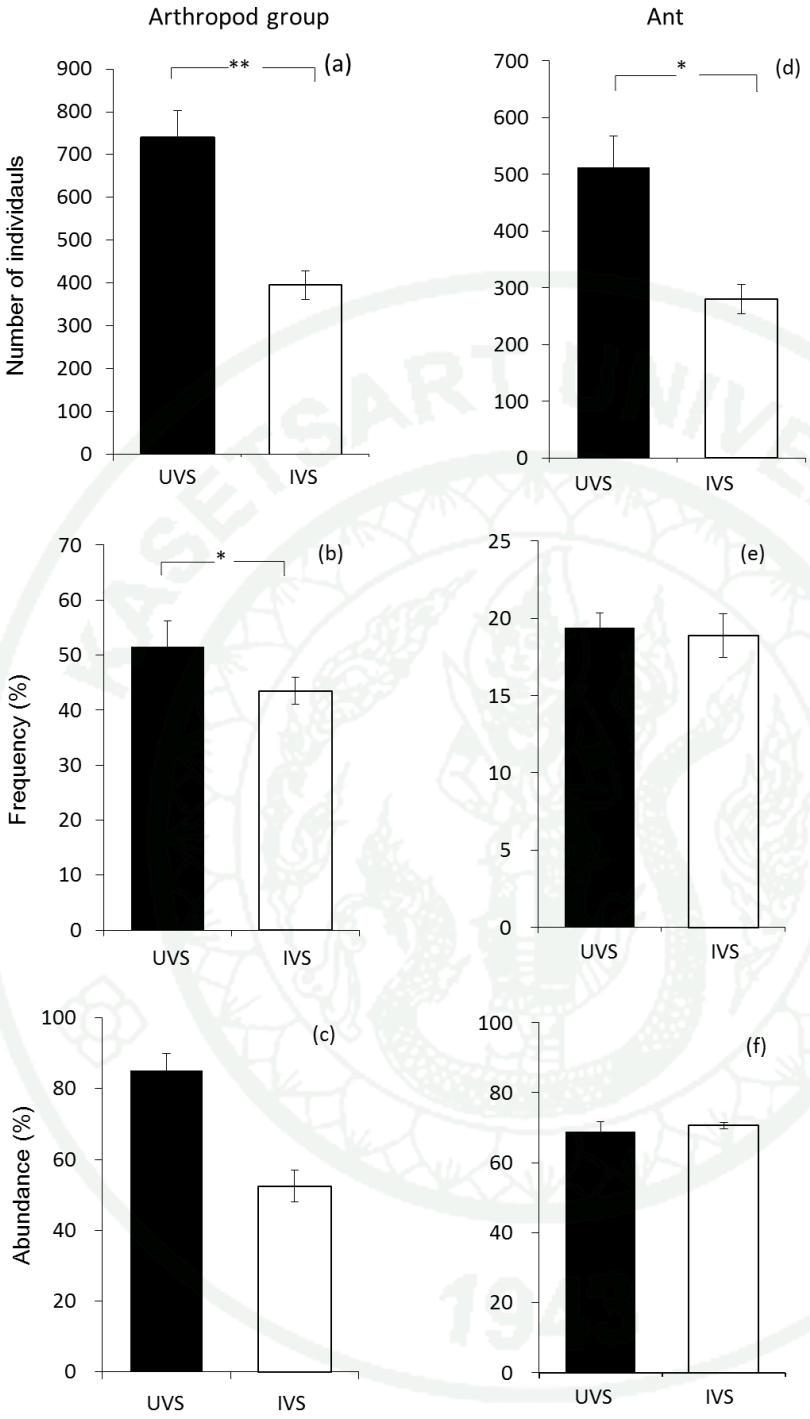

Figure 14 Numbers of individuals, frequency and abundance of soil arthropods and ants at UVS and IVS, (n≥7). Asterisk (*) indicated the significant differences at level of P<0.05

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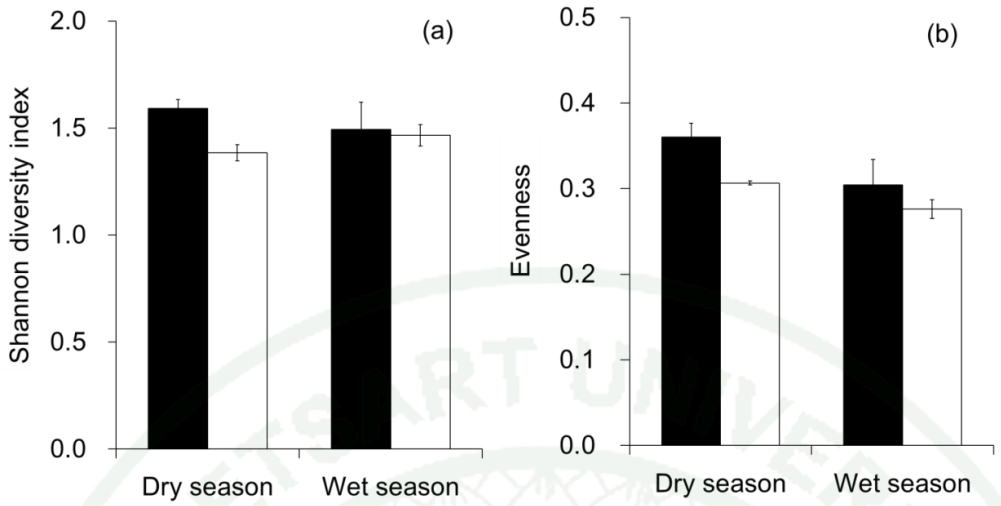

Figure 15 Shannon diversity index (a) and evenness (b) with the standard error of arthropods in UVS (black bars) and IVS (white bars) in the dry and wet season

Table 13 Bray-Curtis coefficients of similarity matrix for non-ant arthropods between un-invaded (UVS) and *A.gracilipes* invaded sites (IVS) in dry and wet season.

season/site		Dry season		Wet season	
		UVS	IVS	UVS	IVS
Dry season	UVS	1	-	-	-
	IVS	0.74	1	-	-
Wet season	UVS	0.91	0.81	1	-
	IVS	0.80	0.95	0.82	1

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The arthropods listed in Table 10 were quite similar to those found by Nagy *et al.,* (2009), which they applied same sampling techniques as in this study. They found 10 non-ant arthropods in invaded sites by *Lasius neglectus* at the mixture of wooded areas and grassy fields in Hungary. The non-ant arthropod diversity and abundance were significantly lowers at invasion area by the other invasive ant such as *Solenopsis invicta* (Epperson and Allen, 2010), *Linepithema humile* (Human and Gordon, 1997) and *Lasius neglectus* (Nagy *et al.,* 2009) which was similar to the result from this study.

For the effect of sites for each arthropod group, the analysis found that the sites had significant effects on the arthropod individuals in beetle, cockroach, termite, centipedes and spider, and also frequency level in cockroach, termite, centipede, millipede, isopod and spider. It is possible that those arthropod communities at invaded sites in this study failed to coexist with *A. gracilipes* because they constitute main food sources for this ant in my study site. It was in effect reported from previous research that this invasive ant preys on many groups of litter arthropods (Lewis *et al.,* 1976; Haines *et al.* 1994; O'Dowd *et al.,* 1999). These effects of *A. gracilipes* at their invasion areas have been observed for the other invasive ant species. For example, Nagy *et al.,* (2009) suggested a strong negative effect of the *L. neglectus* supercolony on the isopods assemblages and beetle abundance. Harvey and Eubanks (2004) found two species of beetles negatively affected on diversity by *Solenopsis invicta*.

A. gracilipes' supercolony might have possible indirect effects on the process of decomposition and nutrient cycling in terrestrial ecosystems by predating termites as foods or suppressing termite community. As it is well known that termites constitute a functional group which plays an important role in the process of litter decomposition and nutrient cycling (Yamada, 2004; 2005). For this study, the diversity and community compositions of termites were lower at invaded sites than uninvaded sites. Similar results were observed for other invasive ant species. For example, Stoker *et al.* (1995) reported that fire ants significantly altered population of invertebrate groups including calliphoridae, muscidae, sarcophagidae, staphylinidae, silphidae and histeridae. which are important decomposers on terrestrial ecosystems. Rodriguez-Cabal *et al.,* (2009) found that invaded sites of *L. humile* had 92% fewer native ants,

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which are seed dispersers, than non-invaded sites. They also concluded that potential shifts in plant diversity and concomitant changes in ecosystem function may be a consequence of the ant invasion. Moreover, there are also indirect effects on energy flow through terrestrial food webs. In ecosystems of conservation value, arthropods are most favorable sources of nutrition for insectivores such as reptiles, amphibians, rodent, birds and bats (Zahn *et al.*, 2010). Špaldoňováa and Frouza (2014) reported that the terrestrial isopod *Armadillidium vulgare* greatly negative affected the decomposition of leaf litters.

2. Impact on native ant

A total of 83 ant species from 27 genera were collected from all sites (Table 14, 15). There was a greater number of ant species in un-invaded sites (61 species) than in invaded sites (53 species). The effect of tree factors (species, seasons and sampling sites) and their interaction are shown in Table 16. The results were shown whether ant individuals, frequency of occurrence and abundance varied among ant species (P<0.001), and ant individuals and frequency of occurrence levels varied between sites and seasons (P<0.01). Arthropods individuals, frequency of occurrence and abundance was highly significant statistical interaction found between sampling sites and ant species (P<0.01). Variable index (i.e. frequency and abundance) differed between sites in six ant species that the difference was found in dry season including *M. pharaonis*, *O. denticulata*, *P. parva*, *P. hongkongensis*, *P. plagiaria* and *P. diversu*s, and in ten species in wet season including *D. thoracicus*, *M. pharaonis*, *Nylanderia* sp.2 near *N. fulva*, *O. denticulata*, *P. parva*, *P. hongkongensis*, *Pheidole* sp.1, *P. affinis*, *Pseudolasius* sp. 1 and *Tetramorium* sp.8 (Bonferroni post hoc tests; P<0.001; Table 14; 15), which average numbers of individuals of ant at invaded sites were significantly lower than those in un-invaded sites(P<0.05, Figure 14d), however, the difference was not found in the frequency (Figure 14e) and abundance (Figure 14f).

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Table 14 Numbers of individuals, and frequency and abundance of ants in 16 pitfall traps at UVS and IVS. Values are averaged per site (Ave. ± SE) and n=3 for each site. Difference lower case letters indicate a significant difference between the UVS and IVS within the season (P<0.05). Different capital letters (A and B for UVS, A' and B' for IVS) indicated the significant difference between wet and dry season (P<0.05)

Species	Total number of ant individuals				Number of ant individuals (N per plots)			
	Dry season		Wet season		Dry season		Wet season	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Aenictus sp.1	2	0	5	0	1 ± 1	0	2 ± 1	0
Aenictus sp.2	0	0	5	0	0	0	2 ± 2	0
Anochetus graeffei	15	0	14	1	5 ± 4	0	5 ± 2	1 ± 0
Anochetus sp.3	15	2	0	3	5 ± 3	1 ± 1	0	1 ± 1
Anoplolepis gracilipes [1]	0	352	0	411	0	117±33	0	137±39
Aphaenogaster sp. 1	16	10	31	11	5 ± 1	4 ± 3	11 ± 2	4 ± 3
Cardiocondyla nuda [1]	0	5	0	11	0	2 ± 1	0	4 ± 2
Crematogaster sp.1	12	0	11	0	0	0	4 ± 2	0
Crematogaster sp.2	0	0	6	23	0	0	2 ± 2	8 ± 8
Crematogaster sp.3	0	0	14	7	0	0	5 ± 5	3 ± 2
Diacamma vargens	0	2	0	9	0	1 ± 0	0	3 ± 1
Dolichoderus thoracicus	24	4	40	2	8±4A	2±1A'	14±7a,B	1±1b,B'
Dorylus orientalis	5	0	9	0	2 ± 2	0	3 ± 2	0
Gnamptogenys binghamii	3	1	6	5	1 ± 1	1 ± 0	2 ± 2	2 ± 0

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Table 14 (Continue)

Species	Total number of ant individuals				Number of ant individuals (N per plots)			
	Dry season		Wet season		Dry season		Wet season	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Hypoponera sp.1	2	0	0	0	0	0	0	0
Hypoponera sp.2	0	0	0	1	0	0	0	1 ± 0
Leptogenys diminuta	0	9	0	11	0	3 ± 2	0	4 ± 3
Leptogenys sp.1	0	0	1	0	0	0	1 ± 0	0
Leptogenys sp.2	4	0	2	0	1 ± 1	0	1 ± 0	0
Leptogenys sp.3	0	0	5	0	0	0	2 ± 2	0
Leptogenys sp.4	1	0	1	0	1 ± 0	0	1 ± 0	0
Leptogenys sp.5	0	1	0	3	0	1 ± 0	0	1 ± 1
Leptogenys sp.6	1	0	1	0	1 ± 0	0	1 ± 0	0
Monomorium chinense [1]	0	0	0	6	0	0	0	2 ± 2
Monomorium floricola	0	0	0	16	0	0	0	6 ± 5
Monomorium pharaonis [1]	1	37	3	52	1 ± 0 a	13±11b	1 ± 1 a	18 ±7b
Monomorium talpa	6	0	7	0	2 ± 1	0	3 ± 2	-
Monomorium sp. 1	2	12	19	16	1 ± 1	4 ± 2	7 ± 4	6 ± 3
Myrmicina sp. 1	1	0	2	0	1 ± 0	0	1 ± 1	0
Nylanderia sp.1	4	0	14	26	2 ± 1	0	5 ± 3	9 ± 4
Nylanderia sp.2 near *N. fulva*	0	1	1	30	0	1±0A'	1 ± 0a	10±10b,B'

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Table 14 (Continue)

Species	Total number of ant individuals				Number of ant individuals (N per plots)			
	Dry season		Wet season		Dry season		Wet season	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Odontoponera denticulata	187	51	213	69	62±22a	17±5b	71±12a	23 ± 12 b
Oligomyrmex sp.1	19	0	15	0	6 ± 2	0	5 ± 1	0
Oligomyrmex sp.2	35	0	36	0	12 ± 6	0	12 ± 6	0
Oligomyrmex sp.3	8	0	24	0	3±2A	0	8 ± 4 B	0
Oligomyrmex sp.4	2	0	5	0	1 ± 1	0	2 ± 2	0
Oligomyrmex sp.5	14	0	0	0	5 ± 3	0	0	0
Oligomyrmex sp.6	0	0	1	0	0	0	1 ± 0	0
Oligomyrmex sp.7	5	0	21	0	2 ± 2	0	7 ± 7	0
Oligomyrmex sp.8	2	0	0	0	1 ± 1	0	0	0
Pachycondyla astuta	9	2	6	2	3 ± 2	1 ± 1	2 ± 1	1 ± 1
Pachycondyla luteipes	5	0	12	0	2 ± 1	0	4 ± 4	2 ± 2
Pachycondyla sp.1	9	0	0	0	3 ± 3	0	0	0
Pachycondyla sp.2	9	0	1	0	3 ± 3	0	1 ± 0	0
Pachycondyla sp.3	15	3	14	5	5 ± 2	1 ± 1	5 ± 2	2 ± 2
Paratrechina longicornis [1]	0	19	0	37	0	7 ± 3	0	13 ± 7
Pheidole parva	86	4	80	3	29 ±2a	2 ±1b	27 ±2a	1 ±1b
Pheidole dugosi	5	1	13	0	2 ± 2	1 ± 0	5 ± 2	0
Pheidole hongkongensis	137	49	293	67	4 ±12 a	17±3b	98 ± 9 a	23±1b

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Table 14 (Continue)

Species	Total number of ant individuals				Number of ant individuals (N per plots)			
	Dry season		Wet season		Dry season		Wet season	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Pheidole plagiaria	131	21	0	0	44±15a	7 ±3b	0	0
Pheidole sp.1	0	0	0	28	0	0	14 ±14a	10 ±7b
Pheidole sp.2	10	0	0	11	4 ± 3	0	0	4 ± 4
Pheidole sp.3	18	0	0	0	6 ± 4A	0	1 ± 0B	0
Pheidole sp.4	6	0	0	3	2 ± 2	0	1 ± 1	1 ± 1
Pheidole sp.5	10	0	0	0	4 ± 3	0	2 ± 1	0
Pheidole sp.6	1	0	0	0	1 ± 0	0	0	0
Pheidole sp.7	0	2	0	0	0	1 ± 1	0	0
Pheidole sp.8	0	3	0	0	0	1 ± 1	0	0
Pheidole sp.9	0	1	0	0	0	1 ± 0	0	0
Pheidole sp.10	0	2	0	0	0	1 ± 1	0	0
Pheidole sp.11	0	2	0	0	0	1 ± 1	0	0
Pheidole sp.12	0	12	0	0	0	4 ± 4	0	0
Pheidole sp.13	0	6	0	0	0	2 ± 2	0	0
Pheidole sp.14	0	0	0	2	0	0	0	1 ± 1
Pheidologeton affinis	204	0	277	15	68±23	0	93 ±7a	5±5b
Pheidologeton diversus	167	12	223	0	56±29a	4±4b	75 ± 26	0

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Table 14 (Continued)

Species	Total number of ant individuals				Number of ant individuals (N per plots)			
	Dry season		Wet season		Dry season		Wet season	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Plagiolepis sp. 1	0	4	0	6	0	2 ± 1	0	2 ± 2
Pseudolasius sp. 1	33	4	109	4	11±4A	2 ± 1	37±2a,B	2±1b
Smistristruma sp.1	2	0	2	0	1 ± 1	0	1 ± 1	0
Smistristruma sp.2	3	0	2	0	1 ± 1	0	1 ± 1	0
Smistristruma sp.3	0	0	2	0	0	0	1 ± 1	0
Tapinoma melanocephalum [1]	0	13	0	44	0	5 ± 4	0	15 ±15
Tecnomyrmex kraeperinii	2	0	10	0	1 ± 1	0	4 ± 2	0
Tetramorium lanuginisum [1]	81	6	60	7	27±12	2 ± 2	20 ± 4	2 ± 2
Tetramorium sp.1	0	0	0	2	0	0	0	1 ± 1
Tetramorium sp.2	0	2	0	3	0	1 ± 1	0	1 ± 1
Tetramorium sp.3	0	0	0	10	0	0	0	4 ± 2
Tetramorium sp.4	15	4	5	18	5 ± 1	2 ± 1	2 ± 1	6 ± 3
Tetramorium sp.5	0	0	2	2	0	0	1 ± 1	1 ± 1
Tetramorium sp.6	8	5	31	7	3 ± 2	2 ± 1	11±4	3±2
Tetramorium sp.7	1	0	0	0	1 ± 0	0	0	0
Tetramorium sp.8	8	2	24	1	3 ± 3	1 ± 1	8±5a	1±0b
Tetramorium sp.9	9	0	0	1	3 ± 3	0	0	1 ± 0
Total	1350	684	1728	995	450±78	228±23	576±71	332±11

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Table 15 Frequency and abundance of ants in 16 pitfall traps at UVS and IVS. Values are averaged per site (Ave. ± SE) and n=3 for each site. Difference lower case letters indicate a significant difference between the UVS and IVS within the season (P<0.05). Different capital letters (A and B for UVS, A' and B' for IVS) indicated the significant differences between wet and dry season (P<0.05)

Species	Frequency (%)				Abundance (%)			
	Dry season		Wet season		Dry season		Wet season	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Aenictus sp.1	2.1±2.1	0	6.3 ± 3.6	0	1.0 ± 0.1	0	1.0 ± 0.2	0
Aenictus sp.2	0	0	4.2 ± 4.2	0	0	0	1.0 ± 0.3	0
Anochetus graeffei	8.3±2.0	0	12.5±3.6	2.1±2.1	2.0 ± 0.7	0	1.0 ± 0.3	1.0±0.1
Anochetus sp.3	10.4±5.5	2.1 ± 2.1	0	6.3±6.3	2.0 ± 1.0	1.0 ± 0.3	0	1.0±0.4
Anoplolepis gracilipes [1]	0	83.3±10.4	0	85.4±4.1	0	51.5±12.1	0	40.6±15.9
Aphaenogaster sp. 1	20.8±4.1	16.7±137	41.7±9.1	20.8±15.0	2.0 ± 0.2	1.8 ± 1.6	1.8 ± 0.4	1.1 ± 1.5
Cardiocondyla nuda [1]	0	8.3 ± 4.2	0	14.6±7.5	0	1.0 ± 0.4	0	1.1 ± 0.8
Crematogaster sp.1	10.4±2.0	0	8.3 ±5.5	0	1.5 ± 0.3	0	1.5 ± 0.3	0
Crematogaster sp.2	0	0	2.1±2.1a	10.4±10.4b	0	0	1.0±0.4 a	2.4±3.1b
Crematogaster sp.3	0	0	2.0 ± 2.1	8.3 ± 8.3	0	0	1.0 ± 0.9	1.0 ± 0.9
Diacamma vargens	0	4.2 ± 2.1	0	14.6 ± 4.1	0	1.0 ± 0.2	0	1.0 ± 0.4
Dolichoderus thoracicus	16.7±6.3	6.3±9.1	20.8±10.4	4.2 ± 4.1	3.9±0.5 a	1.0±2.2b,A'	2.2 ± 1.1	1.0±0.4B'
Dorylus orientalis	4.2±4.2	0	8.3 ± 5.5	0	1.0 ± 0.3	0	0.6 ± 0.4	0
Gnamptogenys binghamii	4.2±4.2	2.1 ± 2.1	8.3 ± 8.3	8.3 ± 4.1	1.0 ± 0.2	1.0 ± 0.2	1.0 ± 0.3	1.0 ± 0.4
Hypoponera sp.1	2.1±2.1	0	0	0	1.0 ± 0.2	0	0	0

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Table 15 (Continued)

Species	Frequency (%)				Abundance (%)			
	Dry season		Wet season		Dry season		Wet season	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Hypoponera sp.2	0	0	0	2.1 ± 2.1	0	0	0	1.0 ± 0.2
Leptogenys diminuta	0	8.3 ± 5.5	0	10.4 ± 7.5	0	1.5 ± 1.2	0	1.1 ± 1.5
Leptogenys sp.1	0	0	2.1 ± 2.1	0	0	0	1.0 ± 0.1	0
Leptogenys sp.2	2.1±2.1	0	4.2 ± 2.1	0	1.0 ± 0.5	0	1.0 ± 0.1	0
Leptogenys sp.3	0	0	4.2 ± 4.1	0	0	0	1.0 ± 0.2	0
Leptogenys sp.4	2.1±2.1	0	2.1 ± 2.1	0	1.0 ± 0.1	0	1.0 ± 0.1	0
Leptogenys sp.5	0	2.1 ± 2.1	0	4.2 ± 4.1	0	1.0 ± 0.2	0	1.0 ± 0.5
Leptogenys sp.6	2.1±2.1	0	0	0	1.0 ± 0.1	0	1.0 ± 0.1	0
Monomorium chinense [1]	0	0	0	6.3 ± 6.3	0	0	0	1.0 ± 0.8
Monomorium floricola	0	0	0	4.2 ± 4.1	0	0	0	1.5 ± 2.9
Monomorium pharaonis [1]	2.1±2.1	18.8±15.7	6.3 ± 3.6	27.1±15.0	1.0± 01 a	5.0±4.6b	1.0±0.1 a	5.3±2.9 b
Monomorium talpa	6.3±3.6	0	6.3 ± 3.6	0	1.0 ± 0.4	0	1.0 ± 0.3	0
Monomorium sp. 1	4.2±4.2	6.3 ± 3.6	6.3 ± 3.6	8.3 ± 5.5	1.0 ± 0.2	1.6 ± 0.8	1.0 ± 0.5	1.6 ± 1.3
Myrmicina sp. 1	2.1±2.1	0	4.2 ± 4.1	0	1.0 ± 0.1	0	1.0 ± 0.1	0
Nylanderia sp.1	4.2±2.1	0	8.3 ± 5.5	6.3±3.6	1.0 ± 0.2	0	5 ± 1.8	2.6 ± 2.1
Nylanderia sp.2 near *N. fulva*	0	2.1±2.1A'	2.1±2.1a	10.4±10.4b,B'	0	1.0±0.1A'	1.0±0.7a	3.8±3.9b,B'
Odontoponera denticulata	72.9±15.0a	22.9±4.2b	85.4±4.1a	31.3±12.7b	12.7±3.3	7.4±1.8	12.7±2.8	7.0±6.3

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Table 15 (Continued)

Species	Frequency (%)				Abundance (%)			
	Dry season		Wet season		Dry season		Wet season	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Oligomyrmex sp.1	10.4±2.1	0	14.6±2.1	0	1.4 ± 0.4	0	1.0 ± 0.1	0
Oligomyrmex sp.2	14.6±7.5	0	12.5±7.2	0	2.2 ± 1.2	0	2.4 ± 1.2	0
Oligomyrmex sp.3	6.3±3.6	0	8.3 ± 5.5	0	1.0 ± 0.4	0	1.4 ± 0.8	0
Oligomyrmex sp.4	2.1±2.1	0	4.2 ± 4.2	0	1.0 ± 0.1	0	1.0 ± 0.3	0
Oligomyrmex sp.5	4.2±2.0	0	0	0	1.0 ± 0.6	0	0	0
Oligomyrmex sp.6	0	0	2.1 ± 2.1	0	0	0	1.0 ± 0.1	0
Oligomyrmex sp.7	2.1±2.1	0	8.3 ± 8.3	0	1.0 ± 06	0	1.0 ± 0.9	0
Oligomyrmex sp.8	2.1±2.1	0	0	0	1.0 ± 0.2	0	0	0
Pachycondyla astuta	14.6±5.5	2.1 ± 2.1	10.4±5.5	2.1 ± 2.1	1.0 ± 0.6	1.0±0.3	1.0 ± 0.2	1.0 ± 0.3
Pachycondyla luteipes	8.3±5.5	0	10.4±10.4a	2.1±2.1b	1.0 ± 0.4	0	1.0 ± 0.6	1.0 ± 0.9
Pachycondyla sp.1	6.3±6.3	0	0	0	1.0 ± 1.0	0	0	0
Pachycondyla sp.2	8.3±8.3	0	2.1 ± 2.1	0	1.0 ± 0.5	0	0	0
Pachycondyla sp.3	20.8±4.1	4.2±4.2	25.0±7.2	6.3±6.3	1.4 ± 0.8	1.0±0.5	1.0 ± 0.2	1.0 ± 0.9
Paratrechina longicornis [1]	0	6.3±3.6A'	0	16.7±8.3B'	0	2.5±1.2	-	3.7 ± 2.6
Pheidole parva	43.8±9.5a	4.2±4.1b	33.3±2.1a	2.1±2.1 b	6.9±1.8a	1.0±0.7b	4.7±0.2a	1.0±0.4 b
Pheidole dugosi	2.1±2.1	2.1±2.1	6.3 ±3.6	0	1.0 ± 0.3	1.0±0.1	1.0 ± 0.5	-
Pheidole hongkongensis	45.8±8.3	23±2.1	77.1±5.5a	33.3±2.1b	11.2±3.6	7.5±1.5	17.5±2.8a	6.7±0.8 b

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Table 15 (Continued)

Species	Frequency (%)				Abundance (%)			
	Dry season		Wet season		Dry season		Wet season	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Pheidole plagiaria	25.0±3.6	14.6±5.5	0	0	9.1±1.9a	3.2±1.2b	0	0
Pheidole sp.1	0	0	12.5±12.5	16.7±7.5	0	0	1.0 ± 1.9	2.9 ± 2.7
Pheidole sp.2	2.1±2.1	0	0	10.4±10.4	1.0 ±0.6	0	0	1.2 ± 1.5
Pheidole sp.3	4.2±2.1	0	2.1±2.1	0	1.1 ± 0.7	0	1.0 ± 0.0	0
Pheidole sp.4	2.1±2.1	0	2.1 ± 2.1	2.1±2.1	1.0 ± 0,4	0	1.0 ± 0.1	1.0 ± 0.5
Pheidole sp.5	2.1 ± 2.1	0	4.2±4.1	0	1.0 ± 0.6	0	1.0 ± 0.3	0
Pheidole sp.6	2.1 ± 2.1	0	0	0	1.0 ± 0.1	0	0	0
Pheidole sp.7	0	2.1 ± 2.1	0	0	0	1.0±0.4	0	0
Pheidole sp.8	0	2.1 ± 2.1	0	0	0	1.0±0.5	0	0
Pheidole sp.9	0	2.1 ± 2.1	0	0	0	1.0±0.1	0	0
Pheidole sp.10	0	2.1 ± 2.1	0	0	0	1.0±0.3	0	0
Pheidole sp.11	0	2.1 ± 2.1	0	0	0	1.0±0.3	0	0
Pheidole sp.12	0	2.1 ± 2.1	0	0	0	1.6±1.6	0	0
Pheidole sp.13	0	2.1 ± 2.1	0	0	0	1.0±0.8	0	0
Pheidole sp.14	0	0	0	2.1 ± 2.1	0	0	0	1.0 ± 0.4
Pheidologeton affinis	16.7±2.1	0	20.8±2.1a	2.1±2.1 b	14.1±3.4	0	16.4±1.8a	1.4±2.8b
Pheidologeton diversus	8.3 ± 4.1	2.1± 2.1	10.4±2.1	0	10.5±5.4a	1.6±1.6b	12.2±2.9	0
Plagiolepis sp. 1	0	6.3 ± 6.3	0	8.3 ± 8.3	0	1.0 ± 0.5	0	1.0 ± 0.8

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Table 15 (Continued)

Species	Frequency (%)				Abundance (%)			
	Dry season		Wet season		Dry season		Wet season	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Pseudolasius sp. 1	31.3±9.5	4.2 ± 4.1	45.8±8.3a	4.2±4.1b	2.2 ± 0.6	1.0 ± 0.5	5.7±2.6a	1.0±0.5b
Smistristruma sp.1	2.1 ± 2.1	0	2.1 ± 2.1	0	1.0 ± 0.1	0	1.0 ± 0.1	0
Smistristruma sp.2	2.1 ± 2.1	0	2.1 ± 2.1	0	1.0 ± 0.3	0	1.0 ± 0.1	0
Smistristruma sp.3	0	0	2.1 ± 2.1	0	0	0	0	0
Tapinoma melanocephalum [1]	0	4.2 ± 4.1	0	6.3 ± 6.3	0	1.8 ± 1.8	0	4.3 ± 8.1
Tecnomyrmex kraeperinii	2.1 ± 2.1	0	10.4±5.5	0	1.0 ± 0.1	0	1.0 ± 0.4	0
Tetramorium lanuginisum [1]	33.3 ±4.1	4.2 ± 4.1	35.4±7.5	6.3 ± 6.3	7.6 ± 4.7	1.0±0.8	3.5 ± 0.6	1.0 ± 0.9
Tetramorium sp.1	0	0	0	2.1 ± 2.1	0	0	0	1.0 ± 0.3
Tetramorium sp.2	0	4.2 ± 4.1	0	6.3 ± 6.3	0	1.0±0.3	0	1.0 ± 0.5
Tetramorium sp.3	0	0	0	8.3 ± 4.1	0	0	0	1.0 ± 0.8
Tetramorium sp.4	16.7±2.1A	4.2 ± 4.1	4.2±2.1B	12.5±7.2	1.2 ± 0.3	1.0±0.3	1.0 ± 0.2	1.8 ± 1.2
Tetramorium sp.5	0	0	2.1 ± 2.1	2.1 ± 2.1	0	0	1.0 ± 0.1	1.0 ± 0.3
Tetramorium sp.6	8.3 ± 5.5	6.3 ± 3.6	27.1±9.1	10.4±7.5	1.0 ± 0.5	1.0±0.5	1.7 ± 0.4	1.0 ± 0.7
Tetramorium sp.7	2.1 ± 2.1	0	0	0	1.0 ± 0.1	0	0	0
Tetramorium sp.8	2.1 ± 2.1	4.2 ± 4.1	10.4±7.5	2.1 ± 2.1	1.0 ± 0.5	1.0±0.4	1.6 ± 0.9	1.0 ± 0.2
Tetramorium sp.9	2.1 ± 2.1	0	0	2.1 ± 2.1	1.0 ± 1.0	0	0	1.0 ± 0.1
Total					100	100	100	100

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Table 16 Results from the GLM univariate anlysis showing *F* values and levels of significance for each source of variation and each dependent variable.

Source of variation	Dependent Variable [1]								
	Number of individuals (N per plots)			Frequency (%)			Abundance (%)		
	d.f.n.	*d.f.d.*	*F*	*d.f.n*	*d.f.d.*	*F*	*d.f.n.*	*d.f.d.*	*F*
species	80	112	8.07 ***	80	112	4.70 ***	80	112	9.24***
season	1	112	8.03**	1	112	13.49***	1	112	0.19
site	1	112	20.07***	1	112	0.63	1	112	0.22
season * site	1	112	2.04	1	112	0.55	1	112	2.73
season * species	49	112	0.93	49	112	0.68	49	112	0.72
site * species	27	112	3.50 ***	27	112	2.19**	27	112	3.15 ***
season * site* species	13	112	1.15	13	112	0.69	13	112	1.02

[1] *, ** and *** (*P*<0.05, *P*<0.01 and *P*< 0.001, respectively) indicate significant differences with the 95% confidence interval

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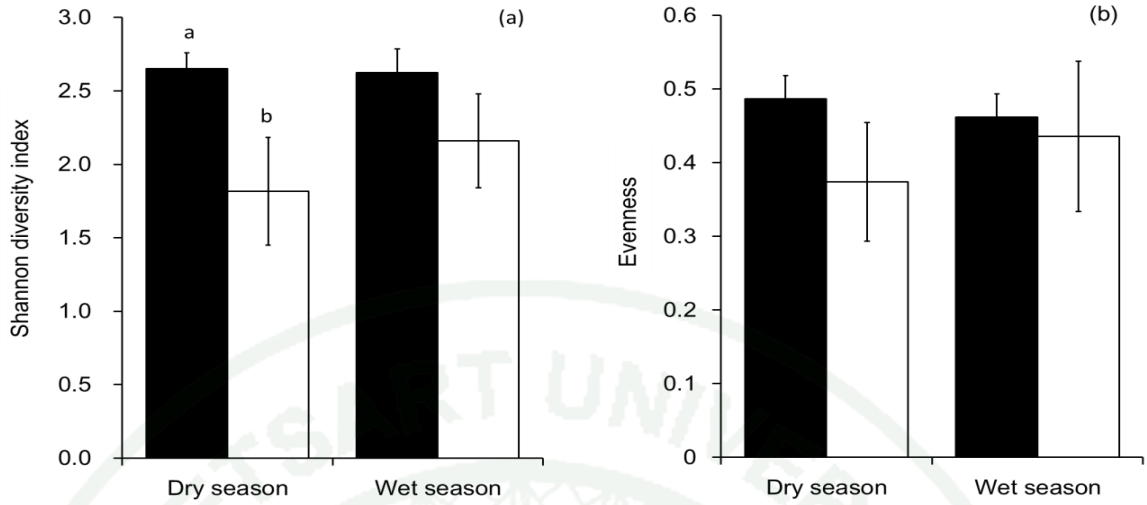

Figure 16 Shannon diversity index (a) and evenness (b) with the standard error of ants in UVS (black bars) and IVS (white bars) in the dry and wet season. The difference in Shannon diversity index for ant ($P<0.05$). Different lower case letters indicated the significant difference of mean Shannon diversity index between the UVS and IVS within the season ($P<0.05$).

Table 17 Bray-Curtis coefficients of similarity matrix for ants between UVS and IVS in dry and wet season.

season/site		Dry season		Wet season	
		UVS	IVS	UVS	IVS
Dry season	UVS	1			
	IVS	0.42	1		
Wet season	UVS	0.79	0.41	1	
	IVS	0.45	0.66	0.53	1

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There was no statically significant difference in the Shannon diversity index (*H'*) and Evenness (*E*) between sites and season ($P>0.05$; Figure 16a; 16b).However, both *H'* and *E* at uninvaded site were greater in value when compared to with invaded site. For the similarity index, the classified sampling sites in the seasons have shown in Table 17. At uninvaded sites in dry and wet season have shown the highest similarity index with the value of 79 %. While the similarity index between uninvaded and invaded sites was lower than 50 % in both dry and wet season.

The number of individuals, frequency and abundance values of *A. gracilipes* was extremely high at the supercolony sites and strongly exceeded the total number of the other ants (Table 14; 15). Hence, this species had negatively impact on the diversity and community of other ant species at invasion areas in agreement with other studies on invasive ant species (Cole *et al.*1992; Holway 1998; Touyama *et al.* 2003; Rodriguez-Cabal *et al*. 2009; Cooling *et al.*, 2015). Moreover, similarly to these effects of *A. gracilipes* on native ant communities were also reported from the other ecosystems such as Island (O'Dowd *et al.*, 1999) and plantation (Boss *et al.*, 2008).

From previous investigations, the mechanisms to explain the reduction of the native ant at invasion areas including interference competition have been proposed (Human and Gordon 1997, Holway 1999) which highly aggressive interactions between invasive ant species and the other ant species were also examined (Human and Gordon 1999; Cremer *et al*. 2006; Rowles and O'Dowd, 2007). At invaded sites in this study, it is possible to record that the presence of *A. gracilipes* has the potential to dominate and negatively impact on the native ant communities in its distribution range by their competition with the other ant species. *A. gracilipes* can also have the direct impact on diversity and community of native ant species within its distribution range by their killed and competing for food and habitat. While *A. gracilipes* can indirectly affect on a change of food web structure of native ant species. These observations were consistent with previous results that Human and Gordon (1999) documented the interference and exploitation competition appearing to be important in the displacement of native ant species from areas invaded by *Linepithema humile*. Berman *et al.* (2013a) suggested that generalized Myrmicinae and opportunists were

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particularly affected by invasion. There was a strong negative relationship between the abundance of *Wasmannia auropunctata*, and abundance and richness of native ant. Berman *et al.* (2013b) reported that native ant diversity parameters (total abundance, richness, species composition, functional group richness and the abundance of Forest Opportunists) declined independently from microhabitat variables but in direct association with high *Wasmannia auropunctata* abundance.

Due to my observation in the wet seasons, I found a high number of *A. gracilipes*' workers (approximately 2,000-5,000) seeking for food on the road at un-invaded sites (data not shown). I also found small tentative nests with only ant workers dwelling near the roadside at un-invaded sites but never further. However, I did not find any established nest of *A. gracilipes* within the forest areas of the un-invaded sites. Due to, both of un-invaded and invaded sites located in same forest fragmented and roadside way. The uninvaded area is in of the invaded area. They are sided by a common road. Therefore, it is physically possible that *A. gracilipes*' supercolonies move into the nearby uninvaded area, whether by walking or and by winged ants. Consequently, based on the above results and observations, I would imply that *A. gracilipe*s shared common traits for competition with native ant communities and native ant species in the uninvaded area of dry evergreen forest is a major biotic barrier to the invasion of *A. gracilipes* at SERS. These phenomena has been pointed out by Holway *et al.* (2002), that a key consequence of the condition-specific nature of the competitive asymmetry between *Linepithema humile* and native ants is that community-level vulnerability to invasion appears to depend primarily on the suitability of the physical environment from the perspective of *L. humile*.

3. Impact on nesting habitats of native ants

A total 4414 nests of 64 ant species from 27 genera were conducted in entire sampling study areas by food baiting and direct sampling (Table 18).Total of 2281 nests builded by 51 ant species were observed in un-invaded sites, and 2133 nests builded by 54 ant species were in invaded sites. In this observation, all ant nests were found in six nesting sites , including liter-layers, rotten log, soil, termite mound (i.e.

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mound soil and hole), tree trunk and under substrate, i.e. stone, log and scientific tool where set up on forest, (Figure 17; 18). The detail of ant species found in the difference nesting sites and seasons were listed in Appendix Table 1.

From all sampling site, I found 53 species constructed nests in soil, 29 species in rotten logs nest, 24 species in liter layers, 23 species in tree trunk, 11 species sounder substrates and 4 species in termite mound. Larger number of ant nests were the subterranean nests with 2805 nests (64.3% of total numbers of ant nests of all microhabitats within both sites) followed by liter layers with 440 nests (10.2%), termite mound with 419 nests (9.1%), rotten logs with 375 nests (8.0%), tree trunk with 235 nests (5.0 %) and under substrates with 140 nests (3.4%). For un-invaded sites, high numbers of nests were found in Odontoponera denticulata with 1184 nests (52 %) and Odontomachus rixosus with 216 nests (10%). For invaded sites high numbers of nests were found in Anoplolepis gracilipes with 811 nests (38 %) and O. denticulata with 612 nests (29%) (Appendix Table 1). *A. gracilipes* was found in almost nesting sites except in the soil. Larger numbers of *A. gracilipes* nests were found in termite mound particularly in old entrance hole on the mound followed by tree trunk (crack, hole, tree base), rotten logs, under substrate (Table 18).

The effect of the three factors (microhabitat, season and sampling site) and their interaction are shown in Table 20. The results were shown whether the number, frequency of occurrence and abundance of ant nest varied among nesting sites ($P<0.001$), and number of nest and frequency of occurrence levels varied by sites and seasons ($P<0.05$).

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Figure 17 Nesting sites of ant community in dry evergreen forest at SERS, including (a, b) liter-layers, (c, d) rotten log, and (e) termite mound and hole

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Figure 18 Nesting sites of ant community in a dry evergreen forest at SERS, including (a) tree trunk, (b) under substrate, and (c, d) soil

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Table 18 Numbers of ant species found in nest locations. Values are averaged per site (Ave.±SE) and n=3 for each site. Difference lower case letters indicate a significant difference between the UVS and IVS within the season (P<0.05). Differences capital letters (A and B for UVS, A' and B' for IVS) indicate significant differences between wet and dry season (P<0.05). The number in parentheses means number of nests of *Anoplolepis gracilipes*

Nest location	Total number of ant species				Total number of ant nest				number of ant nest (N per plot)			
	Dry season		Wet season		Dry season		Wet season		Dry season		Wet season	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Liter layers	9	7	18	3	89	162(64)	145	44(4)	30 ± 0	54 ± 1 A'	48 ± 0 a	15 ± 0 b, B'
Rotten logs	4	7	25	6	40	71(43)	160	104(74)	13 ± 1 A	24 ± 0	53 ± 0 B	35 ± 0
Soil	38	39	31	36	784	471(0)	978	572(0)	261 ± 0	157 ± 0	326 ± 0	191 ± 0
Termite mound/ hole	0	1	3	1	0	186(186)	13	223(223)	0	65 ± 0	4±2.3a	75 ± 0 b
Tree trunk holes/crack	4	9	13	14	8	84(57)	29	114(70)	3 ± 1 a	28 ± 0 b	10 ± 3 a	38 ± 0 b
Under substrate	6	1	6	3	20	41(41)	28	51(49)	7 ± 0 a	14 ± 0 b	9 ± 0	17 ± 0
Total	43	46	48	45	941	1015	1340	1118	314 ± 0	341 ± 0	447 ± 0	370 ± 0

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Table 19 Frequency and abundance of ant nests found in each nest location. Values are averaged per site (Ave.±SE) and n=3 for each site. Difference lower case letters indicate a significant difference between the UVS and IVS within the season (P<0.05). Differences capital letters (A and B for UVS, A' and B' for IVS) indicate significant differences between wet and dry season (P<0.05)

Nest location	Frequency (%)				Abundance (%)			
	Dry season		Wet season		Dry season		Wet season	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Liter layers	18.2 ± 2.7 A	38.0 ± 5.8 A'	40.6 ± 5.5a,B	18.2 ± 6.4b,B'	9.5 ± 2.3	16.0 ± 1.3A'	10.8 ± 1.1 a	3.9 ± 0.8b,B'
Rotten logs	2.6 ± 0.5 a, A	9.4 ± 4.5 b	21.4 ± 0.5a,B	9.4 ± 3.2 b	4.2 ± 0.5 A	6.8 ± 1.2	12 ± 0.9 B	9.4 ± 1.7
Soil	96.9 ± 2.4	74.5 ± 3.8	94.8 ± 0.5	71.4 ± 6.0	83.3 ± 1.9	45.8 ± 2.1	71.8 ± 1.4	51.3 ± 4.3
Termite mound/ hole	0	26.6 ± 3.1	1± 0.5a	27. ± 2.3b	0	18.9 ± 3.1	1.1 ± 0.9a	20.2 ± 3.5b
Tree trunk holes/crack	4.7 ± 1.6 a, A	21.4 ± 6.4b	13.5 ± 5.1B	22.4 ± 4.5	0.8 ± 0.7 a	8.6 ± 3.4 b	2.2 ± 0.7 a	10.4 ± 2.6 b
Under substrate	4.2 ± 2.8	8.9 ± 4.2	5.7 ± 3.1a	12.0 ± 3.1b	2.1 ± 1.4	3.9 ± 3.2	2.1 ± 1.4 a	4.7 ± 2.1 b
					100	100	100	100

Table 20 Results from the GLM univariate anlysis showing *F* values and levels of significance for each source of variation and each dependent variable for nesting sites

Source of variation	Dependent Variable [1]								
	Number of individuals (N per plots)			Frequency (%)			Abundance (%)		
	d.f.n.	*d.f.d.*	*F*	*d.f.n.*	*d.f.d.*	*F*	*d.f.n.*	*d.f.d.*	*F*
nesting	5	41	53.57 ***	5	41	42.41***	5	41	72.07 ***
season	1	41	8.35 **	1	41	10.52**	1	41	0.51
site	1	41	4.69 *	1	41	0.75	1	41	7.89**
season*site	1	41	10.24 **	1	41	8.56 **	1	41	3.10
nesting*season	5	41	2.34	5	41	2.31	5	41	2.84*
nesting*site	4	41	8.20 ***	4	41	3.85 *	4	41	9.35***
nesting*season*site	4	41	1.36	4	41	3.68*	4	41	2.05

[1] *, ** and *** (*P*<0.05, *P*<0.01 and *P*< 0.001, respectively) indicate significant differences with the 95% confidence interval

Ant nest number individuals, frequency of occurrence and abundance was also found significant statistical interaction between sampling sites and nesting sites ($P<0.05$). Regardless of seasonality, ant nest was a significant difference between sites ($P<0.001$). Results was showed that three nesting habitat were had significant high number of nest in invaded sites compared with uninvaded sites for termite mound, tree trunk and under substrate (Bonferroni post hoc tests; $P<0.01$; Table 18). Litter layer were had significant high number of nest in uninvaded sites compared with invaded sites. Two nesting habitats, litter-layer nesting and rotten log, had high frequency values in uninvaded sites than invaded sites which found in wet season (Bonferroni post hoc tests; $P<0.01$; Table 19). Three nesting habitats had high frequency values in invaded sites than uninvaded sites for rotten log and three trunk in dry season, and for under substrate in wet season. For ant nest abundance, the result shown that liter-layer nesting had high abundance in uninvaded sites than invaded sites, while tree trunk and under substrate nest had high abundance in invaded sites than uninvaded sites (Bonferroni post hoc tests; $P<0.001$).

Generally, all parameters of ant nests were high values at un-invaded sites than invaded sites. These observations were shown that the nesting habitats of native ants in the forest ecosystem being lower in the presence of *Anoplolepis gracilipes* than in its absence areas. Similarly, the effects of invasive ant species on disrupting nest site selection and nest abandonment of native species have been reported on the other animals such as native ground-nesting birds (Dickinson, 1995; Giuliano *et al.*, 1996; Feare, 1999; Fisher and Bonter, 2013). At invaded sites, *A. gracilipes* can establish nests in various habitats except in rotten logs and most of the nests were found in termite mounds. In contrast to previous studies, *A. gracilipes* was reported to have very general nesting requirements, and can be found within trees, in cracks and crevices, and under the ground (Abbott, 2005; Csurhes and Hankamer, 2012). However, there is no record of *A. gracilipes* used old termite mounds as the center place nesting for supercolonies establishment as in this study. This new finding led on the specific idea that *A. gracilipes* represents a species-specific habitats impact not only on native ant community but also on native termites communities. The results of impact on non-ant arthropod in this study also supported this idea which termites were one of six of non-ant arthropod groups that

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failed to coexist with *A.gracilipes*. Together, both observation result showed native termite species might be failed to occupy parts of their nesting colony on the above ground mound because of *A. gracillipes* invasion had occupied within an areas.

Following the concept of invasion success, invasive ant species must first overcome natural barriers (i.e. abiotic and biotic factors; Figure1) during the establishment before they can become invasive in new areas (Richardson *et al.*, 2000; McNeeley *et al.*, 2001). This concept led to the central question of my thesis "what are the barriers to the establishment of *A. gracilipes* in un-invaded sites at Sakaerat?". The answers to this question arose from my research results. The results showed that there were no differences in ecological conditions between un-invaded and invaded sites while differences in diversity and compositions of arthropod communities were evident, particularly for native ants. These observations were also indicated that some native ant species was able to also repel *A. gracillipes* or, at least, reduce the spread rate of *A. gracilipes'* colony establishment in new locations. It is thus possible that dominant ant species (i.e. high value in population and nest abundance) play an important role as a biotic barrier to the invasion, particularly *Odontoponera denticulata* and *Odontomachus rixosus*, *Monomorium* sp.1, *Pachycondyla astuta* and *Nylanderi*a sp.1, which have similar nesting habits to *A. gracilipes* and higher in numbers of nests and population compared to other native ants (data were not shown). Hence, those ants may be able to resist to *A. gracilipes*' invasion which the outcome of interspecific fights. As well as native ant species play an important role as liming factors for introduction of *A. gracilipes* in un-invaded sites. However, the species-specific data, who is either not, or only slightly reduced in the presence of *A. gracilipes*' supercolony are not provided by this present study. Consequently, it is necessary to conduct surveys in order to identify the role of native ant in the organization of forest ant communities, particularly the interspecific competition among native ant and *A. gracilipes* should be assessed, and the role of native ant species as the biotic barrier to invasion of *A. gracilipes* should be evaluated in the future.

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4. Impact on CO_2 efflux from subterranean nests of ant communities

4.1. CO_2 efflux from ant nests in the wet and dry seasons

We measured CO_2 efflux from 61 subterranean ant nests; 34 nests in the wet season and 27 nests in the dry season (Table 6). In both seasons, the season-specific mean CO_2 efflux rates from ant nests were significantly higher than those from the controls (Table 21). The mean CO_2 efflux rates from ant nests were 2.5 and 2.0 times higher than those of the controls in the wet and dry seasons, respectively (P<0.001, Figure 19).

Table 21 Comparison of CO_2 efflux between location, season and ant species

Source of variation	CO_2 efflux ($\mu mol\ CO_2\ m^{-2}\ s^{-1}$) [1]		
	d.f.n.	*d.f.d.*	*F*
Location	1	37	227.65***
Seasons	1	37	63.65***
Species	12	37	5.96***
Location × Season	1	37	9.21***
Location × Species	12	37	9.58***
Species × Season	11	37	1.26
Location × Species × Season	11	37	1.10

[1] *** (P< 0.001) indicate significant differences with the 95% confidence interval

The results showed that the CO_2 efflux from ant nests was significantly higher than that from the surrounding soil in a seasonal tropical forest (Figure 19). Similar effects of ant nests on soil CO_2 efflux have been reported in boreal forests (Domisch *et al.*, 2006; Ohashi *et al.*, 2005; 2007b), subalpine forest (Risch *et al.*, 2005), wetland (Wu *et al.*, 2013), pasture (Bender and Wood, 2003) and coastal plains (Sousa-

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Souto *et al.*, 2012). Given that ecosystem structure is more complicated and biodiversity is greater in tropical forests than in other ecosystems (Allaby, 2006), we expected larger variations in CO_2 efflux from ant nests in tropical forests. The results showed that there was significantly greater CO_2 efflux from ant nests than from the surrounding soil, and that this CO_2 efflux is ant-species-specific in a tropical forest.

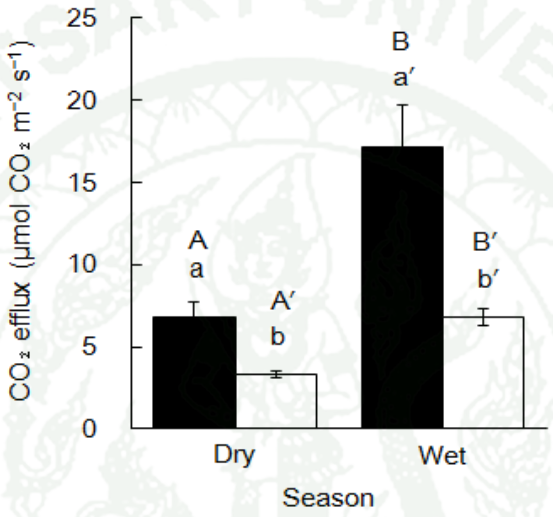

Figure 19 CO_2 efflux in ant nests (black bars) and the surrounding soil (white bars) in the dry and wet season. Error bars represent standard error (n≥25). Different lower case letters indicate significant differences between nests and soil for dry (a and b) and wet seasons (á and b́) (P<0.001). Different capital letter indicates a significant difference between dry and wet seasons for ant nests (A and B) and for the surrounding soil (A´ and B´) (P<0.001)

We measured the CO_2 efflux from subterranean-type ant nests, whereas other studies have focused on mound-type nests (Ohashi *et al.*, 2005; Wu *et al.*, 2013; Sousa-Souto *et al.*, 2012). Even though mound-type nests are easy to find and are relatively common in their ecosystems, non-mound-type nests, (i.e., subterranean nests) are more common in other ecosystems such as tropical forests (Hölldobler and Wilson, 1990). To my knowledge, there are no reports on CO_2 efflux from non-mound-type nests, probably because subterranean nests are difficult to find. There are many differences between

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subterranean and mound-type nests, including the nest structure, material of construction, relationships with other animals within the nest/mound, foraging behavior of the ants, and nest size (Hölldobler and Wilson, 1990). These differences may result in different patterns, limitation factors, and different mechanisms of CO_2 efflux between the two nest types.

There was a significant seasonal variation in CO_2 efflux rates from the ant nests and the surrounding controls (Table 21). The location-specific mean CO_2 efflux rates were 2.6 and 2.1 times higher in the wet season than the dry season, in the nests and controls, respectively ($P < 0.001$, Figure 19). CO_2 efflux rates from ant nests during the wet season ranged from 6.1 to 63.2 µmol CO_2 m^{-2} s^{-1}, a larger range than that in the dry season (0.8–24.7 µmol CO_2 m^{-2} s^{-1}). Similarly, CO_2 efflux rates from the controls showed larger fluctuations during the wet season, 3.6–14.5 µmol CO_2 m^{-2} s^{-1}, than during the dry season, 1.3–6.1 µmol CO_2 m^{-2} s^{-1}, but the range of fluctuation was smaller than that of the nests.

We found that CO_2 efflux from nests was significantly higher than that from the surrounding control soil in the wet and dry seasons, but the difference was larger in the wet season than in the dry season. Variations in the magnitude of differences in CO_2 efflux between nest and controls have been reported in boreal and subalpine forests, where ant mound CO_2 efflux was 2–12 times higher than that from surrounding soils during the active ant time, but there was no difference in dormant ant times (Risch *et al.*, 2005; Domisch *et al.*, 2006; Ohashi *et al.*, 2007b). These findings suggest that the nesting and forging activity of ants is an important factor in increasing CO_2 efflux from nests. Because ants in tropical rain forests do not have a dormant period (Gove *et al*., 2005), it is plausible that these ants are active throughout the year in a warm climate (Allaby, 2006). In this study ecosystem, the climate is warm enough for ants to remain active in both the wet and dry seasons, so the CO_2 efflux differs between nests and the control throughout the year. However, ants may vary their activity between seasons, causing a seasonal change in CO_2 efflux between nests and controls. For example, the size of the ant population may change between seasons, affecting the amount of ant-originated CO_2. In the tropical forest, leaf litter containing food resources for the ants resulted in higher

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ant diversity/abundance during the wet season than the dry season (Kaspari and Weiser, 2000; Hahn and Wheeler, 2002). The increased food sources in the wet season would allow ants to establish new nests and the ant queen to produce more workers and increase in the production of reproductive caste, thus increasing the ant population (Hölldobler and Wilson, 1990; Kaspari, 2000). The larger ant population may increase nesting and foraging activity (Wagner *et al*., 2004), raising their metabolic activity (Rosengren *et al.*, 1987), resulting in higher CO_2 efflux. However there is no study about the impact of changes in ant population size on nest CO_2 efflux. Future study is necessary to confirm the idea.

4.2 Inter-species variations of CO_2 efflux

Regardless of seasonality, species-specific mean CO_2 efflux rates from the ant nests were significantly higher compared with the controls (P<0.001, Table 22). The mean CO_2 efflux from ant nests varied from 4.3 (± 0.9 SE, n=4) in *A. graeffei* to 27.5 (± 9.7 SE, n=5) µmol CO_2 m^{-2} s^{-1} in *P. plagiaria*. The CO_2 efflux from the controls were relatively stable, from 2.7 (± 0.8 SE, n=4) in *E. astuta* to 7.7 (± 0.6 SE, n= 3) µmol CO_2 m^{-2} s^{-1} in *H. venator*. Pairwise comparisons showed significantly higher CO_2 efflux rates from nests compared with the controls in nine out of 13 ant species. These species were: *Anochetus* sp.2 of AMK, *A. gracilipes*, *Aphaenogaster* sp.1 of AMK, *D.* cf. *vagans, H. venator, O. rixosus, E. astuta, P. plagiaria* and *P. parva* (Figure 20).

There was significantly greater CO_2 efflux from *H. venator* nests than from nests of *O. denticulata*, *E. astuta, A. graeffei, P. hongkongensis,* and *T. lanuginosum* (Table 22). CO_2 efflux for *O. rixosus* and *P. plagiaria* were significantly higher than for most of the other species. Conversely, nest CO_2 efflux for *A. graeffei, Anochetus* sp.2 of AMK, *Aphaenogaster* sp.1 of AMK, *O. denticulata*, *E. astuta*, *P. hongkongensis* and *P. parva* was significantly lower than that of the other two or three species.

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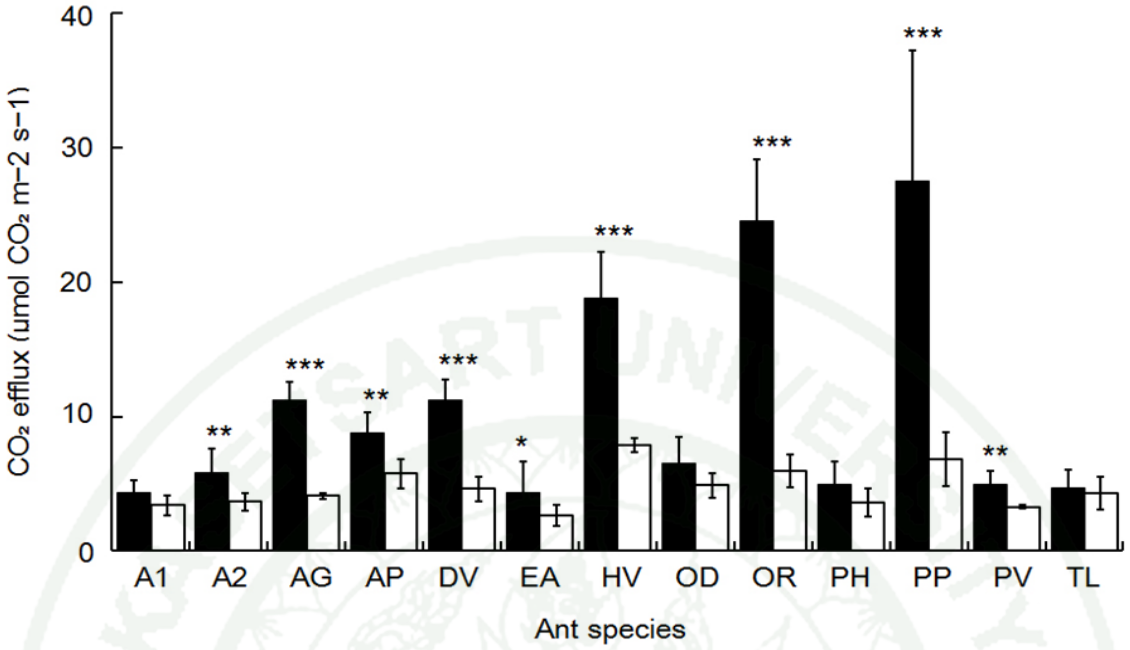

Figure 20 CO_2 efflux in ant nests (black bars) and surrounding soil (white bars) for each species. Error bars represent standard error (n>3). *, ** and *** (P<0.05, P<0.01 and P< 0.001, respectively) indicate significant differences between the nest and soil CO_2 effluxes within the ant species with the 95% confidence interval.

Significantly lower CO_2 efflux occurred in *T. lanuginosum* compared with *A. gracilipes*, *D.* cf. *vagans*, *H. venator*, *O. rixosus* and *P. plagiaria*. CO_2 efflux from ant nests was highly variable among the different ant species (Figure 20). Significantly higher CO_2 efflux occurred in three ant species, *H. venator*, *O. rixosus* and *P. plagiaria* than those of other 5-8 species, significantly while lower efflux was recorded in eight other species, *A. graeffei*, *Anochetus* sp.2 of AMK, *Aphaenogaster* sp.1 of AMK, *O. denticulata*, *E. astuta*, *P. parva*, *P. hongkongensis* and *T. lanuginosum* than those of other 2-5 species (see Figure 20; Table 22).

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Table 22 Results of pairwise comparisons for CO_2 efflux among ant species for ant nests (upper-right) and surrounding soil points (lower-left). Significant differences are given as *P*-values with the 95% confidence interval. NS represents not statistically significant results. Ant species abbreviations are presented in Table 6.

Ant species	A1	A2	AG	AP	DV	EA	HV	OD	OR	PH	PP	PV	TL
A1		NS	NS	NS	NS	NS	**0.02**	NS	**0.001**	NS	**0.001**	NS	NS
A2	NS		NS	NS	NS	NS	NS	NS	**0.01**	NS	**0.01**	NS	NS
AG	NS	NS		NS	NS	NS	NS	NS	NS	NS	NS	NS	**0.05**
AP	NS	NS	NS		NS	NS	NS	NS	**0.02**	NS	**0.01**	NS	NS
DV	NS	NS	NS	NS		NS	NS	NS	NS	NS	NS	NS	**0.04**
EA	NS	NS	NS	NS	NS		**0.01**	NS	**0.001**	NS	**0.001**	NS	NS
HV	NS	NS	NS	NS	NS	NS		**0.01**	NS	**0.05**	NS	NS	**0.001**
OD	NS	NS	NS	NS	NS	NS	NS		**0.001**	NS	**0.001**	NS	NS
OR	NS	NS	NS	NS	NS	NS	NS	NS		**0.001**	NS	**0.001**	**0.001**
PH	NS	NS	NS	NS	NS	NS	NS	NS	NS		**0.001**	NS	NS
PP	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS		**0.001**	**0.001**
PV	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS		NS
TL	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	

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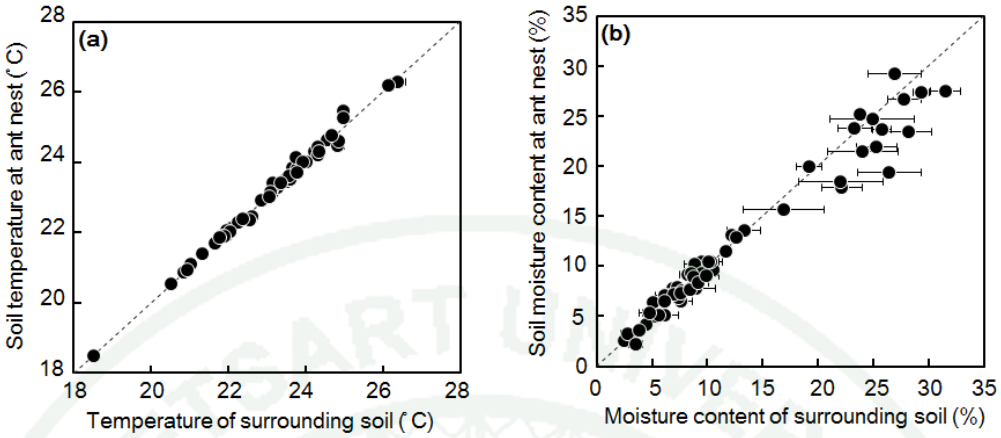

Figure 21 Comparison of the soil environment between the ant nest and their surrounding soil: temperature (a) and moisture content (b)

4.3 Relationship between CO_2 efflux and environmental factors

The large variations in soil temperature and moisture content were mainly related to the season. Soil temperature and moisture content were similar for each of the ant nests and control pairs except those above 18% (Figure 21a), where the soil moisture content was lower in the nests (Figure 21b). Seasonal changes in soil temperature and moisture affected the soil CO_2 efflux. The linear regression analysis showed a significant positive relationship between CO_2 efflux rates and temperature in the control (Figure22a), but there was no significant relationship for ant nests (Figure 22b).

This observation showed that soil moisture content was lower in the nest compared with their surrounding soil when the soil moisture range was 18–31%, mainly during the wet season (Figure 21b). The decrease in soil moisture could be explained by the soil modification from ant nesting activity (Lavelle and Spain, 2003). Nest construction decreases soil bulk density and increases the number of soil macrospores with the size of tunnels and chamber within ant territories (Lobry de Bruyn, 1999; Cerdà and Jurgensen, 2008), allowing rapid water infiltration in ant nests

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compared with soils without nests (Cerdà and Jurgensen, 2008; James *et al.*, 2008; Whitford *et al.*, 2008). At the study site, the soil consisted of dense loam/clay loam containing numerous micropores and small macropores, making water flow very slowly through this substrate. Therefore, the increase in macropores and the continuous porosity from ant nesting activity may have increased soil water drainage, decreasing soil moisture content at nest sites during the wet season.

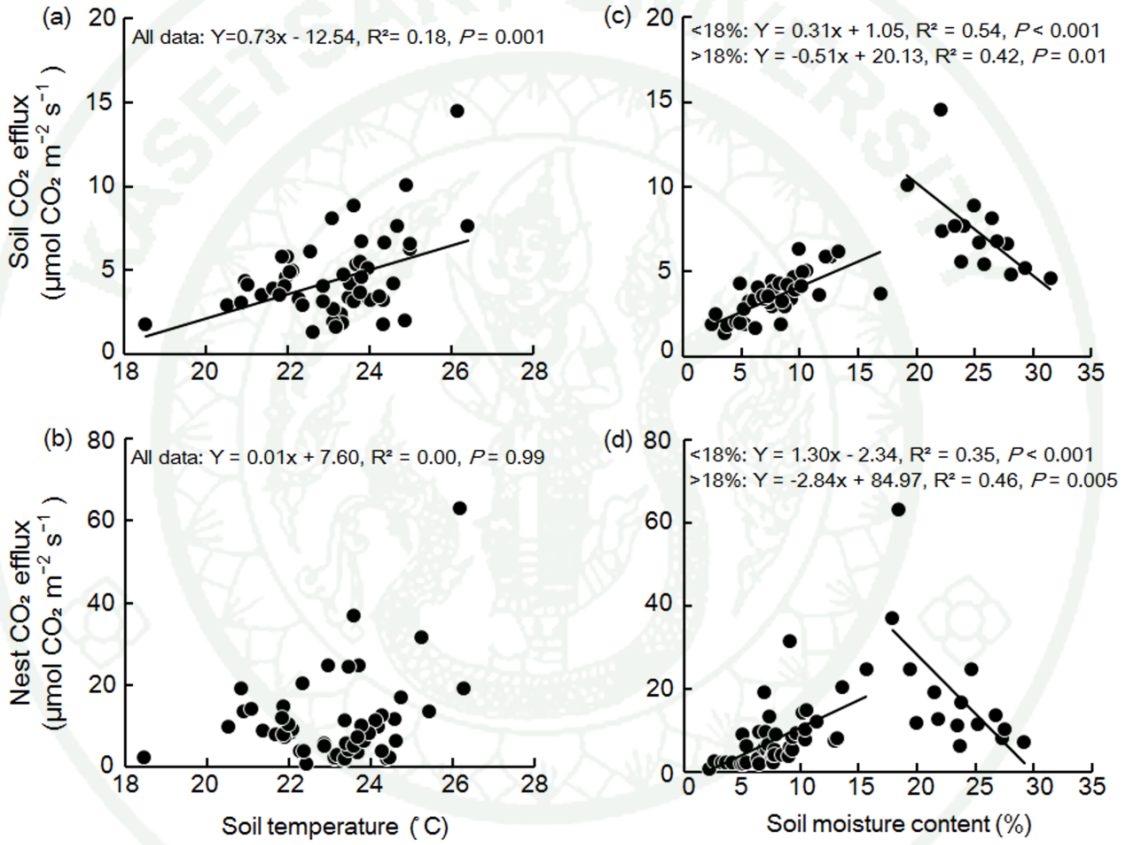

Figure 22 Changes in nest and soil CO_2 efflux with the soil temperature in the surrounding soil (a) and nest (b); the soil moisture in the surrounding soil (c) and nest (d). The regression analysis for soil moisture content was run separately for soil moisture content was greater and less than 18%.

This results showed positive relationships between soil CO_2 efflux and temperature (Figure 22a), similar to previous studies (e.g. Ohashi *et al.*, 2008), but there was no significant relationship between soil temperature and nest CO_2 efflux

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(Figure 22b). The different temperature effects between nest and soil could result from the differences in CO_2 producers between ant nests and soil. The main sources of CO_2 efflux from soil are soil microbes and plant roots (Adachi *et al.,* 2006; Ohashi *et al.,* 2008; Schwendenmann *et al.*, 2003).

Soil temperature is an important factor for microbes and roots activity, with studies on soil respiration reporting exponential and/or linear increases in soil CO_2 efflux with increasing temperature (Luo and Zhou, 2006). In many tropical systems soil temperature is not a strong predictor of soil CO_2. In this study, R^2 value for the relationship between soil CO_2 efflux and temperature was only 0.18 (Figure 22a). Given that tropical seasonal forests in this region have constantly high temperatures with little variation compared with other climate regions (Hashimoto *et al.*, 2007), the slight changes in temperature may not have a significant impact on ant activity. Therefore, no clear relationship occurred between CO_2 efflux from ant nests and temperature.

I found positive and negative relationships between CO_2 efflux and soil moisture content both in the ant nests and the surrounding soil (Figure 22c, d), even though the source of CO_2 production may differ between the nest and soil. The effects of soil moisture content, both negative and positive, under relatively high and low moisture conditions, respectively, in tropical forests has been reported (Schwendenmann *et al.,* 2003; van Straaten *et al.,* 2009). These results suggest that there may be the most preferable moisture content for the CO_2 producers in soil in these ecosystems and if soil moisture content increase or decrease more than the most preferable content, the amount of CO_2 production starts to decrease, as we found in this study. The results suggest that all of ant, soil microbe and root activity may be controlled by soil moisture content. However, the steeper regression slope for the nest CO_2 efflux (Figure 22d) suggests that ants are more sensitive to soil moisture content compared with the source of CO_2 efflux from surrounding soils.

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4.4 Impacts of the hole type and diameter on nest CO_2 efflux

There was no significant difference in CO_2 efflux rates between single- and multiple-hole type nests (hole type, $F_{1, 58} = 0.5$, $P = 0.48$; season, $F_{1, 58} = 24.8$, $P<0.001$; interaction, $F_{1, 58} = 0.77$, $P = 0.39$). There were significant positive relationships between CO_2 efflux rates and hole diameter in the wet and dry season (Figure 23). The regression coefficient in the wet season was larger compared with that of the dry season.

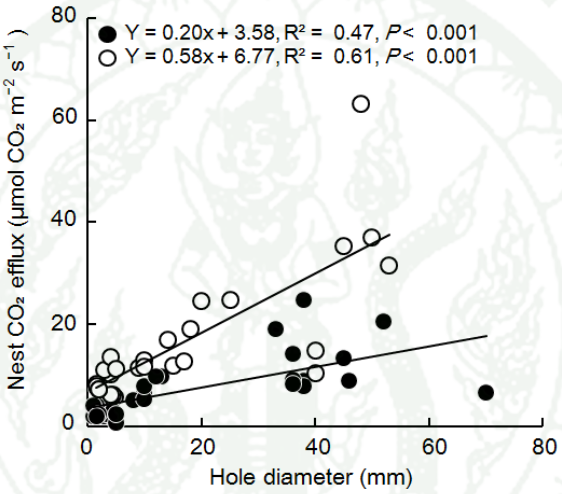

Figure 23 Relationship between nest entrance diameter and CO_2 efflux. Black circles represent the dry season and white circles the wet season.

The relationship between entrance hole diameter and nest CO_2 efflux from ant nests (Figure 23) supported the idea that nest structure is an important factor in nest CO_2 efflux variations. There may be other reasons for these variations, including the number of ants in the colony, ant body size and behavior, indirect effect of ants on other CO_2 sources, and the phenology of each colony. Nest structure may explain the difference, as the structure of subterranean nests varies depending on the ant species (Tschinkel, 2003). After experiments, we excavated all of the nests to see the nest structure (data not shown). We found that three ant species *H. venator, O. rixosus* and *P. plagiaria*, with higher nest CO_2 efflux than others, built a simple nest with a big chamber and straight tunnels of relatively short distances (2 to 10 cm) (Figure 24a). In

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contrast, the eight species that emit less nest CO_2 flux built a complex nest with many small chambers and long narrow tunnels connecting the chambers (Figure 24b). The straight tunnel of the three former species would facilitate CO_2 efflux, but CO_2 probably fail to emerge from the narrow complex tunnels and chambers in the eight (latter) species resulting in higher within nest concentrations.

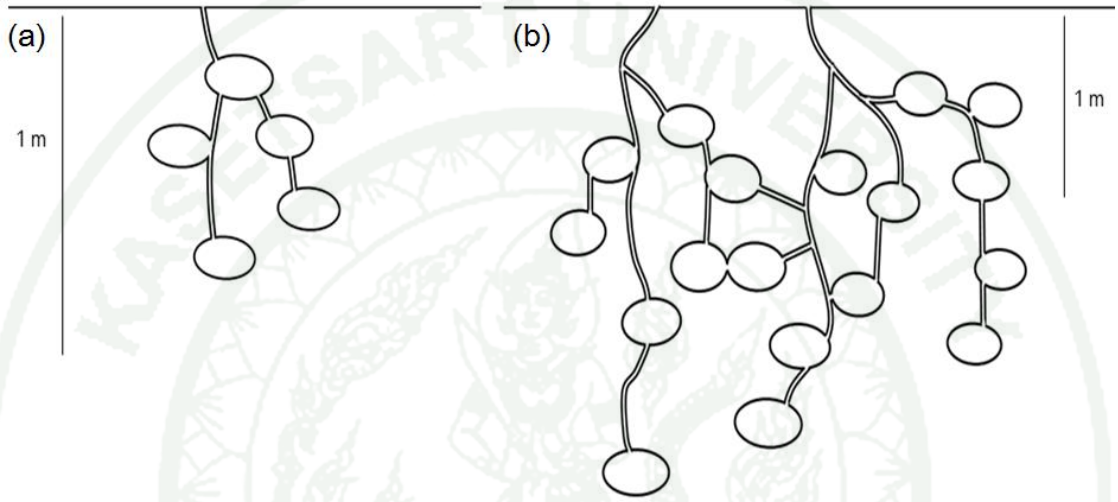

Figure 24 Examples of the structure of subterranean ant nests. Simple nests consisted of a single large chamber and a small horizontal chamber connected with a vertical and horizontal tunnel (a). Complex nests consisted of multiple small chambers with long narrow tunnels connecting each chamber (b). These illustrations were modified from Tschinkel, (2003) based on observations from this study

Regarding the ant communities, this research indicates that subterranean nests of ant communities affect CO_2 efflux from forest floor (Carbon output). The reduction of ant diversity and community compositions as well as of the abundance of nests can alter the CO_2 efflux from the soil. Therefore, the impact of *A. gracilipes* displacing ant communities can have indirect effects in carbon output from terrestrial ecosystems.

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CONCLUSION AND RECOMMENDATIONS

Conclusion

Part 1: Ant diversity and distribution of the invasive ant, *Anoplolepis gracilipes*, in Thailand

1. Two-hundred-twenty-one species of ants were found in Thailand, of which 24 species are invasive. These invasive ant species have been classified as invasive species in the Pacific region, with consistently documented ecological and economic impacts, particularly *Anoplolepis gracilipes, Solenopsis geminata, Monomorium pharaonis*, and *M. destructor*.

2. High percentage frequencies of occurrence in each habitat-type showed that *A. gracilipes* was present in all forest types, and it also has been considered as an invasive species in Thailand. Therefore, *A. gracilipes* is a most important invasive species within forest ecosystems in Thailand and should be chosen for further studies on the impact of invasive ant species in forest ecosystems. Larger numbers of invasive ant species were found in disturbed habitats and tourist zones in forest areas, while lower numbers were found in other forest areas. These data showed that the primary spread of invasive ant species in forest areas was strongly associated with habitats disturbed by human activities.

3. Interestingly, *Anoplolepis gracilipes* has the highest frequency of occurrence (82 % of the total study sites) and currently occupies all habitats-types (i.e. forest areas, plantation, agricultural, and urban areas), except hill evergreen forest. High frequencies were recorded in forest areas and plantation areas with lower frequencies in urban areas. Together, these data provide strong evidence that *A. gracilipes* is a very common invasive species found in Thailand within forest ecosystems. Therefore, *A. gracilipes* was chosen to investigate its ecological impact on forest ecosystems in further studies.

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Part 2: Ecological impact of the yellow crazy ant (*Anoplolepis gracilipes* Smith, 1857; Hymenoptera: Formicidae) in dry evergreen forest at Sakaerat Biosphere Reserve

1. Impact on non-ant arthropods

There were observable site effects, with the frequency of occurrence of species and individuals of non-ant arthropods being significantly greater in uninvaded sites compared with invaded sites. There was also an observable interaction between non-ant arthropod group and sites. *Anoplolepis gracilipes* had a negative impact on native non-ant arthropod diversity and communities resulting in a potential loss of six groups of non-ant arthropods consisting of isopods, cockroaches, termites, centipedes, millipedes, and spiders. The establishment of nests of *A. gracilipes* can often be found in termite mounds (*Macrotermes sp*.). Together with the above results, these findings provide evidence that invasion by *A. gracilipes* results in losses of not only species diversity of termites but its invasion might also be the cause of a reduction in the abundance of termite nests.

2. Impact on ant diversity and community composition of and its microhabitats

Comparisons of individual ant numbers, frequency, and abundance revealed significant interactions between ant species and sampling sites. Most ant species had significantly higher numbers of individuals, frequencies of occurrence, and abundance at uninvaded sites compared to invaded sites. For both site types, the highest ant diversity and more ants were found nesting in the soil than in other microhabitats. The results showed the number of ant nests, their frequency and abundance in each microhabitat differed between the sites. The number of nests, frequencies of occurrence and abundance of three microhabitats (termite mound, tree trunk holes/crack, under substrate) at invaded sites were significantly greater than at uninvaded sites. The reduction in native ant diversity and nest abundance at invaded sites may be important to understand the general role of interspecific competition in ant communities. In addition, some native ant species can repel *A. gracilipes* or, at least,

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reduce the rate of spread of *A. gracilipes* in new locations. Thus, it is possible that some native ant species play an important role as a biotic barrier to invasion, where they have similar nesting habits to *A. gracilipes* and higher numbers of nests compared to other native ants. In particular, *O. denticulate, O. rixosus* and *Pachycondyla astuta*, are polydomous ant species and have high numbers of ants.

3. Impact on ecosystem process

The presence of subterranean nests of *Anoplolepis gracilipes* can increase the CO_2 efflux from the soil in dry evergreen forest. They are also able to alter the CO_2 efflux from the soil. This research found that subterranean nests of ant communities affected the CO_2 efflux from the forest floor (carbon output). The reduction in ant diversity and community composition as well as in the abundance of nests can alter the CO_2 efflux from the soil. Therefore, the impact of *A. gracilipes* displacing ant communities can have indirect effects on the carbon output from terrestrial ecosystems. Moreover, this result shows that *A. gracilipes* has a negative impact on termite and ant diversity and community composition by predation of termites for food and displacing termite nests. It is well known that termites constitute a functional group which plays an important role in the process of litter decomposition and nutrient cycling (Yamada, 2004; 2005). As a consequence, *A. gracilipes'* invasion must affect ecosystems process by indirectly altering the litter decomposition, nutrient cycling, and soil CO_2 efflux in dry evergreen forest.

Recommendations

1. Establishment of permanent monitoring plots in forest ecosystems: (1) to continue to determine the distribution of prior invasive ants in forest ecosystems in SERS, (2) to evaluate the need for control in SERS, and (3) to develop a plan for invasive ant management in invaded sites.

2. The status of Thailand is unclear with regard to the native range or the region of introduction among other locations in the world. In fact, Southeast Asia and Africa

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are two possible native regions of *A. gracilipes* (ISSG, 2011). A study clearly pointed out that Thailand was in the native range of this species (CABI, 2014). From this perspective, it is not surprising to find this invasive ant throughout Thailand. It would still be interesting to fine-tune the distribution of *A. gracilipes* in Thailand in order to gain more information on its ecological requirements.

3. More concerted effort is required to study the consequences of *A. gracilipes* on other arthropod species and communities as well as on endemic species of reptiles, amphibians, and mammals associated with arthropod communities. They are important drivers of forest ecosystems in the Sakaerat Biosphere Reserve Station (Nabhitabhata and Chan-ard, 2005). In particular, the species that are specialists and feed on a limited number of arthropods may be at greater risk from ant invasion.

4. Based on the results and observations, I would deduce that *A. gracilipes* shares common traits for competition with native ant communities and that native ant species in the dry evergreen forest of uninvaded sites form a major biotic barrier to the invasion of *A. gracilipes* in SERS. Therefore, it is necessary to conduct surveys in order to identify the role of dominant ants in the organization of forest ant communities, particularly the interspecific competition among ant species and communities should be assessed, and the role of native ant species as a biotic barrier to the invasion of *A. gracilipes* should be evaluated in the future.

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APPENDIX

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Appendix Table 1 Presence and absent data, and total number of ant nest were observed from nesting location at UVS and IVS.

Species	Nesting sites												Total number of ant nest					
	LL		RL		ST		TM		TT		US		Dry season		Wet season		Whole year	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Anochetus graeffei	0	0	0	0	1	1	0	0	0	0	0	0	7	2	7	3	14	5
Anochetus sp.1	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0
Anochetus sp.2	1	0	0	0	1	1	0	0	0	1	0	0	1	3	4	3	5	6
Anochetus sp.3	1	0	1	0	1	1	0	0	0	0	0	0	1	0	6	2	7	2
Anoplolepis gracilipes	0	1	0	1	0	0	0	1	0	1	0	1	0	391	0	420	0	811
Aphaenogaster sp. 1	0	0	0	0	0	1	0	0	0	0	0	0	11	9	11	7	22	16
Cardiocondyla nuda	0	0	0	0	0	1	0	0	0	0	0	0	0	6	0	5	0	11
Cerapachys sp.1	1	0	0	0	0	0	0	0	0	1	0	1	0	0	3	2	3	2
Cerapachys sp.2	1	0	0	0	1	0	0	0	1	0	0	0	1	0	4	0	5	0
Cerapachys sulcinodis	1	0	1	0	0	0	0	0	1	1	1	1	4	0	7	2	11	2
Crematogaster sp.1	0	0	0	0	0	1	0	0	0	0	0	0	0	8	0	9	0	17
Crematogaster sp.2	1	0	0	0	1	1	0	0	0	1	1	0	3	2	10	2	13	4
Crematogaster sp.3	1	0	0	0	1	0	0	0	0	0	0	0	0	0	8	0	8	0
Crematogaster sp.4	1	0	0	0	1	1	0	0	1	1	0	0	3	6	7	4	10	10
Diacamma rugosum	0	0	0	0	0	1	0	0	1	1	0	0	2	10	5	2	7	12
Diacamma vagans	0	0	0	0	1	1	0	0	1	0	0	0	10	15	20	12	30	27

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Appendix Table 1 (Continued)

Species	Nesting sites												Total number of ant nest					
	LL		RL		ST		TM		TT		US		Dry season		Wet season		Whole year	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Dolichoderus thoracicus	1	0	1	1	0	0	1	0	1	1	1	0	1	8	12	29	13	37
Gnamptogenys binghamii	0	0	0	0	0	1	0	0	0	1	0	0	0	11	0	3	0	14
Harpegnathos venator	0	0	0	0	1	0	0	0	0	0	0	0	3	0	0	0	3	0
Leptogenys birmana	0	0	1	0	1	0	0	0	0	0	1	0	23	0	29	0	52	0
Leptogenys diminuta	1	0	1	0	1	1	1	0	0	0	0	0	3	0	4	2	7	2
Leptogenys sp.1	1	0	0	0	0	1	0	0	1	0	0	0	0	1	3	3	3	4
Leptogenys sp.2	0	0	0	0	1	0	1	0	0	0	0	0	1	0	0	2	1	2
Leptogenys sp.3	1	0	1	0	0	0	0	0	1	0	0	0	1	0	4	0	5	0
Leptogenys sp.4	1	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0
Leptogenys sp.5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
Monomorium floricola	1	0	1	0	1	1	0	0	0	0	0	0	10	8	17	8	27	16
Monomorium pharaonis	0	1	0	0	0	1	0	0	0	0	0	0	0	8	0	3	0	11
Monomorium sp.1	1	1	1	0	1	1	0	0	0	1	0	0	44	50	85	17	129	67
Odontomachus rixosus	1	0	1	0	1	1	0	0	1	0	1	0	108	6	108	0	216	6
Odontoponera denticulata	0	0	0	0	1	1	0	0	0	0	0	0	522	265	662	347	1184	612
Pachycondyla astuta	0	0	0	0	1	1	0	0	1	0	0	0	25	22	42	29	67	51

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Appendix Table 1 (Continued)

Species	Nesting sites												Total number of ant nest					
	LL		RL		ST		TM		TT		US		Dry season		Wet season		Whole year	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Pachycondyla sp.1	0	0	1	0	0	1	0	0	0	0	0	0	0	2	3	0	3	2
Pachycondyla sp.2	0	0	1	0	1	1	0	0	0	0	0	0	2	1	3	0	5	1
Paratrechina longicornis	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	1
Nylanderia sp.2	1	1	1	0	0	1	0	0	1	1	1	0	14	30	14	39	28	69
Pheidole dugosi	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	0	2
Pheidole hongkongensis	0	0	1	0	0	1	0	0	0	1	0	0	0	4	15	6	15	10
Pheidole inornata	0	0	1	0	1	1	0	0	0	0	0	0	3	2	6	4	9	6
Pheidole plagiaria	0	0	0	0	1	1	0	0	1	1	1	0	8	5	18	6	26	11
Pheidole sp.1	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	2	0	4
Pheidole sp.2	1	0	1	1	1	1	0	0	0	0	0	0	19	3	38	10	57	13
Pheidole sp.3	0	0	0	1	1	1	0	0	0	0	0	0	21	13	24	12	45	25
Pheidole sp.4	0	0	1	1	1	0	0	0	0	0	0	0	1	6	20	3	21	9
Pheidole sp.5	0	0	0	0	1	1	0	0	0	0	0	0	4	2	1	3	5	5
Pheidole sp.6	0	0	0	0	1	1	0	0	0	0	0	0	2	0	5	4	7	4
Pheidole sp.7	0	0	0	0	1	1	0	0	0	0	0	0	2	0	2	1	4	1
Pheidole sp.8	0	0	1	0	1	1	0	0	0	0	0	0	5	0	8	1	13	1

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Appendix Table 1 (Continued)

Species	Nesting sites												Total number of ant nest					
	LL		RL		ST		TM		TT		US		Dry season		Wet season		Whole year	
	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS	UVS	IVS
Pheidole sp.9	0	0	1	1	1	1	0	0	0	0	0	0	2	3	4	4	6	7
Pheidole sp.10	1	1	0	0	1	1	0	0	0	1	0	0	8	9	3	16	11	25
Pheidole sp.11	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	0	2
Pheidologeton affinis	1	0	1	0	1	0	0	0	1	1	1	0	8	0	18	5	26	5
Plagiolepis sp.1	0	1	0	1	0	1	0	0	0	0	0	0	0	24	0	4	0	28
Polyrhachis proxima	0	0	0	0	1	1	0	0	0	0	0	0	3	0	3	1	6	1
Tapinoma melanocephalum	0	0	0	0	0	0	0	0	0	1	0	0	0	4	0	0	0	4
Tecnomyrmex kraeperinii	0	0	0	0	0	0	0	0	0	1	0	0	0	2	0	2	0	4
Tetramorium lanuginisum	0	0	1	0	1	1	0	0	0	0	0	0	13	21	45	25	58	46
Tetramorium sp.1	0	0	0	0	1	1	0	0	0	0	0	0	1	12	0	27	1	39
Tetramorium sp.2	0	0	0	0	1	1	0	0	0	0	0	0	4	1	0	0	4	1
Tetramorium sp.3	0	0	1	0	1	1	0	0	0	0	0	0	6	3	6	7	12	10
Tetramorium sp.4	0	0	1	0	1	1	0	0	0	0	0	0	8	1	4	1	12	2
Tetramorium sp.5	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	2	0	4
Tetramorium sp.6	0	0	0	0	0	1	0	0	0	0	0	0	0	3	0	2	0	5
Total													941	1015	1340	1118	2281	2133

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Appendix Table 1 (Continued)

LL = Liter layers nesting type

RL = Rotten logs nesting type

ST = Soil nesting type

TM = Termite mound

TT = Tree trunk

US = Under substrate

“1” = Presence nest of ant

“0” = Absence nest of ant

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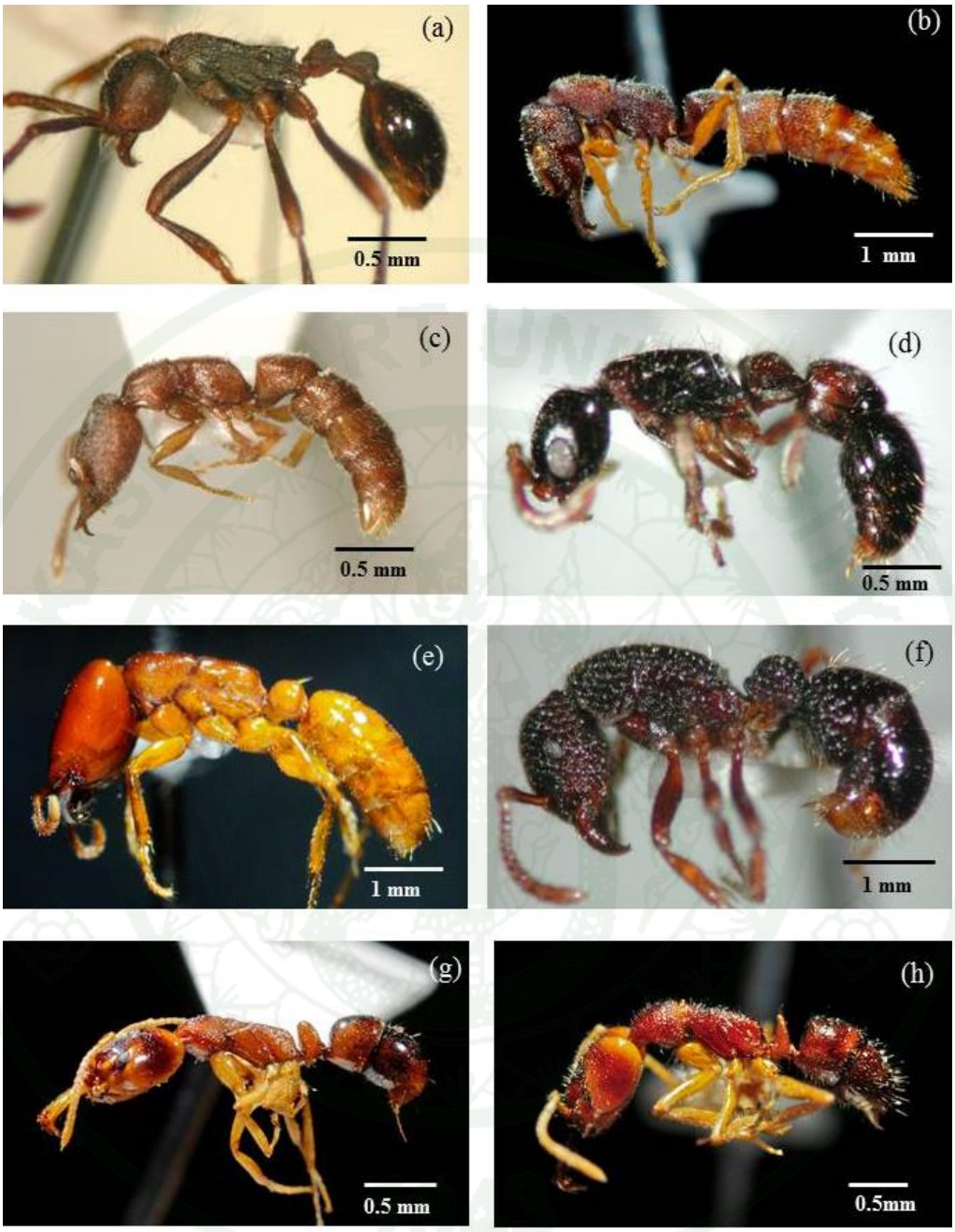

Appendix Figure 1 The sample of invasive ant species found in this study area, Subfamily Aenictinae; (a) *Aenictus* sp., Subfamily Amblyoponinae; b) *Amblyopone reclinata*, (c) *Amblyopone* sp.1, Subfamily Cerapachyinae; (d) *Cerapachys* sp.1, Subfamily Dorylinae; (e) *Dorylus oreientalis*, Subfamily Ectatomminae; (f) *Gnamptogenys binghami*, Subfamily Ponerinae; (g) *Anochetus* sp.1 and (h) *Anochetus* sp.2

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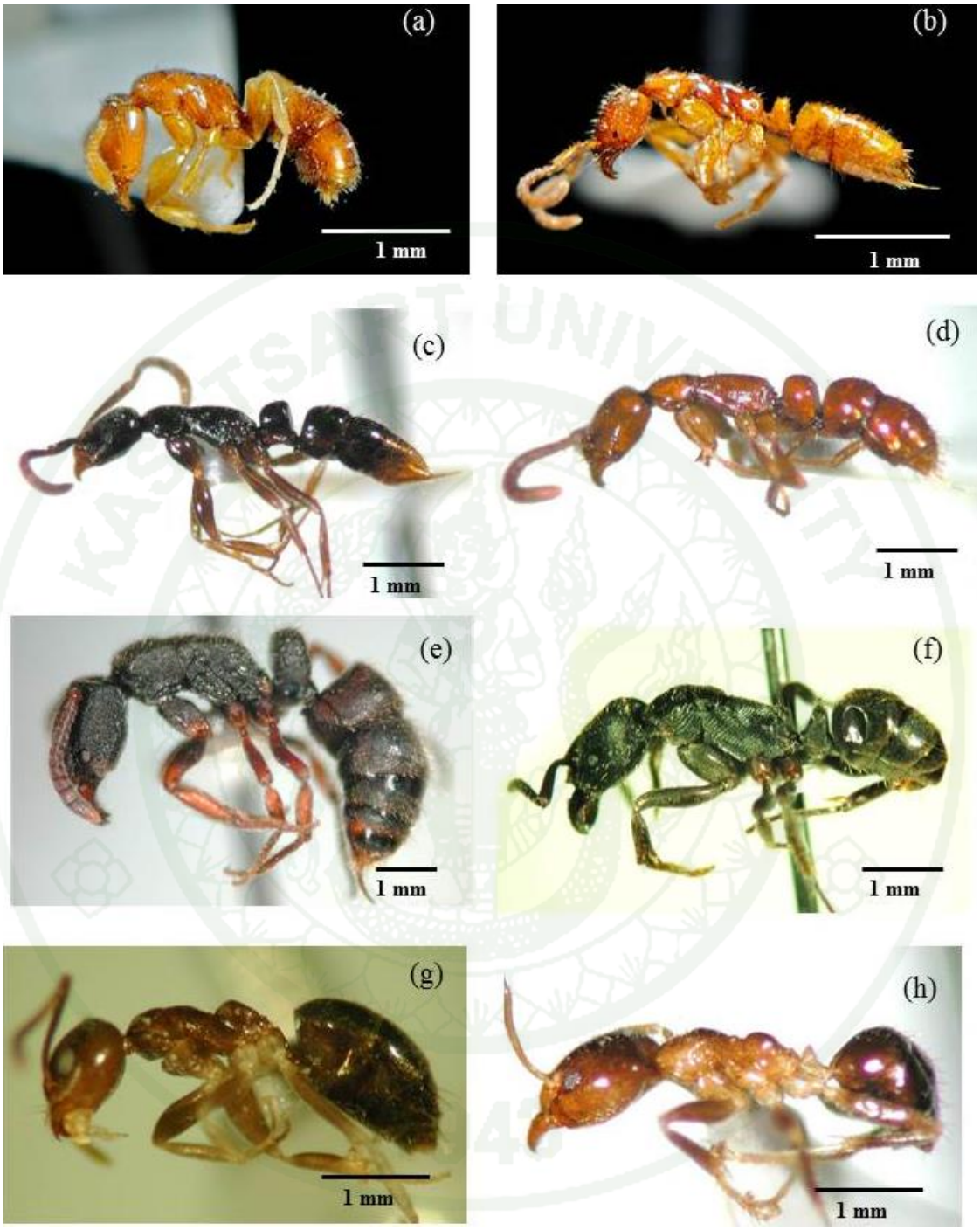

Appendix Figure 2 The sample of invasive ant species found in this study area, Subfamily Ponerinae; (a) *Hypoponera* sp.1, (b) *Leptogenys* sp.1 (c) *Leptogenys* sp.2, (d) *Leptogenys* sp.3, (e) *Pachycondyla leeuwenhoeki* , (f) *Odontoponera denticulata*, Subfamily Dolichoderinae; (g) *Technomyrmex* sp.1 and (h) *Philidris* sp.1

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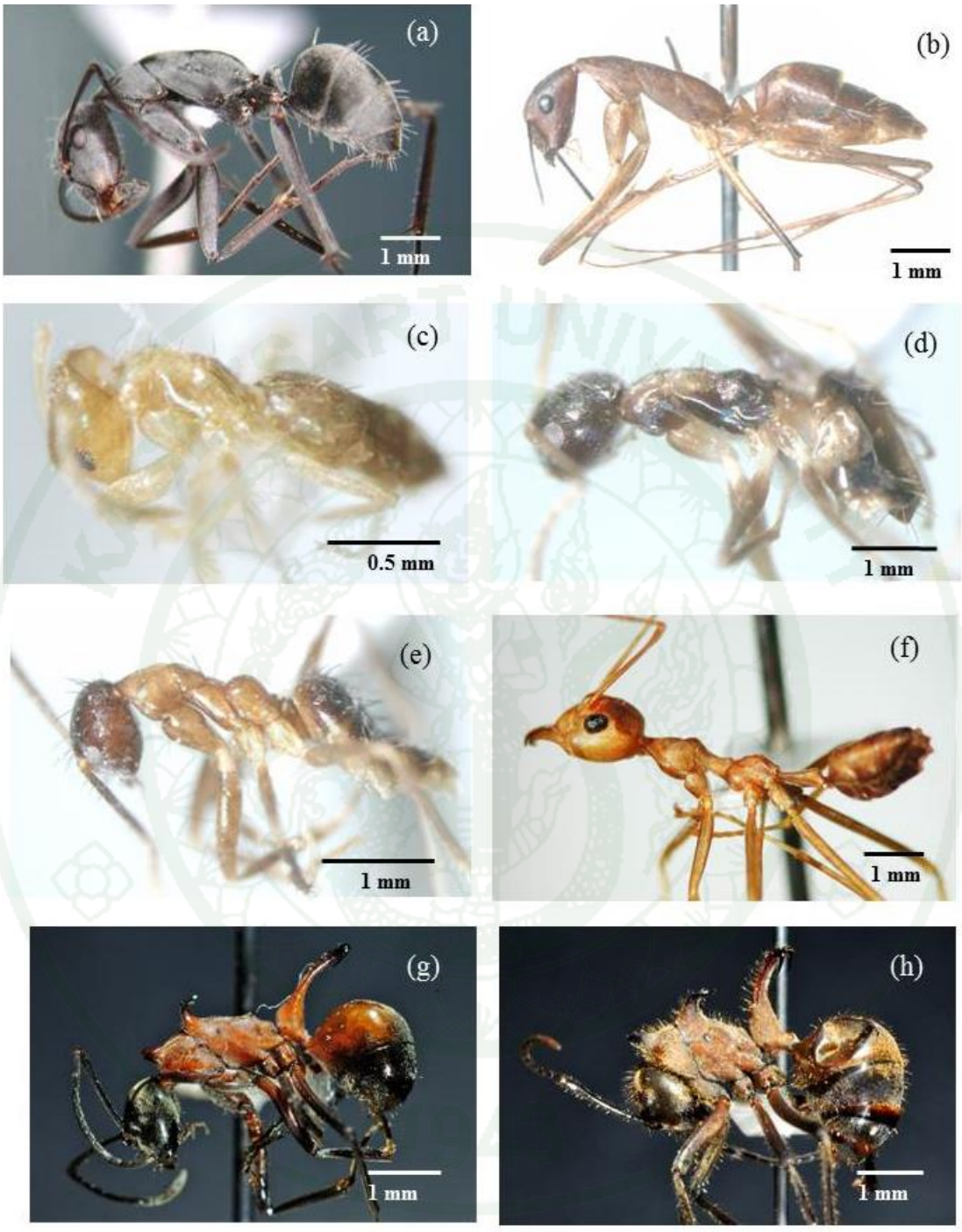

Appendix Figure 3 The sample of invasive ant species found in this study area, Subfamily Formicinae; (a) *Camponotus rufoglaucus*, (b) *Camponotus* sp.2 (c) *Nylanderia* sp.1, (d) *Nylanderia* sp.3, (e) *Nylanderia* sp.4, (f) *Oecophylla smaragdina*, (g) *Polyrachis* sp.1 and (h) *Polyrhachis* sp.2

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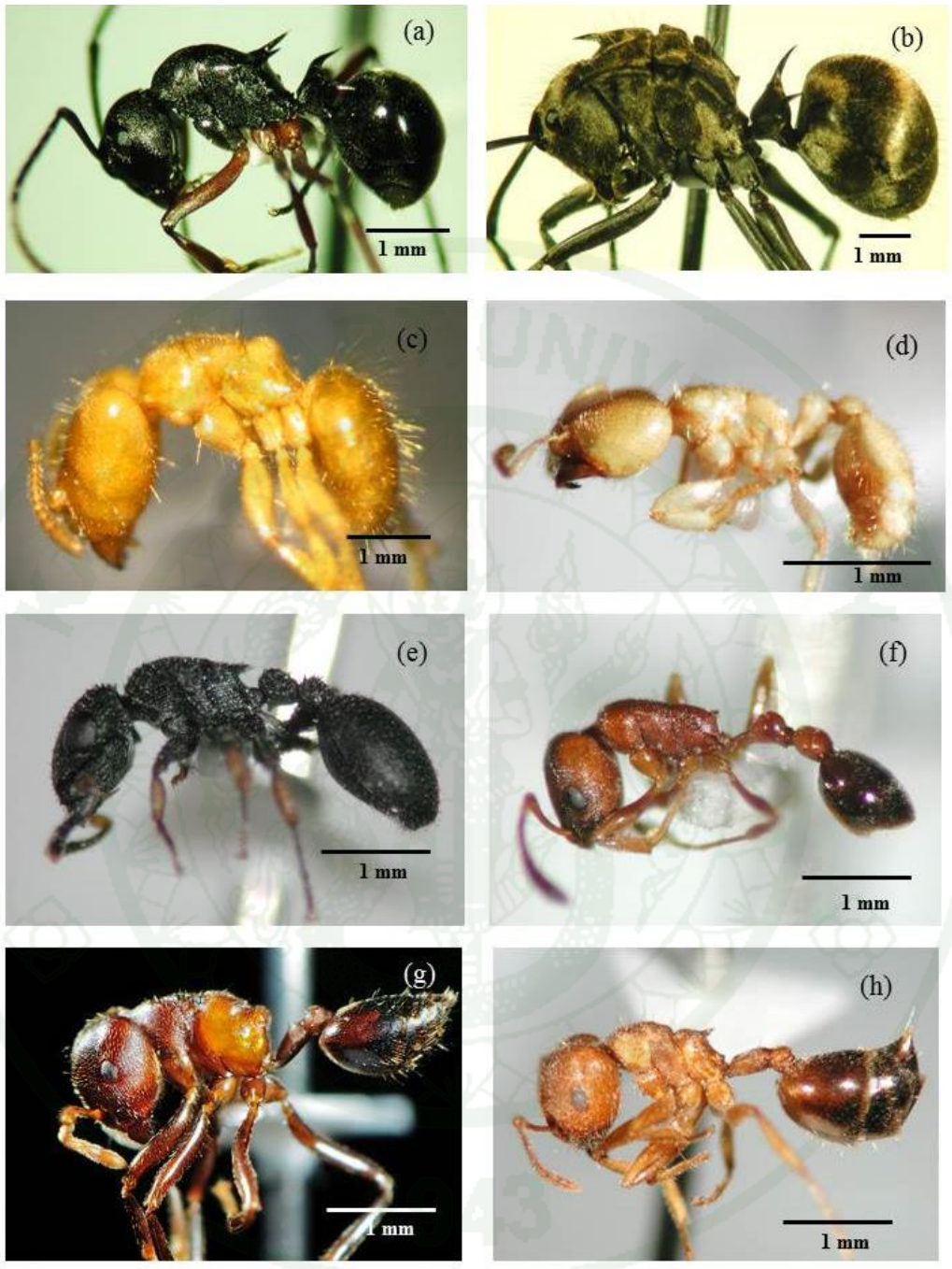

Appendix Figure 4 The sample of invasive ant species found in this study area, Subfamily Formicinae; (a) *Polyrhachis hippomanes*, (b) *Polyrhachis proxima*, (c) *Pseudolasius* sp. 1, Subfamily Myrmicinae; (d) *Carebara* sp. 1, (e) *Cardiocondyla nuda*, (f) *Cataulacus granulatus*, (g) *Crematogaster aurita* and (h) *Crematogaster rogenhoferi*

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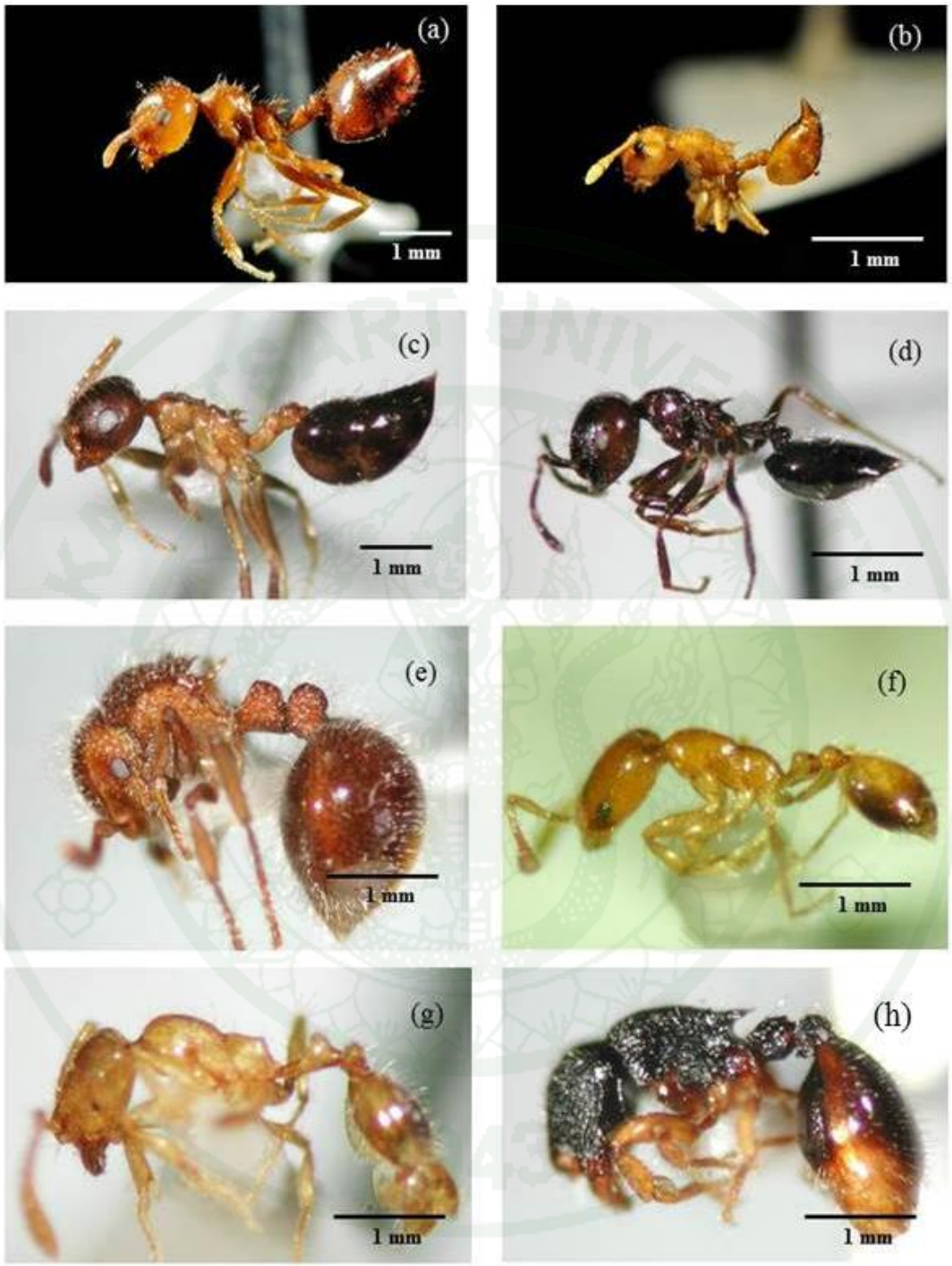

Appendix Figure 5 The sample of invasive ant species found in this study area, Subfamily Myrmicinae; (a) *Crematogaster* sp.1, (b) *Crematogaster* sp.2, (c) *Crematogaster* sp.3, (d) *Crematogaster* sp.4, (e) *Meranoplus* sp.1, (f) *Monomorium* sp.1, (g) *Monomorium talpa* and (h) *Myrmicina* sp.1

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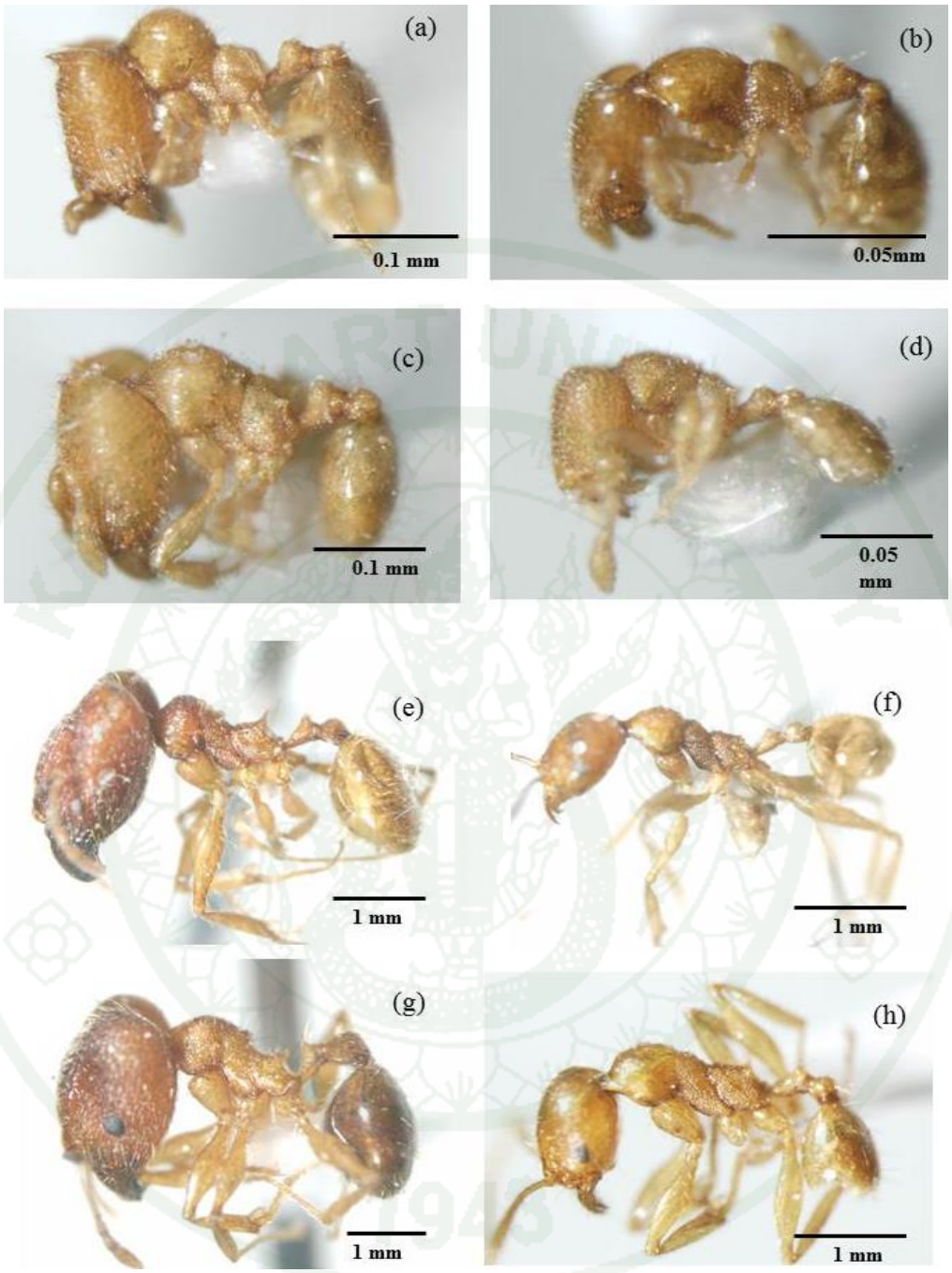

Appendix Figure 6 The sample of invasive ant species found in this study area, Subfamily Myrmicinae; (a) *Oligomyrmex* sp.1 (Major), (b) *Oligomyrmex* sp.1 (Minor), (c) *Oligomyrmex* sp.2 (Major), (d) *Oligomyrmex* sp.2 (Minor), (e) *Pheidole* sp.1 (Major), (f) *Pheidole* sp.1 (Minor), (g) *Pheidole* sp.2 (Major) and (h) *Pheidole* sp.2 (Minor)

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