ความหลากหลายของชนิดและนิเวศวิทยาประชากรของกิ้งกือกระสุนพระอินทร์วงศ์ Zephroniidae ในจังหวัดน่าน

นางสาวณัฐรินทร์ วงศ์ธรรมวานิช

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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ปีการศึกษา 2554

SPECIES DIVERSITY AND POPULATION ECOLOGY OF GIANT PILL MILLIPEDES, FAMILY ZEPHRONIIDAE IN NAN PROVINCE

MISS NATTARIN WONGTHAMWANICH

A Dissertation Submitted in Partial Fulfillment of the Requirements

for the Degree of Doctor of Philosophy Program in Biological Sciences

Faculty of Science

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Thesis Title	SPECIES DIVERSITY AND POPULATION ECOLOGY OF GIANT PILL MILLIPEDES, FAMILY ZEPHRONIIDAE IN NAN PROVINCE
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Field of Study	Biological Sciences
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ณัฐรินทร์ วงศ์ธรรมวานิช : ความหลากหลายของชนิดและนิเวศวิทยาประชากรของกิ้งกือกระสุนพระอินทร์ วงศ์ Zephroniidae ในจังหวัดน่าน. (SPECIES DIVERSITY AND POPULATION ECOLOGY OF GIANT PILL MILLIPEDES, FAMILY ZEPHRONIIDAE IN NAN PROVINCE) อ. ที่ปรึกษาวิทยานิพนธ์หลัก: รศ. ดร.กำธร ธีรคุปต์, อ. ที่ปรึกษาวิทยานิพนธ์ร่วม: ศ. ดร. สมศักดิ์ ปัญหา, 135 หน้า.

การศึกษาครั้งนี้มุ่งเน้นในด้านความหลากหลายของชนิดและนิเวศวิทยาของกิ้งกือกระสุนพระอินทร์ วงศ์ Zephroniidae ที่พบในจังหวัดน่าน การศึกษาความหลากหลายของชนิดได้ทำการเก็บตัวอย่างในช่วงฤดูฝนระหว่างปี พ.ศ. 2552-2554 พบกิ้งกือวงศ์ Zephroniidae จำนวน 2 สกุล ได้แก่ สกุล *Sphaerobelum* Verhoeff, 1924 และสกุล *Zephronia* Gray, 1832 โดยพบสกุล *Sphaerobelum* ในป่าที่มีความชื้นสูง เช่น ป่าดงดิบและป่าผสมผลัดใบชื้น ขณะที่สกุล *Zephronia* พบในป่าเต็งรังและป่าผสมผลัดใบ

นิเวศวิทยาประชากรของกิ้งกือกระสุนพระอินทร์ *Zephronia* cf. *viridescens* ได้แก่ ขนาดประชากร การกระจาย กิจกรรมในรอบวัน อาหารและการเติบโตของกิ้งกือ ได้ทำการศึกษาในพื้นที่สถานีวิจัยและป่าไม้ของจุฬาลงกรณ์มหาวิทยาลัย อำเภอเวียงสา จังหวัดน่าน โดยขนาดประชากรและการกระจายของกิ้งกือได้ดำเนินการศึกษาในปี พ.ศ. 2553 โดยได้วางแปลงแบบสุ่มอย่างขนาด 2×2 ตารางเมตร จำนวน 20 แปลง และทำการสุ่มตัวอย่างทุกเดือนเป็นเวลา 1 ปี ในส่วนของการศึกษากิจกรรมในรอบวันได้ทำการบันทึกข้อมูลของตัวอย่างกิ้งกือแต่ละตัวทุกๆ 30 นาทีตลอดทั้งวัน ผลการศึกษาแสดงให้เห็นว่ากิ้งกือใช้เวลาส่วนใหญ่ในการกินอาหารบริเวณใต้เศษซากพืชและพบว่ากิจกรรมการสืบพันธุ์มีแนวโน้มว่าเกิดขึ้นส่วนใหญ่ในช่วงเวลากลางคืน อาหารของกิ้งกือได้ทำการศึกษาจากตัวอย่างเศษซากพืชที่กำลังถูกกินในบริเวณที่อยู่อาศัย โดยพบว่าอาหารหลักได้แก่ ไผ่ไร่ (*Gigantochloa albociliata*) พืชในสกุลเดียวกับกาหลง (*Bauhinia* spp.) สำหรับการเติบโตได้ทำการศึกษาภายในกล่องสี่เหลี่ยมก้นเปิดที่ฝังในถิ่นที่อยู่อาศัยระหว่างปี พ.ศ. 2552-2554 ผลการศึกษาแสดงให้เห็นว่ากิ้งกือที่เพิ่งฟักออกจากไข่ต้องทำการลอกคราบทั้งสิ้น 8 ครั้งจึงจะมีจำนวนปล้องคงที่ โดยกิ้งกือขนาดเล็กจะมีความถี่ในการลอกคราบบ่อยกว่าขนาดใหญ่ จากข้อมูลหลายๆด้านประมาณได้ว่าอายุขัยของกิ้งกือชนิดนี้มีแนวโน้มมากกว่า 5 ปี จากการศึกษาความแตกต่างทางสัณฐานวิทยาเปรียบเทียบระหว่างเพศพบว่ากิ้งกือตัวผู้มีลักษณะเด่นในปล้องที่สอง ปล้องที่ 9 10 11 12 และปล้องสุดท้าย รวมทั้งจำนวนกรวยรับสัมผัสบนหนวด จากข้อมูลทางนิเวศวิทยาดังกล่าวข้างต้นแสดงให้เห็นว่ากิ้งกือกระสุนพระอินทร์มีการปรับตัวอย่างเหมาะสมเพื่อการอยู่รอดและสืบพันธุ์ในบริเวณที่อยู่อาศัย

สาขาวิชา วิทยาศาสตร์ชีวภาพ ลายมือชื่อนิสิต.....

ปีการศึกษา 2554 ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก.....

ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์ร่วม.....

507 38402 23 : MAJOR BIOLOGICAL SCIENCES

KEYWORDS : TAXONOMY / DISTRIBUTION / ACTIVITY / LIFE PATTERN / GROWTH

NATTARIN WONGTHAMWANICH : SPECIES DIVERSITY AND POPULATION ECOLOGY OF GIANT PILL MILLIPEDES, FAMILY ZEPHRONIIDAE IN NAN PROVINCE. ADVISOR : ASSOC. PROF. KUMTHORN THIRAKHUPT, Ph.D., CO-ADVISOR : PROF. SOMSAK PANHA, Ph.D., 135 pp.

This study focused on species diversity and ecology of the giant pill-millipedes family Zephroniidae in Nan Province. The millipedes were collected in rainy seasons of 2009-2011 for species diversity study. Two genera of the giant pill-millipedes; genus *Sphaerobelum* Verhoeff, 1924 and genus *Zephronia* Gray, 1832 of family Zephroniidae were dominated in this area. Genus *Sphaerobelum* occupied in higher moisture habitat such as moist deciduous forest and evergreen forest, while genus *Zephronia* presented in mixed deciduous forest and dry deciduous dipterocarp forest.

Population ecology such as population size, dispersion, daily activities, diet and growth of the giant pill-millipedes, *Zephronia* cf. *viridescens*, from Chulalongkorn University Forestry and Research Station, Wiang Sa District, Nan Province was studied. Population size and dispersion were studied during 2009. Twenty of 2×2 m^2 quadrats were sampling randomly each month for one year. For daily activities study, the data of each millipede sample were recorded every 30 minutes throughout the day. The result showed that they spent most of the time under leaf litter for feeding and another major activity tended to be mating at nighttime. Diets of the giant pill millipedes were observed in the habitat. Parts of plants and litter being consumed by them were collected and it was found that the major food items were *Gigantochloa albociliata* and *Bauhinia* spp. Growth was observed and recorded in enclosures within the habitat during 2009-2011. The data showed that hatchlings had to pass through eight moltings before having a constant number of segments and small millipedes molted more frequently than the larger sizes. From all information, the life span of *Z.* cf. *viridescens* was estimated to be more than 5 years. Differences in morphology between sexes were measured and compared. The dominant morphological characters of males were thoracic shield, ninth, tenth, eleventh and twelfth body segments, anal shield and sensorial cone number of the antennae. Most of their ecological data represented the adaptation of *Z.* cf. *viridescens* for survival and reproduction within the habitat.

Field of Study : Biological Sciences Student's Signature .....

Academic Year : 2011 Advisor's Signature .....

Co-advisor's Signature .....

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CHAPTER I

INTRODUCTION

One of the largest classes within Phylum Arthropoda following Class Insecta and Class Arachnida is Class Diplopoda (Golovatch *et al*., 1995), which has been described approximately 8,000-12,000 species in the world (Sierwald and Bond, 2007; Shear, 2011). Millipede diversity and richness are occupied mostly in the tropical forest due to their medium to high moisture preference (Golovatch *et al*., 1995; Sierwald and Bond, 2007). Thailand located in Indo-Burma biodiversity hotspot (Myer *et al*., 2000), which most millipedes are risky to extinct by habitat destruction. Before 2005, 105 species of millipedes were reported in Thailand (Enghoff, 2005), but there is only one species of the giant pill millipedes, *Zephronia siamensis* Hirst, 1907, in order Sphaerotheriida has been recorded. The pill millipedes in this order have been reported in the tropical zones of Australia, New Zealand, tropical Asia, South Africa and Madagascar (Jeekel, 1974; Shelley, 1999; Wesener and Van den Spiegel, 2009), combining of more than 300 species worldwide (Sierwald and Bond, 2007; Wesener *et al.,* 2010). Therefore, it is expected that there should be more species of the giant pill millipedes in Thailand.

Nan Province has plenty of natural resources especially flora and fauna. There are several forest types in this province where giant pill millipedes are expected to inhabit. Comparing to other millipede groups in the world, the document on order Sphaerotheriida is lacking. Thus, the taxonomic and ecological researches on giant pill millipedes should be urgently conducted because they are important soil/litter macrofauna, which play major role as detritivores which stimulate microbial activity and indirectly influence the fluxes of nutrients (Hopkin and Read, 1992; Golovatch *et al*., 1995). Therefore, this study focused on species diversity, distribution and population ecology of the giant pill millipedes in Nan Province, northern Thailand. The information from this study will improve taxonomic studies of Family Zephroniidae and provide a key to species and distribution map of the giant pill millipedes in Nan Province and will

provide basic knowledge of the giant pill millipede biology and its ecology for further research.

Objectives

1. To investigate species diversity and taxonomic status of giant pill millipedes in Nan Province.

2. To investigate population density, dispersion, activity period, food, reproductive ecology, growth and sexual dimorphism of the giant pill millipedes at Chulalongkorn University Forestry and Research Station, Wiang Sa District, Nan Province.

Anticipated benefit

1. This investigation will improve taxonomic studies of Family Zephroniidae and provide a key to species and distribution map of giant pill millipedes in Nan Province.

2. This study will provide basic knowledge of the giant pill millipede biology and its ecology for further research.

CHAPTER II

LITERATURE REVIEW

Taxonomic Status and Distribution of the Giant-Pill Millipedes

The taxonomic status of millipedes in the world has been reviewed by Sierwald *and* Bond (2007) and Shear (2011). They reported that approximately 12,000-8,000 species have been described from an estimation of 80,000 species (Hoffman, 1979) within 15 orders based on Enghoff's classification in 1984 (Hopkin and Read, 1992). Among these, one of calcareous millipede groups (Subclass Chilognatha) which were restricted their distribution in Southern hemisphere as giant pill-millipedes (infraclass Pentazonia: order Sphaerotheriida), has been comprised around 330 species (Sierwald and Bond, 2007; Wesener *et al*., 2010; Shear, 2011). Before 2009, order Sphaerotheriida was separated into 2 families which included Sphaerotheriida and Zephroniidae. Family Sphaerotheriidae is representing in South Africa, Madagascar, southern India, Sri Lanka, eastern Australia, New Zealand and Tasmania, whereas the family Zephroniidae is found in Southeast Asia (Jeekel, 1974; Hoffman, 1982; Shelley, 1999). After that, this order was divided by Wesener and Van den Spiegel (2009) into 4 families with a discontinuous geographical area (Fig. 2.1): Sphaerotheriidae in South Africa, Artherosphaeriidae in Madagascar and Southern India, Zephroniidae in Southeast Asia and Procyliosomatidae in Tropical Australia and New Zealand.

Family Zephroniidae is the biggest family and also has more problematic than others. Jeekel (2001) reported that there were 131 species in 16 genera of family Zephroniidae and 40 species in 1 genus of family Sphaerotheriidae in Asia. The hierarchical classification of the giant pill-millipedes in Southeast Asia was presented as follows:

Kingdom	Animalia
Phylum	Arthropoda
Subphylum	Myriapoda
Class	Diplopoda
Subclass	Chilognatha
Infraclass	Pentazonia
Order	Sphaerotheriida
Family	Zephroniidae

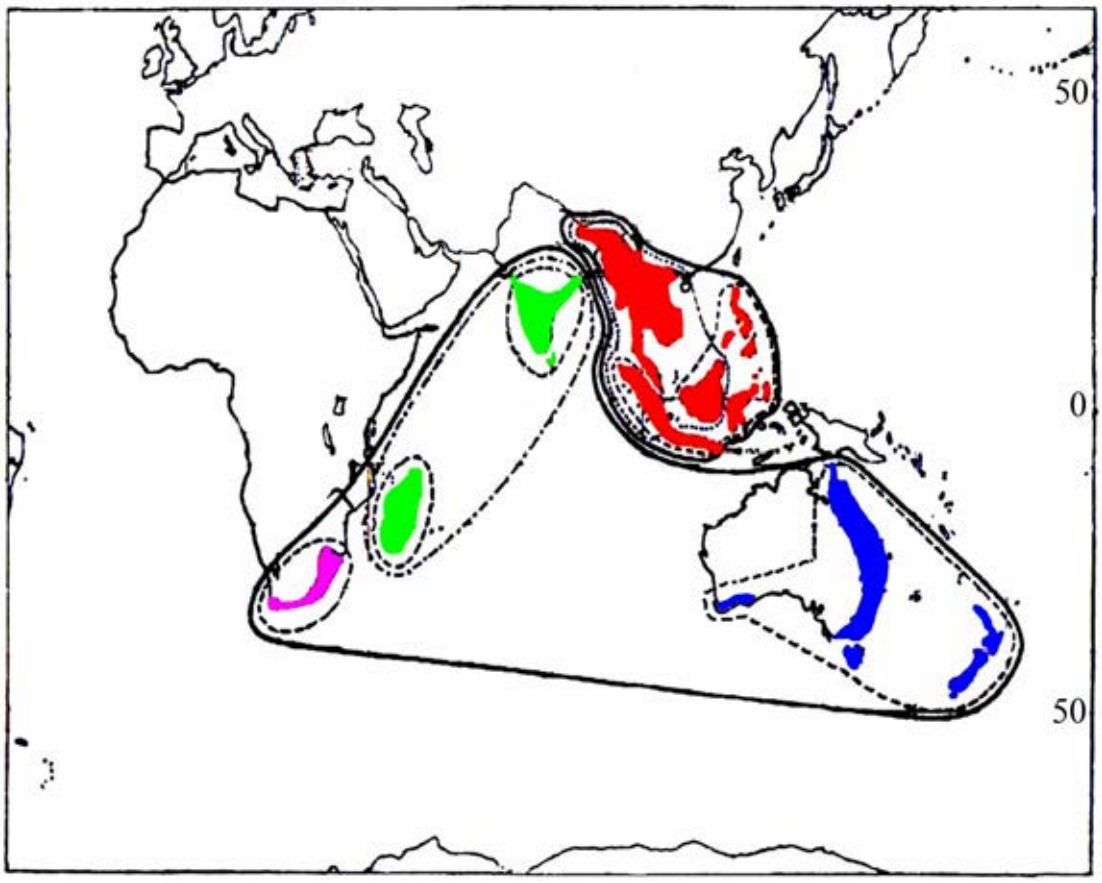

Figure 2.1 Distribution map of the giant pill-millipedes in order Sphaerotheriida modified from Jeekel (1974), Moir *and* Harvey (2008) and Wesener *and* VandenSpiegel (2009). Pink = Sphaerotheriidae, green = Artherosphaeriidae, red = Zephroniidae and blue = Pocyliosomatidae.

Thailand is located in subtropical zone which contains high millipedes diversity. In 2005, Enghoff reported that there were 105 millipede species found in Thailand (Enghoff, 2005). Major millipede group from Enghoff's report and recent works of millipedes were presented by cylindrical millipedes and flat-back millipedes. There is only one species of the giant pill millipede, *Zephronia siamensis*, which was described by Hirst (1907) from Sichang Island and Chanthaburi Province, Thailand; while the giant pill-millipedes have been gradually collected throughout Thailand (Wongthamwanich, Unpublished data). These data showed that the previous studies have been done in small areas of Thailand. Since Thailand has been classified as a member of Indo-Burma biodiversity hot spot from the level of high forest destruction and habitat lost (Myer *et al.*, 2000), the fundamental knowledge such as taxonomy and ecology of the giant pill-millipedes in Thailand needs to be urgently investigated.

General Morphology

The giant pill-millipede, an animal which can roll its body into complete sphere shape, is composed of the head and 13 segments (Fig. 2.2). The head consisted of mouthparts (mandible and gnathochilarium) and sensory structures including ocelli, antennae and Tömösváry organ. Each body ring composes of five cuticular components, i.e. a tergal arch, two pleurites and two sternites, which are separated (Hopkin and Read, 1992). The first segment, legless and connected with head, is called collum. It is followed by the large segment called thoracic shield, then other 10 normal segments and the largest segment at the end of body called anal shield. The adult body size is up to 10 cm in length. Comparing to other millipede orders such as cylindrical millipedes and flat-back millipedes, ozopores and defensive secretion are absent in Sphaerotheriida (Hoffman, 1982). Their legs consist of seven podomeres, i.e. coxa, trochanter, prefemur, femur, postfemur, tibia and tarsus. The gonads open on the second leg pair (Sierwald and Bond, 2007). The last two appendices behind the legs in a male are enlarged to form telopods which assist for sperm transfer (Hopkin and Read, 1992) and the anterior pair is always smaller (Hoffman, 1982).

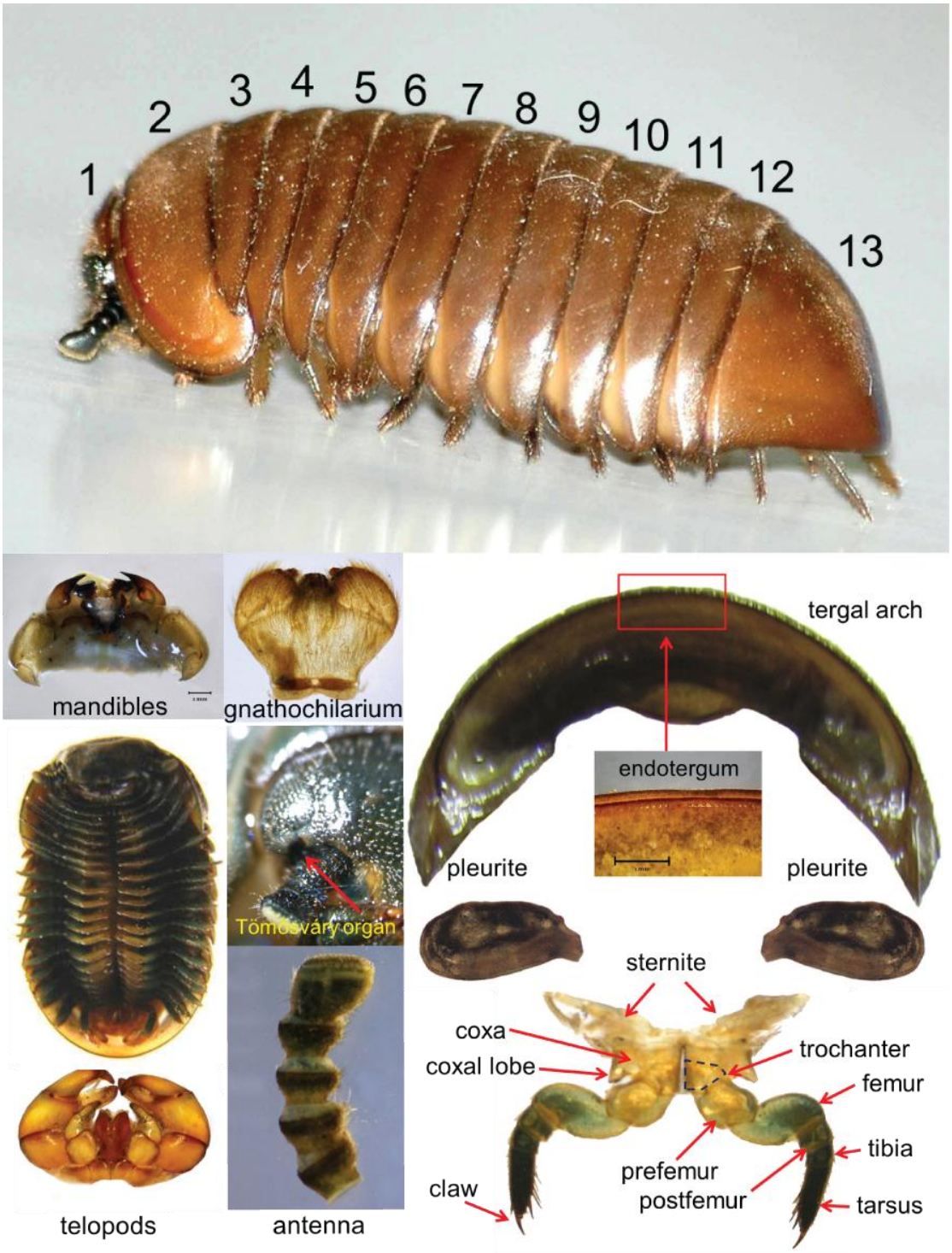

Figure 2.2 Unrolled giant pill-millipede in family Zephroniidae and its external morphology. The number of segments is presented by Arabic numbers. 1 = collum; 2 = thoracic shield; 3-12 = normal segments; 13 = anal shield.

Ecology and Behavior

Habit

Many species of millipedes can be seen during the daytime in moist shady forest (Hoffman, 1990). The giant pill millipedes in South Africa spend most of the daytime in an inactive state, unroll at night to move around and feed. They will quickly react by enrolling when they are disturbed in the course of walking (Lawrence, 1984). Haacker (1972) reported that some of them were arboreal animal such as the specimens of *Sphaerotherium punctulatum* in southern Africa which were collected by shaking tree in order to dislodge them from the branches.

Activity Patterns

Seasonal activity patterns of millipedes are usually associated with feeding or reproduction (Dangerfield and Telford, 1991). The majority of Nearctic millipedes inhabit fairly moist biotopes, typically the upper horizons of litter in broadleaf forest. Abundance and diversity are correlated with the presence of calcareous substrates. Immature stages tend to hide in the deepest organic layer and in mineral soil layer. The presence of a species in an area may be unexpected until the time of maturity. Members of arctic-boreal taxa mature in the autumn months and may be found as adults only during winter. Normally, maturity is reached in late spring or summer, at which time the older instars and new adults occur on the surface or in upper layers of litter (Hoffman, 1990). Many organisms use environmental cues such as changes in temperature, rainfall, day length and food availability to induce particular activity pattern. At first rain, millipede activity peaks soon after emergence from their inactive and after that, a couple of weeks, their activity declines again. Therefore, moisture is the most likely clue to induce soil surface activity of millipedes (Dangerfield and Telford, 1991). In southern India, Ashwini and Sridhar (2006) reported that abundance and biomass of the giant pill-millipedes (*Arthrosphaera magna*) were correlated with rainfall and highest during monsoon season. Banerjee (1967a) recorded that the peak activity of *Cylindroiulus punctatus* in

order Julida occurred during the breeding season when adults were searching actively for mate.

Foraging

Most millipedes play the important roles in ecosystem as detritivore and some of them are carnivore (Hopkin *and* Read, 1992). Thus, the major type of millipedes food consists of both the decayed and living parts of plants. A certain amount of gritty sand, which assists in the detritions of the food, is also swallowed with these items. Haacker (1972) reported that the climbing individuals of *S. punctulatum* were seen feeding on soft bark and green leaves. In order Sphaerotheriida, the relative length of intestine with body length is more than in most millipedes because their intestine bents in the N shape, which can storage enough food material to nourish to large body size (Lawrence, 1984).

Mating

Wesener *et al. (*2011) classified mating of giant pill-millipede genus *Sphaerotherium* into four stages (Fig. 2.3):

1. Detection (Fig. 2.3a): When a male find out rolled-up another one, it moves its anal shield on the posterior body end towards the partner without distinguishing sexes.

2. Courtship behavior (Fig. 2.3b): When the female is not rolled-up, the male produces sound as a short stridulation series (moving stridulation ribs against anal shield) until the male gets to the right mating position. Usually, the female coils when the male is touching and the male keeps on producing sound when the female starts to roll-up. At the same time, the male raises his anal shield under the rolled-up female. Only one species, *S. dorsale*, the male starts the sound production before touching the female. In case of the female is flipped or pushed away, the male follows, walking

backwards and stridulating continuously. The male continuously produces sound, usually 15–20 minutes, until the female is not rolled-up and the mating can begin.

3. Mating: The male moves his anal shield up and holds the anterior legs of the female with his posterior telopods when the female unrolls, (Fig. 2.3c). Most *Sphaerotherium* species stop stridulating during holding the female, while *S. punctulatum* is still stridulating. The male head position is located under the anal shield of the female. After 1-2 minutes, the male ejects sperm through the gonophore on the second leg pair, transports the sperm to posterior half of the body using his legs, and sperm then is transferred to the vulvae on the second leg pair of the female (Fig. 2.3d).

4. Post-mating behavior: After the sperm is transferred for two to five minutes, the male vacates the female and moves away. In some species, the male also produces short stridulation series after mating such as *S. punctulatum*, *S. dorsale*, and *S.convexitarsum*.

Egg laying and development

There is no data of the giant pill-millipede on reproductive ecology. However, the European pill-millipede in order Glomerida which is the nearest group to order Sphaerotheriida has been investigated. The laying of the eggs in the European *Glomeris* takes place in the spring. The female lays eggs on the posterior end of her body. With the last pair of legs, each little egg capsule is moulded with pellets of faeces which are voided from the hind end of the body. About 18 of these capsules are made by the female, each of them containing a single egg. When the female has finished making an egg capsule with the egg in it, she will close and drop it to the ground, taking no further interest in its fate. The egg case usually has thick strong walls and often contains two compartments, in one of which the egg is placed, the other being left empty. The egg capsule of *Glomeris* is round or oval with 3-5 mm in length. When the egg hatches out after about 30 days the minute first larva spends some time with the egg case as chamber is large enough to allow it to move about freely and some authors have stated

that it uses the walls of its own prison as food and so manages to eat its way out at right time.

The egg of giant pill-millipede was only reported in *Cyliosoma* sp. from New Zealand. Dohle (1992) found 1 egg and other stages of the millipede under rotten logs. The egg was oval (1.12 × 1.27 mm in size) and was surrounded by rotten wood material.

Millipedes are the group of animal which have many legs. However, the hatchlings have normally no more than three pairs, like insects. A series of molting in the millipede are necessary for becoming adult (Enghoff, 1993).

The post embryonic development has been named as anamorphosis by Haase (1880) for centipede study and then was applied for millipede study by Latzel (1884). The process of anamorphosis was defined at the starting of the first anamorphosis stadium (post-pupoid) followed by Enghoff (1993). In diplopodological term, “stadium” was used instead of “instar” and the change from one stadium to the next stadium of millipede were determined by molting.

Hemianamorphosis is one of the anamorphosis modes which established in giant pill-millipede (Verhoeff, 1905, 1906) and can be separated into two stages. The first stage is anamorphosis stadia, the millipede molts and increases new segment until a certain stadium. Next stage is epimorphosis stadia, the millipede molts but has no new segment.

The European pill millipedes in order Glomerida as far as are known live two to three years and reproduce several times. During that period, molting is carried out in a roughly made nest. Some of the large South African forms, such as *Sphaerotherium giganteum*, probably have a longer life span judged by the scarred appearance of the external skeleton in some of the older specimens (Lawrence, 1984)

Enemy and Defense Mechanisms

Most millipede orders have glands producing repellent chemicals for protecting themselves but the giant pill-millipedes do not. Rather, they can roll into a complete ball (volvation), which is a good mechanism for protection. For example, volvation in genus *Sphaerotherium* provides an effective protection from predators, such as ants, birds and mice. However, their exoskeleton is not hard enough to provide sufficient protection against being thrown at rocks, such as by mongoose (Eisner and Davis, 1967). The known Thai giant pill-millipedes predators are birds such as *Pitta gurneyi* and beetles such as *Mouhotia batesi* (Aratrakorn and Wiwatwitaya, personal communication). In addition to defence from predators, volvation may decrease energy, air and food requirements, reduce water loss in the dry season and also protect the millipedes from flooding (Lawrence, 1984; Hopkin and Read, 1992).

CHAPTER III

DIVERSITY AND TAXONOMIC STATUS OF FAMILY ZEPHRONIIDAE IN NAN PROVINCE

Introduction

Southeast Asian region has been determined to be the biodiversity hotspot areas because there are high number of endemic species and diverse habitats. However, this region has been threatened from habitat lost (Myers *et al*., 2000). Certainly, the habitat lost affects to the declines of number of species and population density in each organism including millipedes. There are a few scientific data concerning millipedes in this region and most of them are waiting for discovery. The giant pill-millipede belonging to family Zephroniidae is mainly distributed in Southeast Asia and many new species are expected to be found. (Jeekel, 1974, 2001a; Hoffman, 1982; Shelley, 1999; Wesener and VandenSpiegel, 2009). Therefore, their taxonomic status and ecology should be urgently investigated for conservation planning.

Thailand locates at the center of Southeast Asia, presenting various forest types such as mangrove forest, deciduous dipterocarp forest, mixed deciduous forest, tropical evergreen forest, coniferous forest and etc. Enghoff (2005) reviewed the Thai millipedes and found that 105 millipede species were recorded from a few areas of Thailand and had not covered all above habitat types. Recently, the number of millipede species has been increasing more than 50% of Enghoff's report by the extensive survey; and most of them are the millipedes in superorder Juliformia and order Polydesmida (Stoev *et al.,* 2007; Enghoff *et al.,* 2007; Golovatch *et al.,* 2009, 2011a, 2011b; Pimvichai *et al.,* 2009a, 2009b, 2010, 2011a, 2011b; Likhitrakarn *et al.,* 2010a, 2010b, 2010c, 2011; Decker, 2010). To date, only one species of the giant pill-millipedes from eastern Thailand, *Zephronia siamensis* Hirst (1907) was reported (Jeekel, 2001a; Enghoff, 2005).

This work is the first step of taxonomic study in the giant pill-millipedes family Zephroniidae collected during 2009-2011 from Nan Province, Thailand, including their dichotomous key.

Material and Methods

Field surveys were conducted during rainy season when millipedes are more active than at other times of the year in different forest types of Nan Province during 2009-2011 (Table 3.1, Fig. 3.1). Handling capture with 1-hour time limit was used to collect giant pill-millipedes by two persons in each locality. Locality, habitat type and ecological data at each sampling time such as air temperature, relative humidity, soil surface temperature, slope and altitude were recorded.

The specimens were preserved in 70% ethanol for morphological study. Each sample was compared with the original descriptions of millipedes from Burma (Pocock, 1890a, 1890b; Attems, 1936), Vietnam (Pocock, 1895; Verhoff, 1924; Attems, 1936, 1938, 1953), Cambodia (Attems, 1953), Malaysia (Pocock, 1890b, 1895; Silvestri, 1895; Hirst, 1907; Jeekel, 1951) and Singapore (Pocock, 1895; Hirst, 1907; Verhoff, 1910). Specimens were deposited as the collection in the Chulalongkorn University Museum of Zoology.

The giant pill-millipedes were measured during rolled-up using Wongthamwanich *et al*. (2012) method (Fig. 3.4). Morphological character terms follow Van den Spiegel *et al*. (2002) and Wesener and Sierwald (2005b). Specimens were dissected and the body parts were removed following the method of Wesener and Sierwald (2005a). The following characters of each sex were carefully examined for distinguishing species:

Males: -the first leg pair with stigmatic plate
-genital opening on the second leg pair
-the ninth leg pair
-posterior section of the seventh tergite
-anterior telopod and posterior telopod

Females: -genital opening on the second leg pair
-subanal plate

Drawings were made with a camera lucida mounted on an Olympus SZH 10 stereomicroscope. Close up digital photos were taken with an Olympus DP20 camera mounted on an Olympus S261 stereo microscope.

SEM preparation: specimens from Sichang Island (Chonburi Province), Chulalongkorn University Forestry and Research Station (Wiang Sa District, Lai-Nan Sub-district) and Pang Hi Village (Song Khwae District, Na Rai Luang Sub-district) were mounted on aluminum stubs using carbon tape, dehydrated using a vacuum type desiccator and observed under a JEOL JSM-6510A Scanning Electron Microscope. Other specimens were mounted on aluminum stubs, dehydrated using air dry, coated with gold and observed under a JEOL JSM-5410LV Scanning Electron Microscope.

Table 3.1 Localities of giant pill-millipede samples in Nan Province

Site	District	Forest type	Map Datum WGS 84: UTM 47Q	
			N	E
1	Wiang Sa	Mixed deciduous forest	2053452	690270
2	Wiang Sa	Mixed deciduous forest	2050077	676116
3	Chiang Klang	Mixed deciduous forest	2136627	700833
4	Phu Phiang	Deciduous Dipterocarp forest	2074360	696000
5	Na Noi	Deciduous Dipterocarp forest	2018653	680264
6	Song Khwae	Evergreen forest	2145543	678004
7	Bo Kluea	Evergreen forest	2123388	731170
8	Thung Chang	Mixed deciduous forest	2144603	699576
9	Na Noi	Hill evergreen forest	2022084	658201
10	Na Muen	Mixed deciduous forest	2006231	675921
11	Ban Luang	Mixed deciduous forest	2087445	660321
12	Wiang Sa	Dry evergreen forest	2035759	709777
13	Tha Wang Pha	Hill evergreen forest	2114413	673983
14	Song Khwae	Hill evergreen forest	2140919	664808

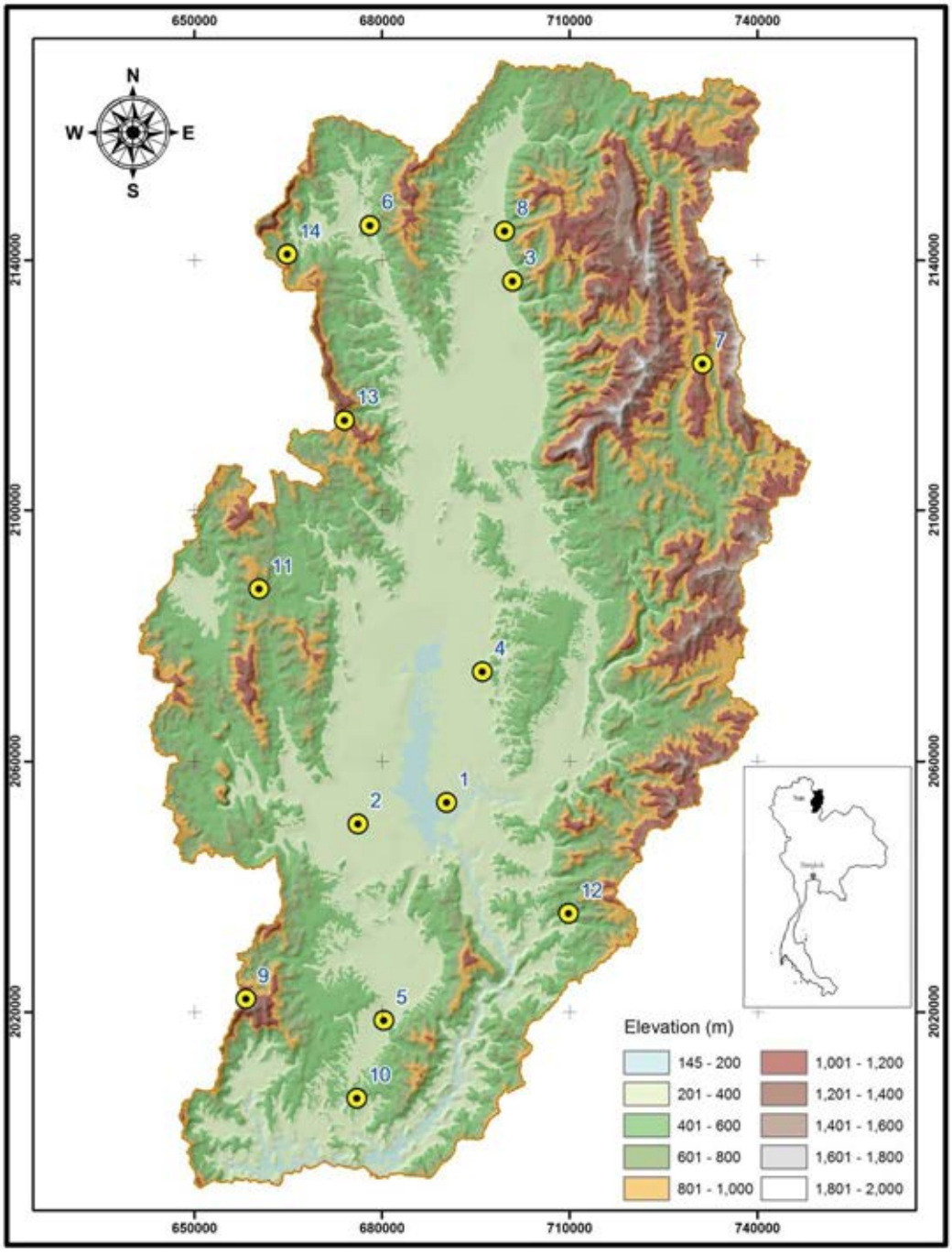

Figure 3.1 Sampling sites of the giant pill-millipedes in Nan Province. Arabic numbers indicate the localities of the giant pill millipede samples.

Results

One new species and 14 morphospecies of the giant pill-millipedes were found in various forest types of Nan Province during 2009-2011. Among these, the new species and five morphospecies belong to genus *Sphaerobelum*, seven morphospecies are in genus *Zephronia* and the other two morphospecies are in the same unknown genus (Table 3.2, Fig. 3.2). The summary characters of these millipedes were provided in table 3.3.

Taxonomy:

Family Zephroniidae Gray, 1843

Subfamily Zephroniinae Gray, 1843

Tribe Zephroniini Jeekel, 2001

Key to genera of the giant pill millipede family Zephroniidae in Nan Province

1. Antenna club-shaped, distal segment enlarged and rounded; second process of posterior telopods posteriorly distally swollen, without membranous lobe…….. 2
- Antenna club-shaped, distal segment enlarged, elliptical and axe shaped; second process of posterior telopods weakly curve with 2 membranous lobes..... *Zephronia*
2. Posterior telopods consisted of 4 podomeres……..... *Sphaerobelum*
- Posterior telopods consisted of 3 podomeres……..Unknown

Table 3.2 Localities of the giant pill-millipedes in Nan Province. Abbreviations: **EF** = evergreen forest; **DEF** = dry ever green forest; **HEF** = hill evergreen forest; **MDF** = mixed deciduous forest; **DDF** = dry deciduous forest.

Name	Site	District	Sub-district	Map Datum WGS 84: UTM 47Q		Elevation (m)	Slope	Forest type	Microhabitats
				N	E				
Sphaerobelum trumcatum	6	Song Khwae	Na Rai Luang	2145543	678004	443	60	EF	close to water way, under leaf litter or in soil socket, near tree base
Sphaerobelum sp.1	7	Bo Kluea	Dong Phaya	2123388	731170	715	0	EF	close to river, under seedling
Sphaerobelum sp.2	7	Bo Kluea	Dong Phaya	2123388	731170	715	0	EF	close to river, under large tree base covered by litter
Sphaerobelum sp.3	9	Na Noi	Santa	2022084	658201	1229	60	HEF	close to water way, under seedling
Sphaerobelum sp.4	13	Tha Wang Pha	Sri Phum	2114413	673983	1163	0	HEF	close to water way, on ground surface covered by leaf litter
Sphaerobelum sp.5	14	Song Khwae	Yod	2140919	664808	839	0	HEF	on ground surface covered by leaf litter, near tree base
Zephronia sp.1	1	Wiang Sa	Lai-Nan	2053452	690270	216	0	MDF	under leaf litter; near bamboo clump; close to termite mound
Zephronia sp.2	2	Wiang Sa		2050077	676116	250	0	MDF	in soil socket, near bamboo clump, close to termite mound
Zephronia sp.3	3	Chiang Klang	Puea	2136627	700833	420	0	MDF	in soil socket under leaf litter close to bamboo clump
Zephronia sp.4	4	Phu Phiang	Nam Kian	2074360	696000	293	0	DDF	under leaf litter, near bamboo clump or tree base
Zephronia sp.5	5	Na Noi	Sathan	2018653	680264	320	30	DDF	near tree base, under leaf litter
Zephronia sp.6	8	Thung Chang		2144603	699576	467	10	MDF	in soil socket under leaf litter covered by bamboo
Zephronia sp.7	12	Wiang Sa		2035759	709777	396	0	DEF	on ground surface, close to bamboo clump
Unknown sp.1	10	Na Muen	Na Tanung	2006231	675921	580	60	MDF	under leaf litter; near bamboo clump
Unknown sp.2	11	Ban Luang	Suat	2087445	660321	737	30	MDF	under leaf litter; near bamboo clump and termite mound

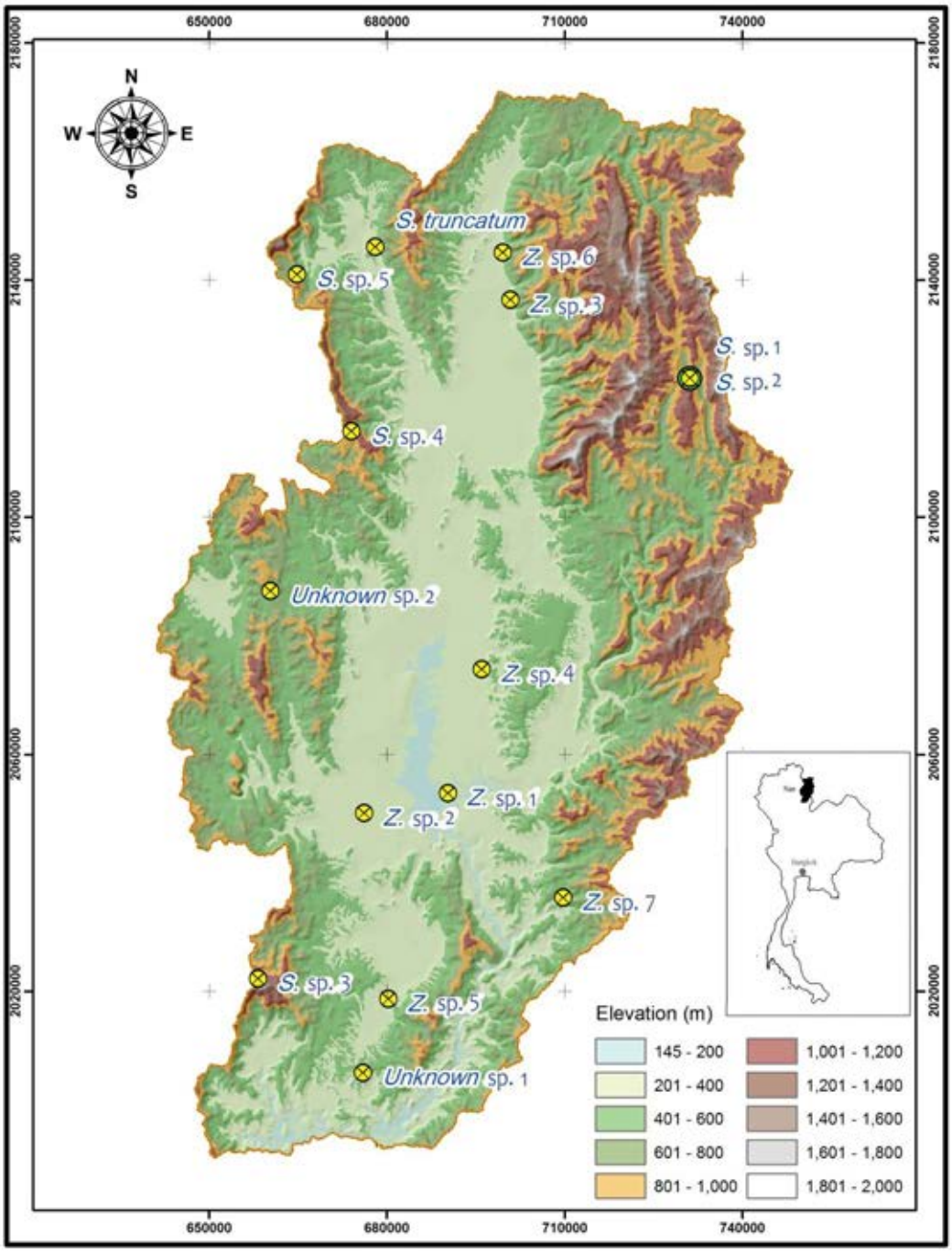

Figure 3.2 Distribution of the giant pill-millipedes in family Zephroniidae in Nan Province.

Genus *Sphaerobelum* Verhoeff, 1924

Type species: *Sphaerobelum clavigerum* Verhoeff, 1924

Diagnosis: Characteristic combination of known species including with new specimen could be distinguished the unique character of genus Sphaerobelum as followed: posterior telopods consist of four podomere with a posteriorly swollen apical process on the second podomere; Antennae club shaped, distal rounded.

Distribution: Vietnam and Thailand (Fig. 3.3).

Key to species of the giant pill millipede genus *Sphaerobelum* in Nan Province

1. Posterior margin normal, without curve feature……2
- Posterior margin with curve feature…….....….3
2. Marginal setae with 2 regular rows, length half time of outer zone; outer zone smooth; lower area of intersegmental membrane with setae; tergite black……*S.* sp.1
- Marginal setae with 3-4 irregular rows beyond margin; outer zone with sparsely triple spines; lower area of intersegmantal membrane without setae; tergite dark yellowish and black posterior margin.....……...……..…*S.* sp.2
3. Endotergum with regularly serrate margin; gonopore bearing small penis……..*S.* sp.5
- Endotergum with regular square-wavy margin; gonopore without penis……4
4. Intersegmental membrane without cone, setae and dimple; marginal setae length approximately two third of outer zone ……*S. truncatum* **n. sp.**
- Intersegmental membrane with setae or dimple; marginal setae length less than two third of outer zone ……5
5. Marginal setae with 2 regular rows, length half time of outer zone; round cuticular impression……..……S. sp.4
- Marginal setae with 3 irregular rows, length one-third of outer zone; without cuticular impression……..…*S.* sp.3

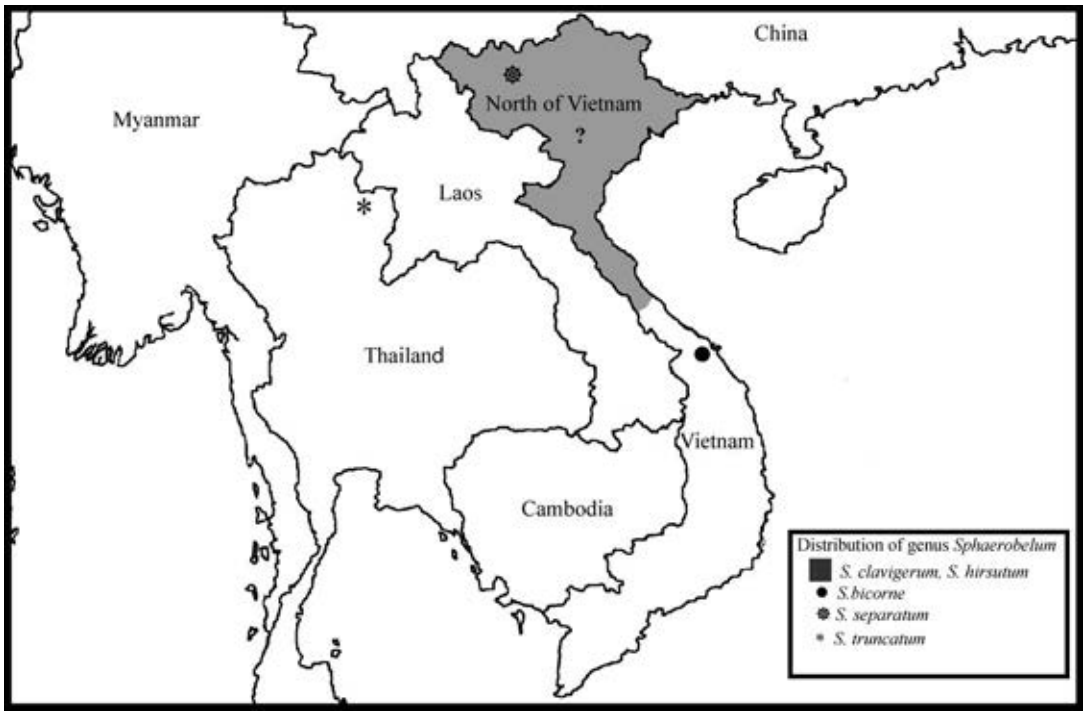

Figure 3.3 Known distribution of giant pill-millipedes of the genus *Sphaerobelum* (Wongthamwanich *et al*., 2012).

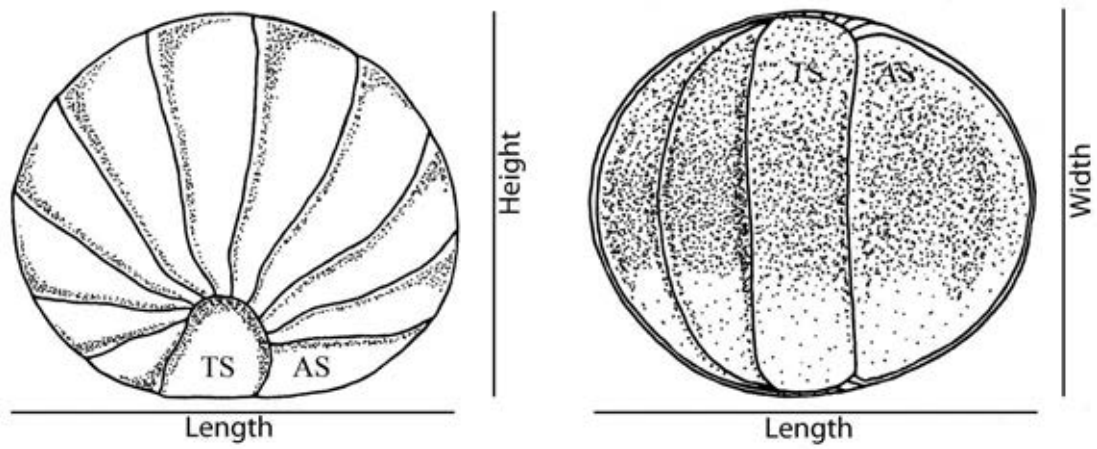

Figure 3.4 Measurements of a volvated giant pill-millipede body size. Abbreviations: TS = thoracic shield; AS = anal shield (Wongthamwanich *et al*., 2012).

Sphaerobelum truncatum Wongthamwanich, n. sp.

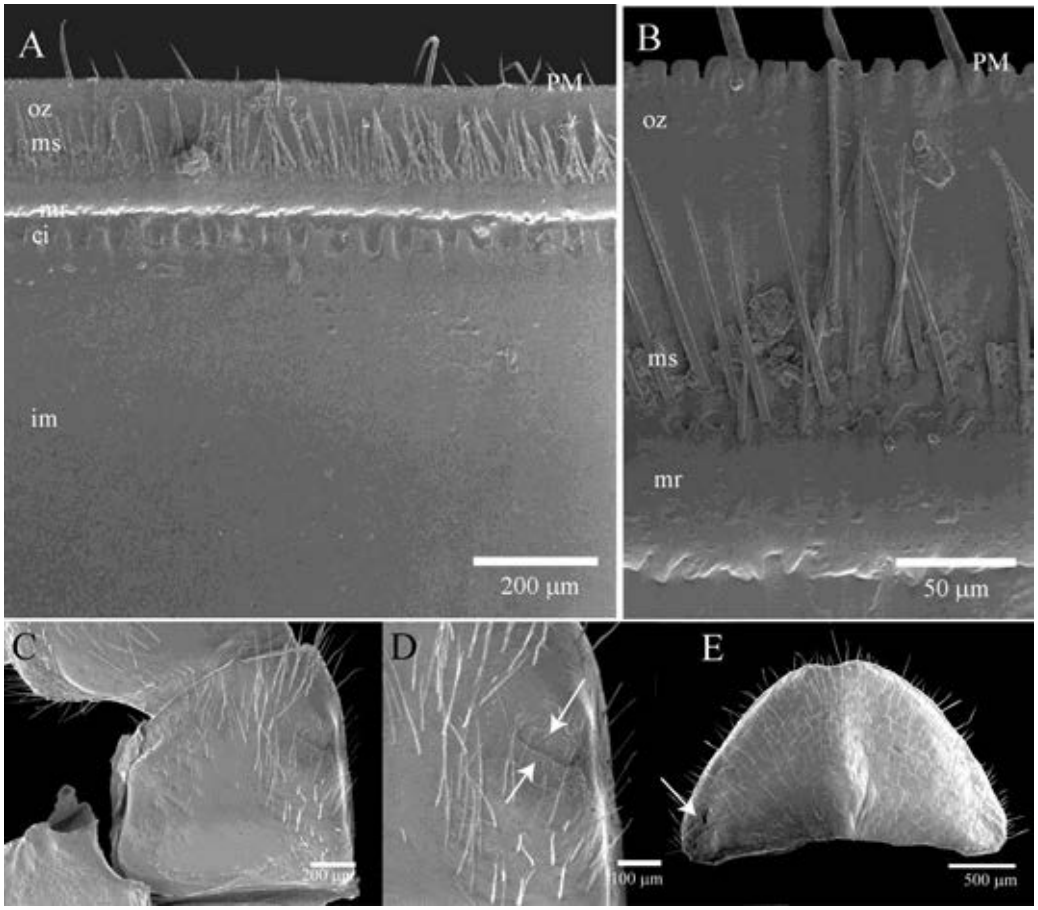

Figure 3.5 *Sphaerobelum truncatum* **n. sp.**, holotype, endotergum, SEM, **A**: overview; **B**: posterior margin; **C-D**: holotype, male gonopore on second coxa, arrows point to gonopore; **E**: female paratype, subanal plate with ribs, arrow points to ribs. Abbreviations: **PM** = posterior margin; **oz** = outer zone; **ms** = marginal setae; **mr** = marginal ridge; **ci** = cuticular impressions; **im** = intersegmental membrane.

Material examined: Holotype male, **CUMZ 2010.11**, Thailand, Nan Province, Song Khwae District, Na Rai Luang Sub-district, Pang Hi Village; secondary forest; 47 Q 2145543 N, 678004 E; coll. N. Wongthamwanich; hand collecting; 22 August 2010. Paratypes: 4 males, **CUMZ 2010.12–15**, 4 females, **CUMZ 2010.16–19**, 1 male, **FMNH-INS 0000 072 674**, 1 female, **FMNH-INS 0000 072 673**, 1 male, **ZFMK Myr 001**, 1 female, **ZFMK Myr 002**, same data as holotype.

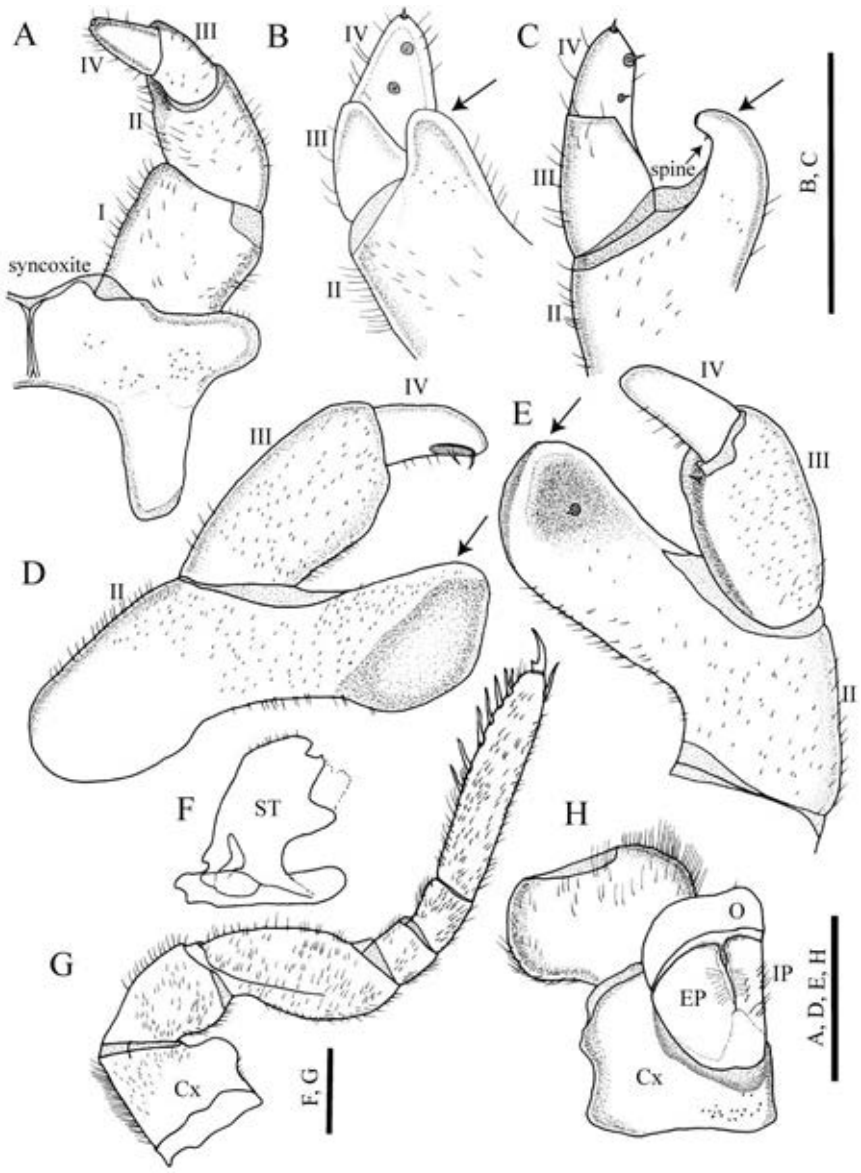

Figure 3.6 *Sphaerobelum truncatum* **n. sp.**, A-G holotype, H female paratype, drawing, **A**: right anterior telopod, anterior view; **B**: last three podomeres of right anterior telopod, posterior view; **C**: last three podomeres of right anterior telopod, lateral view; **D**: last three podomeres of right posterior telopod, posterior view; **E**: last three podomeres of right posterior telopod, anterior view; **F**: stigmatic plate of 9th left leg; **G**: 9th left leg, posterior view; **H**: second right coxa with vulva, posterior view. Arrows point to the second podomere process. Abbreviations: **Cx** = coxa; **ST** = stigmatic plate; **O** = operculum; **EP** = external plate of vulva; **IP** = mesal plate of vulva. Roman numbers refer to number of podomere. Scale bars = 1 mm.

Description:

Measurements: Sizes of volvated male (for epimorphosis stadia, Figs. 3.4A, B): length (tergite 5–tergite 11 or 12) 12.1–13.9 mm, width (tergite 7) 10.2–12.6 mm and height (thoracic shield–tergite 8) 10.7–12.6 mm. Sizes of volvated female: length 13.0–17.6 mm, width 11.5–15.2 mm and height 11.5–15.4 mm.

Habitus: overall shape elliptical, tapering slightly from sixth tergite towards head.

Coloration: head dark brown, collum, thoracic shield, tergite and anal shield black. Antennae and legs light yellow.

Endotergum (Figs. 3.5A, B): with a regularly 'square-wavy' margin (Fig. 3.5B), outer zone with three rows of irregular marginal setae not reaching posterior margin. A single row of small elliptical cuticular impression present next to marginal ridge. Intersegmental membrane smooth, without cones or setae (Fig. 3.5A).

Anal shield: densely covered with long setae; round in both sexes. Inner side with three or four striae. Ventral side with one long black locking carina.

Legs: 9th leg pair with seven ventral spines and one apical spine on tarsus, femur with one long ridge (Fig. 3.6G). Femur of 9th leg pair 2.0 times longer than wide, tarsus 4.8 times longer than wide.

Stigmatic plate of first leg (Fig. 3.31): rounded, short and weakly curved, but forming a steep angle towards the coxa.

Female vulva (Fig. 3.32): consists of two basal plates which are fused proximally and divided distally. Operculum pointed, basal part of operculum surrounding apical part of basal plates, distally protruding above coxa to basal half of prefemur. Vulva covers half (1/2) of coxa width, vulva is one-third (1/3) longer than coxa.

Subanal plate (Fig. 3.5E): brown, semicircular with a central shallow notch, laterally with four rib-like structures.

Male gonopore (Fig. 3.5C, D): covered by an undivided sclerotized plate.

Anterior telopods (Figs. 3.6A–C): syncoxite with small spines, telopodite consist of four podomeres, all podomeres covered by long setae. First podomere width equals height. Second podomere with posterior lobe-like, curved process with rounded edges; process protruding up to end of third podomere; anterior side of process with a single spine at inner margin. Third podomere distally truncate. Fourth podomere as long as third podomere, with three sclerotized spines located on small thin sclerotized fields, one spine at apex and the other two located on posterior side. Sclerotized teeth absent.

Posterior telopods (Figs. 3.6D, E): telopodite consist of four podomeres. First podomere parallelogram-shaped. Second and third podomeres dominated by short setae, margins with long setae. Process of second podomere weakly curved, distally glabrous, posteriorly apically enlarged and swollen (Fig. 3.6D), anteriorly apically concave, spatulate, with a single sclerotized spine (Fig. 3.6E). Movable finger consist of third podomere and small fourth podomere, slightly curved. Third podomere at inner margin with one small light colored spine, without any crenulated teeth. Fourth podomere at inner margin with two small sclerotized spines located in single brown sclerotized field.

Sphaerobelum sp.1

Material examined: 1 male, CUMZ 2011.01 and 3 juveniles, CUMZ 2011.02-4, Thailand, Nan Province, Bo Kluea District, Dong Phaya Sub-district, Sa Pan Village; evergreen forest; 47 Q 2123388 N, 731170 E.; coll. Wongthamwanich, N.; hand collecting; August 21, 2011.

Distribution: Known only from collection locality.

Description:

Measurements: Sizes of volvated male: length 14.7 mm, width 13.1 mm and height 13 mm.

Habitus: overall shape elliptical.

Coloration: Head dark brown. Collum, thoracic shield, tergite and anal shield black. Antennae and legs light yellow.

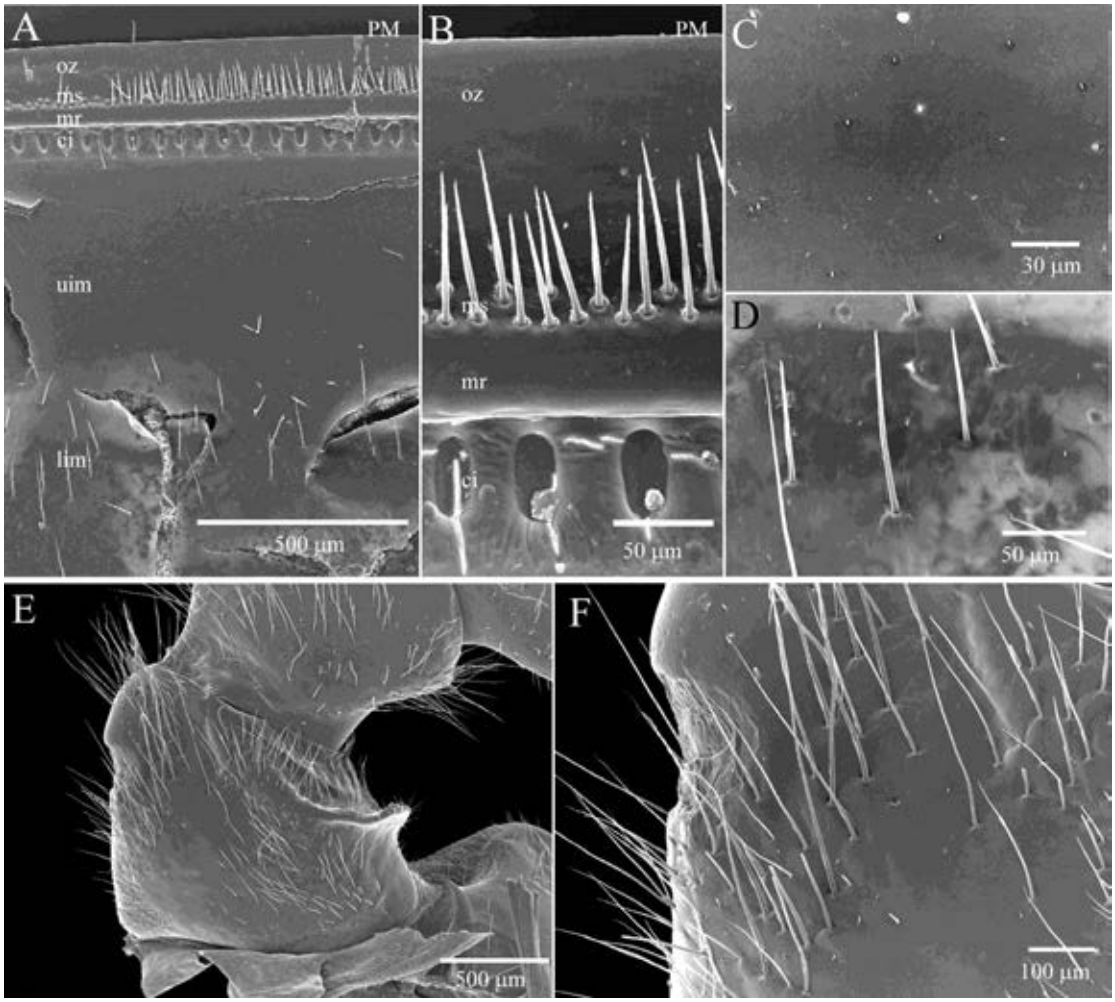

Figure 3.7 *Sphaerobelum* sp.1, male endotergum, SEM, **A**: overview; **B**: posterior margin; **C**: upper intersegmental membrane; **D**: lower intersegmental membrane; **E-F**: male gonopore on second coxa.

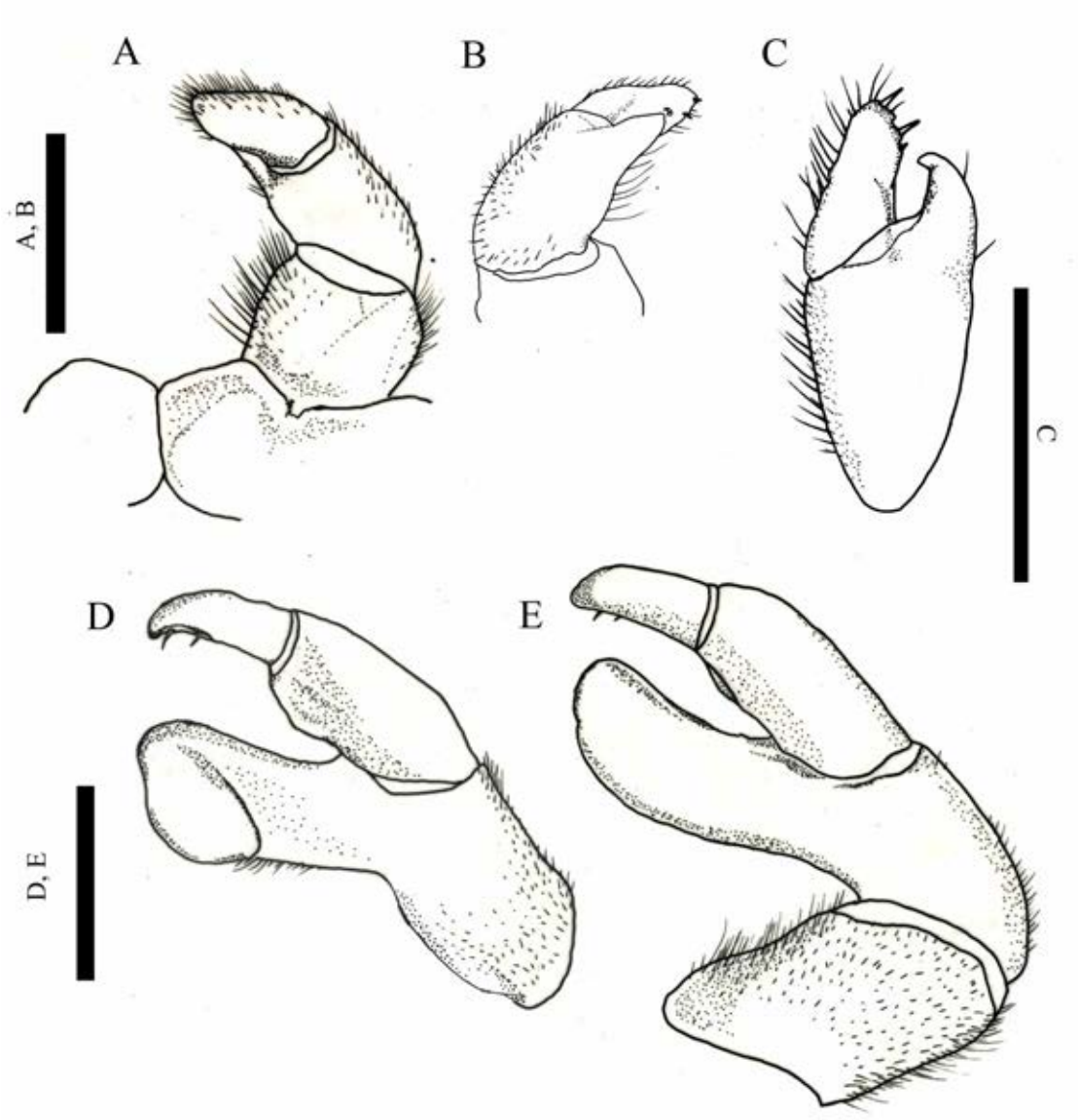

Figure 3.8 *Sphaerobelum* sp.1, drawing, **A**: right anterior telopod, anterior view; **B**: last three podomeres of right anterior telopod, posterior view; **C**: last three podomeres of right anterior telopod, lateral view; **D**: last three podomeres of left posterior telopod, posterior view; **E**: last three podomeres of right posterior telopod, anterior view. Scale bars = 1 mm.

Endotergum (Figs. 3.7A-D): with a smooth margin (Figs. 3.7A, B), outer zone with two rows of regular marginal setae of half posterior margin length. A single row of small elliptical cuticular impression present next to marginal ridge (Fig. 3.7B). Intersegmental membrane covered sparsely with small conical spines (Fig. 3.7C), followed by sparsely long setae (Fig. 3.7D).

Legs: 9th leg pair with 10 ventral spines and one apical spine on tarsus, femur with one long ridge.

Stigmatic plate of first leg (Fig. 3.31): rounded, short and weakly curved.

Anal shield: Ventral side with one long black locking carina

Male gonopore (Figs. 3.7E, F): covered by an undivided sclerotized plate.

Anterior telopods (Figs. 3.8A-C): telopodite consist of four podomeres, all podomeres covered by long setae. First podomere width equals height. Second podomere with posterior lobe-like, curved process with rounded edges; process protruding up to half length of third podomere; anterior side of process without spine. Fourth podomere as long as third podomere, with two sclerotized spines located on small thin sclerotized fields, one spine at apex and another one located on posterior side. Sclerotized teeth are absent.

Posterior telopods (Figs. 3.8D, E): telopodite consist of four podomeres. First podomere is parallelogram-shaped. Second and third podomeres dominated by short setae, margins with long setae. Process of second podomere is weakly curved, distally glabrous, posteriorly apically enlarged and swollen, anteriorly apically concave, spatulate, with a single sclerotized spine. Movable finger consist of third podomere and small fourth podomere, slightly curved. Third podomere at inner margin with one small light colored spine, without any crenulated teeth. Fourth podomere slender with slightly sharped apex, inner margin with two small membranous spines located in single brown sclerotized field.

Sphaerobelum sp.2

Material examined: 10 males, **CUMZ 2011.05-14** and 10 females, **CUMZ 2011.15-24**, Thailand, Nan Province, Bo Kluea District, Dong Phaya Sub-district, Sa Pan Village; evergreen forest; 47 Q 2123388 N, 731170 E; coll. N. Wongthamwanich; hand collecting; August 21, 2011.

Distribution: Known only from collection locality.

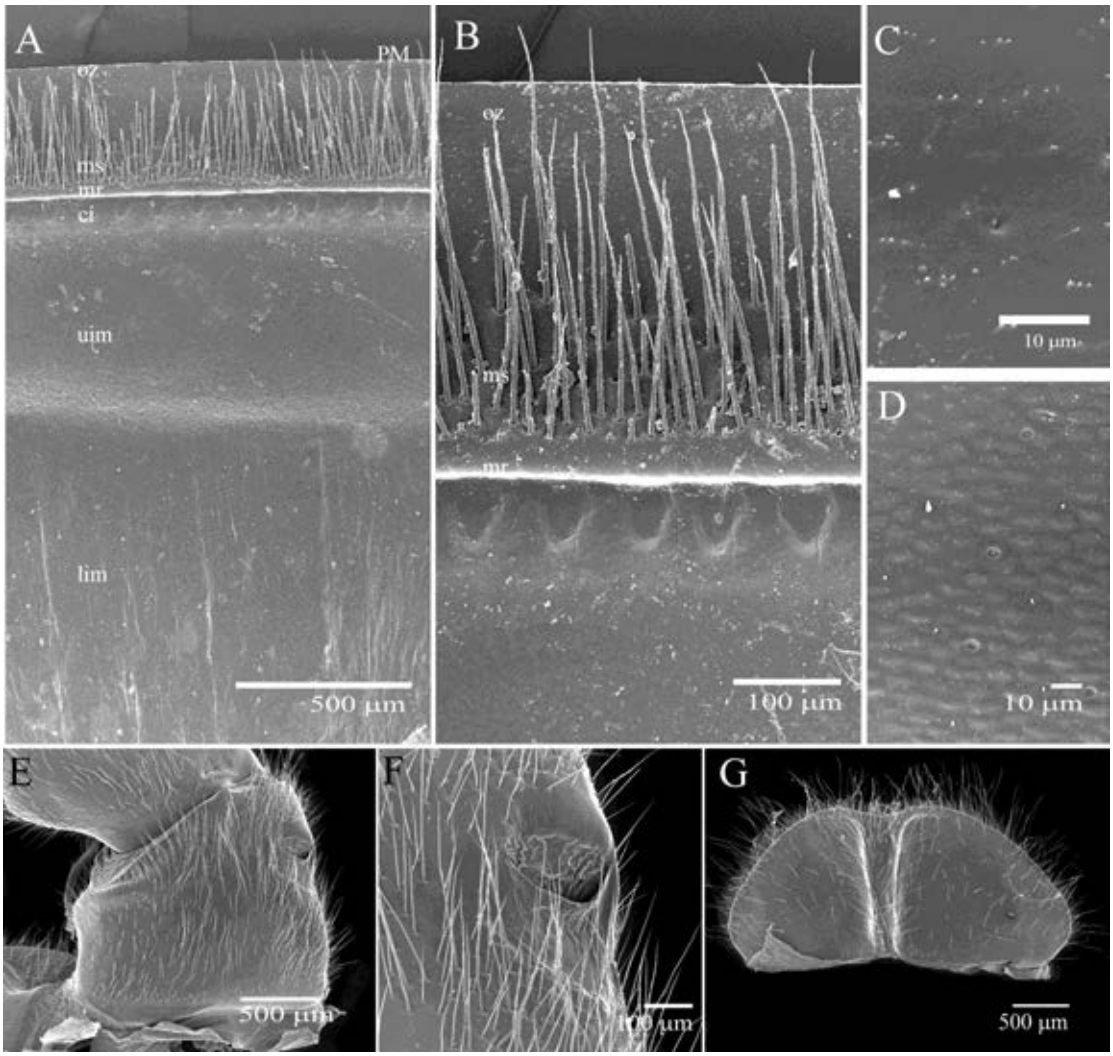

Figure 3.9 *Sphaerobelum* sp.2, male, endotergum, SEM, **A**: overview; **B**: posterior margin; **C**: upper intersegmental membrane; **D**: lower intersegmental membrane; **E-F**: male gonopore on second coxa; **G**: female, subanal plate.

Description:

Measurements: Sizes of volvated male: length 19.3 mm, width 17.2 mm and height 17.6 mm. Sizes of volvated female: length 19.9 mm, width 17.6 mm and height 16.8 mm.

Habitus: overall shape elliptical with minute setae.

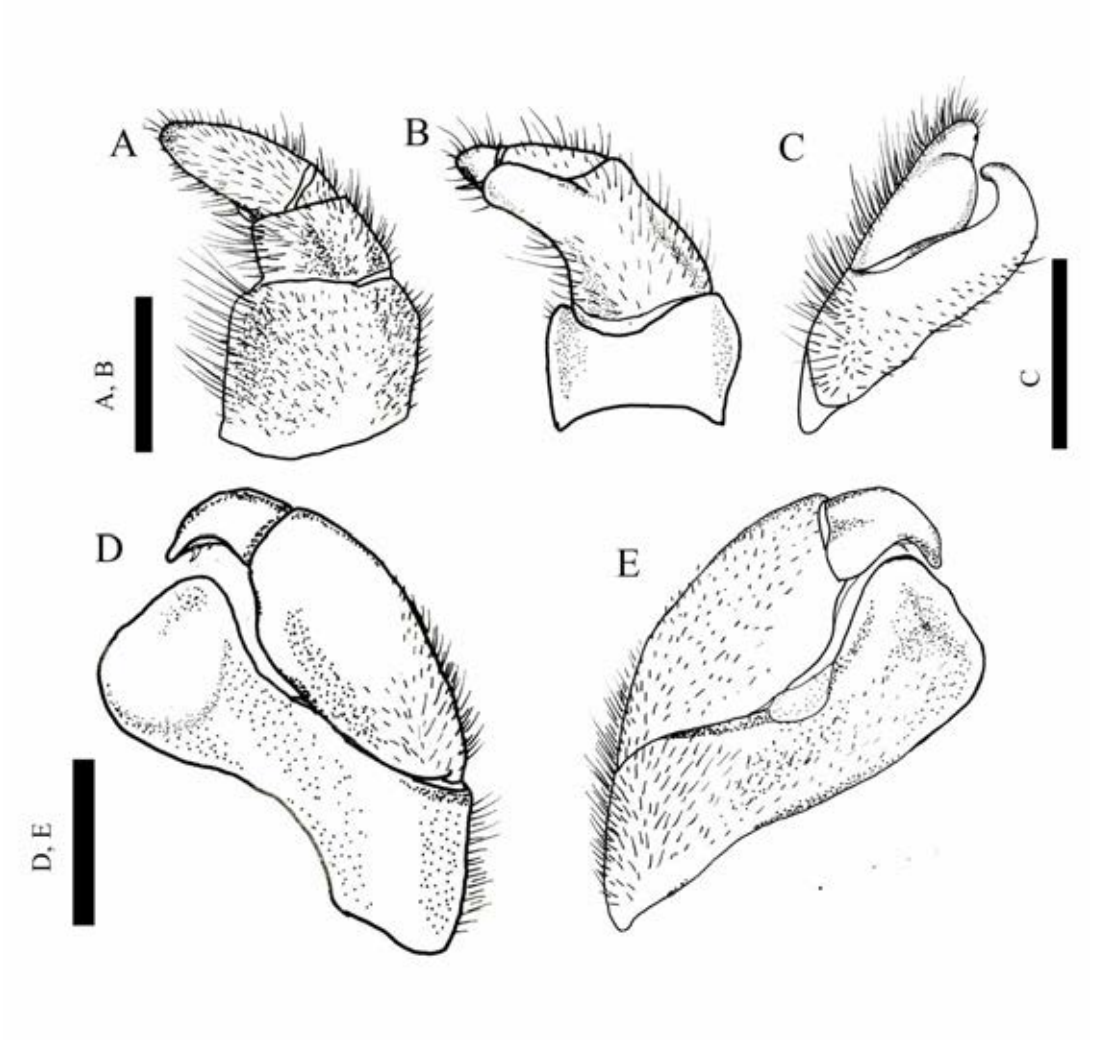

Figure 3.10 *Sphaerobelum* sp.2, drawing, **A**: right anterior telopod, anterior view; **B**: left anterior telopod, posterior view; **C**: last three podomeres of right anterior telopod, lateral view; **D**: last three podomeres of left posterior telopod, posterior view; **E**: last three podomeres of left posterior telopod, anterior view. Scale bars = 1 mm.

Coloration: Dark-yellowish with blackish posterior margin. Antennae and legs yellow.

Endotergum (Figs. 3.9A-D): with a smooth margin (Fig. 3.9A, B), outer zone with three to four rows of irregular marginal setae beyond posterior margin and covered by densely triple spines (Fig. 3.9C). A single row of small round cuticular impression is presented next to marginal ridge. Intersegmental membrane covered sparsely with dimple and small conical spines (Fig. 3.9D).

Anal shield: Ventrally with one short locking carina.

Legs: 9th leg pair with six ventral spines and one apical spine on tarsus, femur with one long ridge.

Stigmatic plate of first leg (Fig. 3.31): rhomboidal.

Female vulva (Fig. 3.32): consists of two basal plates which are fused proximally and divided distally. Operculum sharped, basal part of operculum surrounding apical part of basal plates, distally protruding above coxa to basal half of prefemur. Vulva covers half (1/2) of coxa width, vulva is one-third (1/3) longer than coxa.

Subanal plate (Fig. 3.10G): light-brown, semielliptical with a central shallow notch.

Male gonopore (Figs. 3.10E, F): covered by an undivided sclerotized plate.

Anterior telopods (Figs. 3.10A-C): syncoxite with small spines, telopodite consist of four podomeres, all podomeres covered by long setae. First podomere width equals height. Second podomere with posterior lobe-like, curved process with rounded edges; process protruding up to end of third podomere; anterior side of process with a single spine at inner margin. Third podomere distally truncate. Fourth podomere as long as third podomere, with three sclerotized spines located on small thin sclerotized fields, one spine at apex and the other two located on posterior side. Sclerotized teeth are absent.

Posterior telopods (Figs. 3.10D, E): telopodite consist of four podomeres. First podomere is parallelogram-shaped. Second and third podomeres dominated by short setae, margins with long setae. Process of second podomere is curved, distally glabrous, posteriorly apically enlarged and swollen, anteriorly apically concave, spatulate, with a single sclerotized spine. Movable finger consist of third podomere and small fourth podomere, slightly curved. Third podomere enlarged, inner margin with one small light colored spine, without any crenulated teeth. Fourth podomere curved with sharped apex, inner margin with two small sclerotized spines located in single brown sclerotized field.

Sphaerobelum sp.3

Material examined: 1 male, **CUMZ 2011.25** and 2 females, **CUMZ 2011.26-27**, Thailand, Nan Province, Na Noi District, Santa Sub-district; evergreen forest; 47 Q 2022084 N, 658201 E; coll. N. Wongthamwanich; hand collecting; September 9, 2010.

Distribution: Known only from collection locality.

Description:

Measurements: Sizes of volvated male: length 14.8 mm, width 13.2 mm and height 13.1 mm. Sizes of volvated female: length 15.2 mm, width 13.9 mm and height 13.2 mm.

Habitus: overall shape elliptical.

Coloration: Head is black. Collum, thoracic shield, tergite and anal shield are black. Antennae and legs are light yellow.

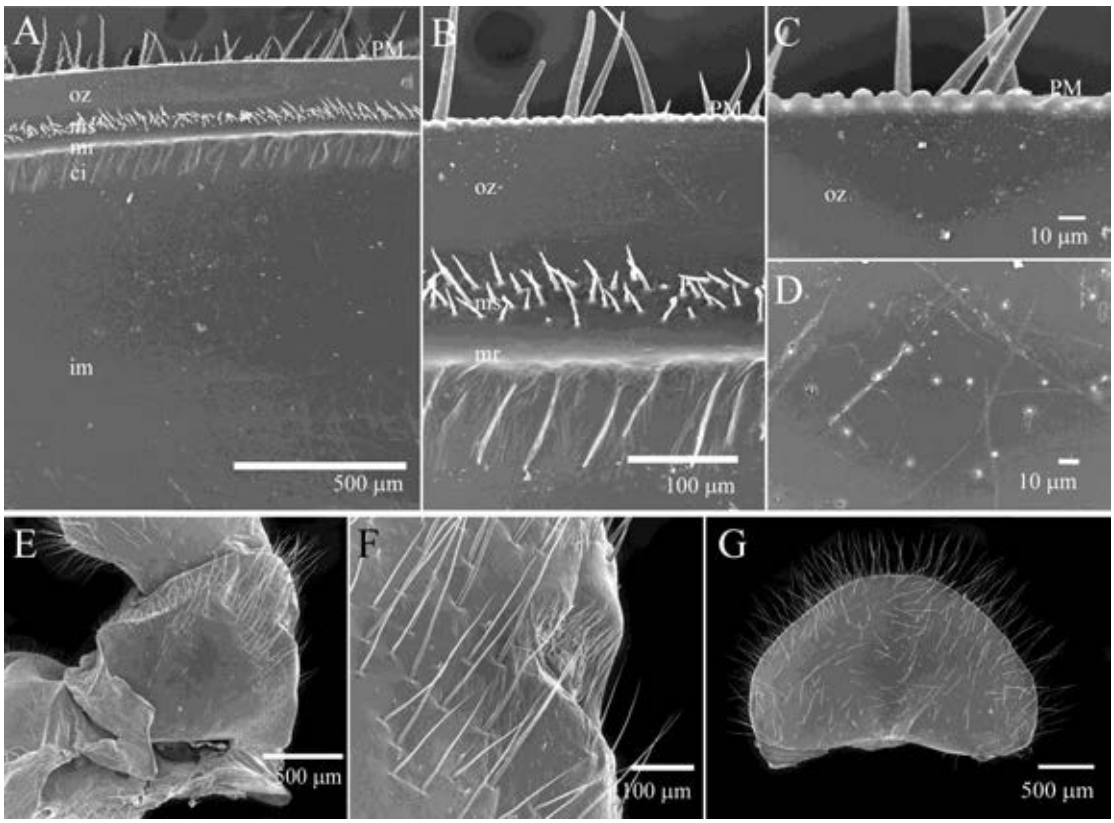

Figure 3.11 *Sphaerobelum* sp.3, male, endotergum, SEM, **A**: overview; **B**: marginal setae; **C**: posterior margin of endotergum; **D**: upper intersegmental membrane; **E-F**: male gonopore on second coxa; **G**: female, subanal plate.

Endotergum (Figs. 3.11A-D): with a regular square-wavy margin (Fig. 3.11C), outer zone with three rows of irregular marginal setae of one third posterior margin length. A row of cuticular impression is absent next to marginal ridge (Fig. 3.11B). Intersegmental membrane covered sparsely with small dimple (Fig. 3.11D).

Legs: 9th leg pair with 9 ventral spines and one apical spine on tarsus, femur with one long ridge.

Stigmatic plate of first leg (Fig. 3.31): overall shape rounded.

Anal shield: Ventral side with one long black locking carina.

Female vulva (Fig. 3.32): Operculum high pointed, basal part of operculum surrounding apical part of basal plates, distally protruding above coxa to basal half of prefemur. Vulva covers half (1/2) of coxa width.

Subanal plate (Fig. 3.11G): brown, semicircular.

Male gonopore (Figs. 3.11E, F): covered by an undivided sclerotized plate.

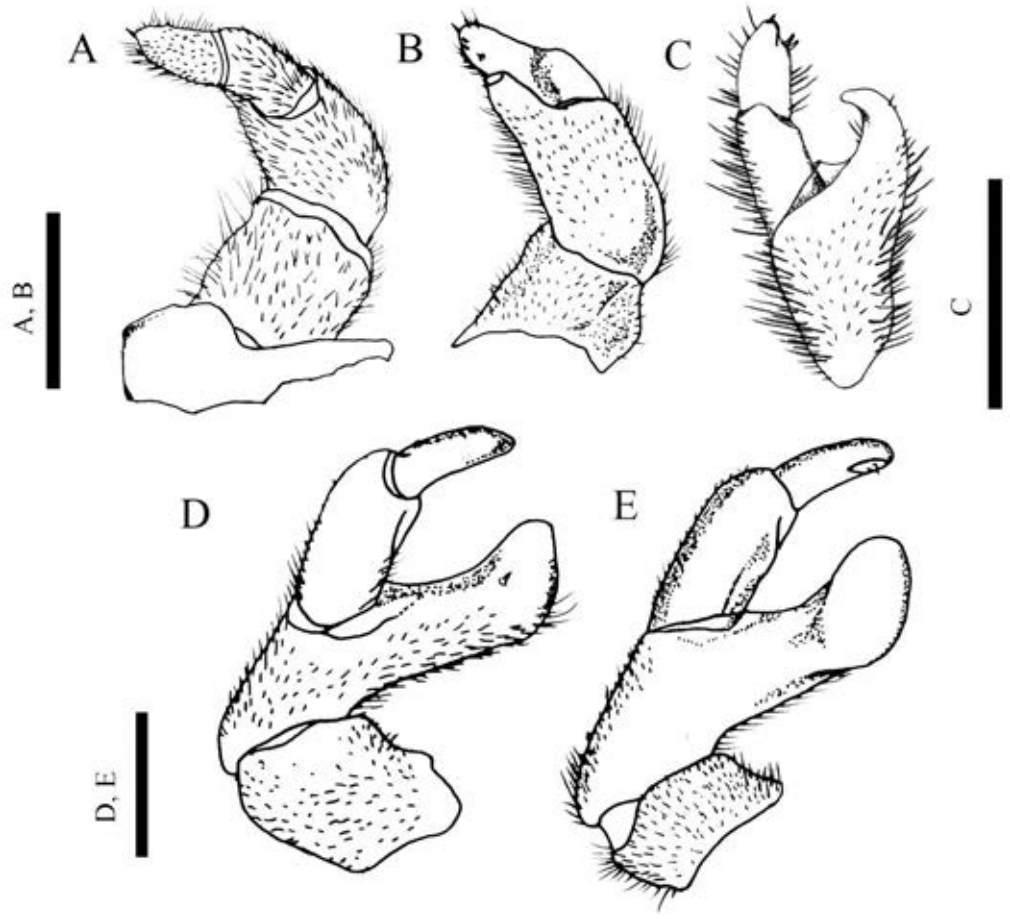

Figure 3.12 *Sphaerobelum* sp.3, drawing, **A**: right anterior telopod, anterior view; **B**: left anterior telopod, posterior view; **C**: last three podomeres of right anterior telopod, lateral view; **D**: last three podomeres of left posterior telopod, anterior view; **E**: last three podomeres of right posterior telopod, posterior view. Scale bars = 1 mm.

Anterior telopods (Figs. 3.12A-C): telopodite consist of four podomeres, all podomeres covered by long setae. First podomere width equals height. Second podomere with posterior lobe-like, curved process with rounded edges; process protruding up to the end of third podomere; anterior side of process without spine. Fourth podomere as long as third podomere, with four sclerotized spines located on small thin sclerotized fields, one spine at apex and the other three spines located on posterior side within two sclerotized fields. Sclerotized teeth are absent.

Posterior telopods (Figs. 3.12D, E): telopodite consist of four podomeres. First podomere is parallelogram-shaped. Second and third podomeres dominated by short setae, margins with long setae. Process of second podomere is weakly curved, distally glabrous, posteriorly apically enlarged and swollen, anteriorly apically concave, spatulate, with a single sclerotized spine. Movable finger consist of third podomere and small fourth podomere, slightly curved. Third podomere at inner margin with one small light colored spine, without any crenulated teeth. Fourth podomere is slender without sharped apex, inner margin with two small membranous spines located in single brown sclerotized field.

Sphaerobelum sp.4

Material examined: 1 juvenile, **CUMZ 2011.28**, Thailand, Nan Province, Tha Wang Pha District, Sri Phum Sub-distric; evergreen forest; 47 Q 2114413 N, 673983 E; coll. N. Wongthamwanich; hand collecting; October 1, 2011.

Distribution: Known only from collection locality.

Description:

Measurements: Juvenile: length 10.2 mm, width at the seventh tergite 9.4 mm, width of thoracic shield 9.0 mm, height of thoracic shield 4.5 mm. Sizes of volvated juvenile: length 11.2 mm, width 9.4 mm and height 9.9 mm.

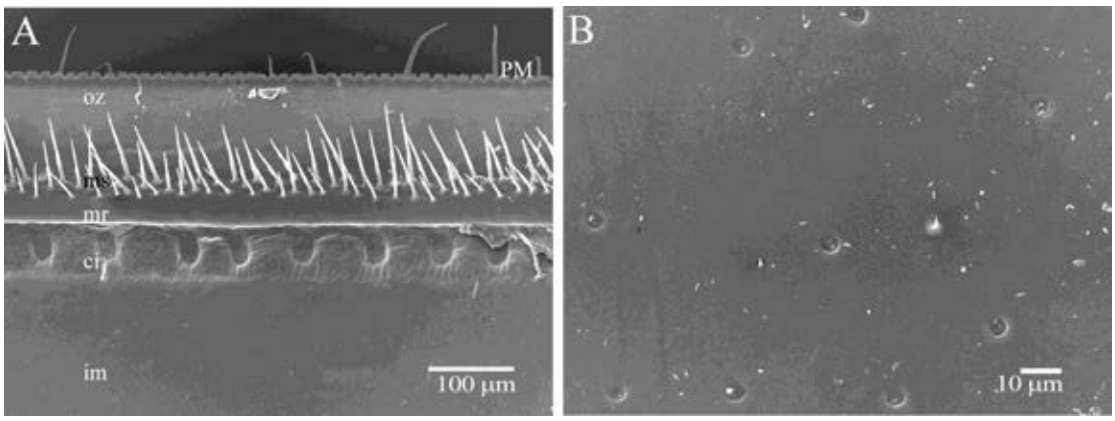

Figure 3.13 *Sphaerobelum* sp.4, male, endotergum, SEM, **A**: overview; **B**: upper intersegmental membrane.

Habitus: overall shape elliptical.

Coloration: Head is black. Collum, thoracic shield, tergite and anal shield are black. Antennae and legs are light yellow.

Endotergum (Figs. 3.13A, B): with a regular square-wavy margin (Fig. 3.13A), outer zone with two rows of regular marginal setae of half posterior margin length. A single row of small oval cuticular impression present next to marginal ridge. Intersegmental membrane covered sparsely with small dimples and spines (Fig. 3.13B).

Anal shield: Ventral side with one long black locking carina.

Sphaerobelum sp.5

Material examined: 6 males, **2011.29-34** and 9 females, **CUMZ 2011.35-43**, Thailand, Nan Province, Song Khwae District, Yod Sub-district, Sa Pan Village; evergreen forest; 47 Q 2140919 N, 664808 E; coll. N. Wongthamwanich; hand collecting; October 1, 2010.

Distribution: Known only from collection locality.

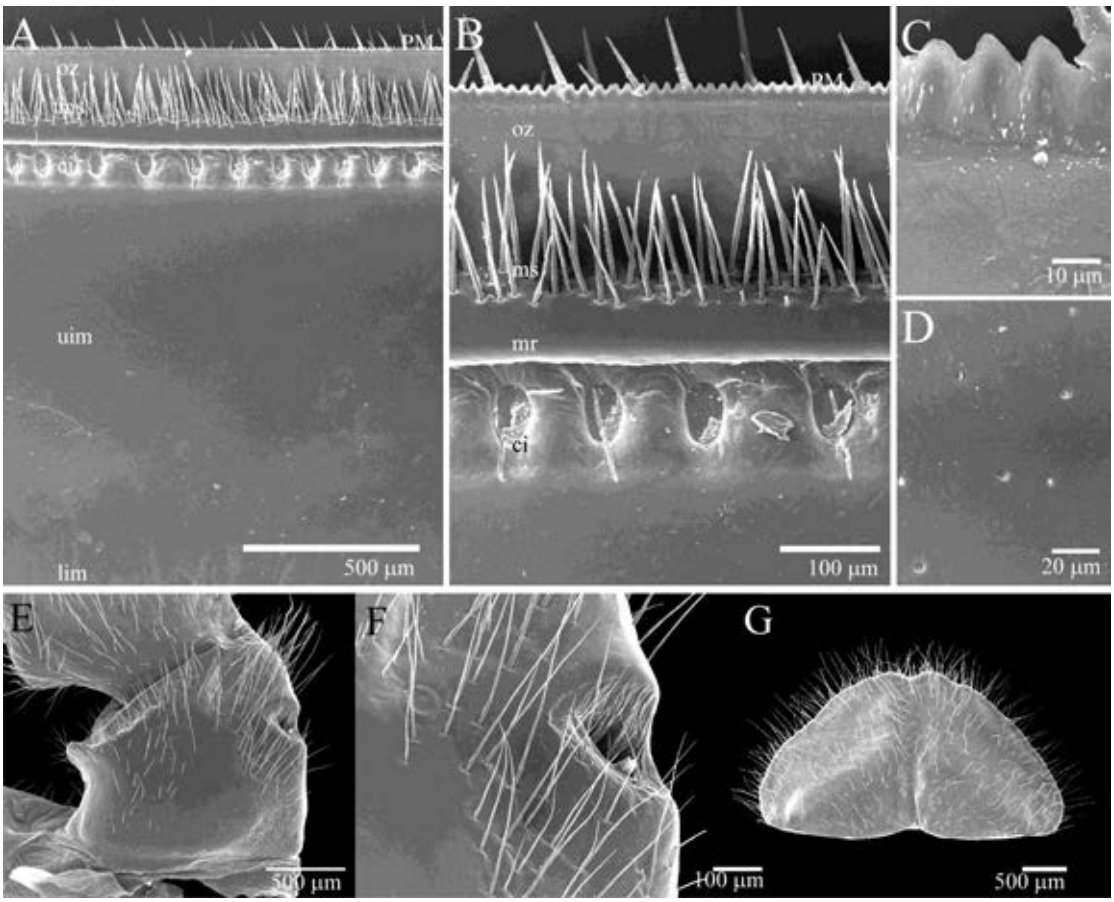

Figure 3.14 *Sphaerobelum* sp.5, male, endotergum, SEM, **A**: overview; **B**: marginal setae; **C**: posterior margin of endotergum; **D**: upper intersegmental membrane; **E-F**: male gonopore on second coxa; **G**: female, subanal plate.

Description:

Measurements: Sizes of volvated male: length 16.3 mm, width 14.7 mm and height 15 mm. Sizes of volvated female: length 18.1 mm, width 16.1 mm and height 16.2 mm.

Habitus: overall shape elliptical.

Coloration: Head is black. Collum, thoracic shield, tergite and anal shield are black. Antennae and legs are light yellow.

Endotergum (Figs. 3.14A-D): with a serrate margin (Figs. 3.14B, C), outer zone with three rows of marginal setae of half posterior margin length (Fig. 3.14B). A row of small elliptical cuticular impression present next to marginal ridge. Intersegmental membrane covered sparsely with small dimple (Fig. 3.14D).

Legs: 9th leg pair with 9 ventral spines and one apical spine on tarsus, femur with one long ridge.

Stigmatic plate of first leg (Fig. 3.31): overall shape rounded.

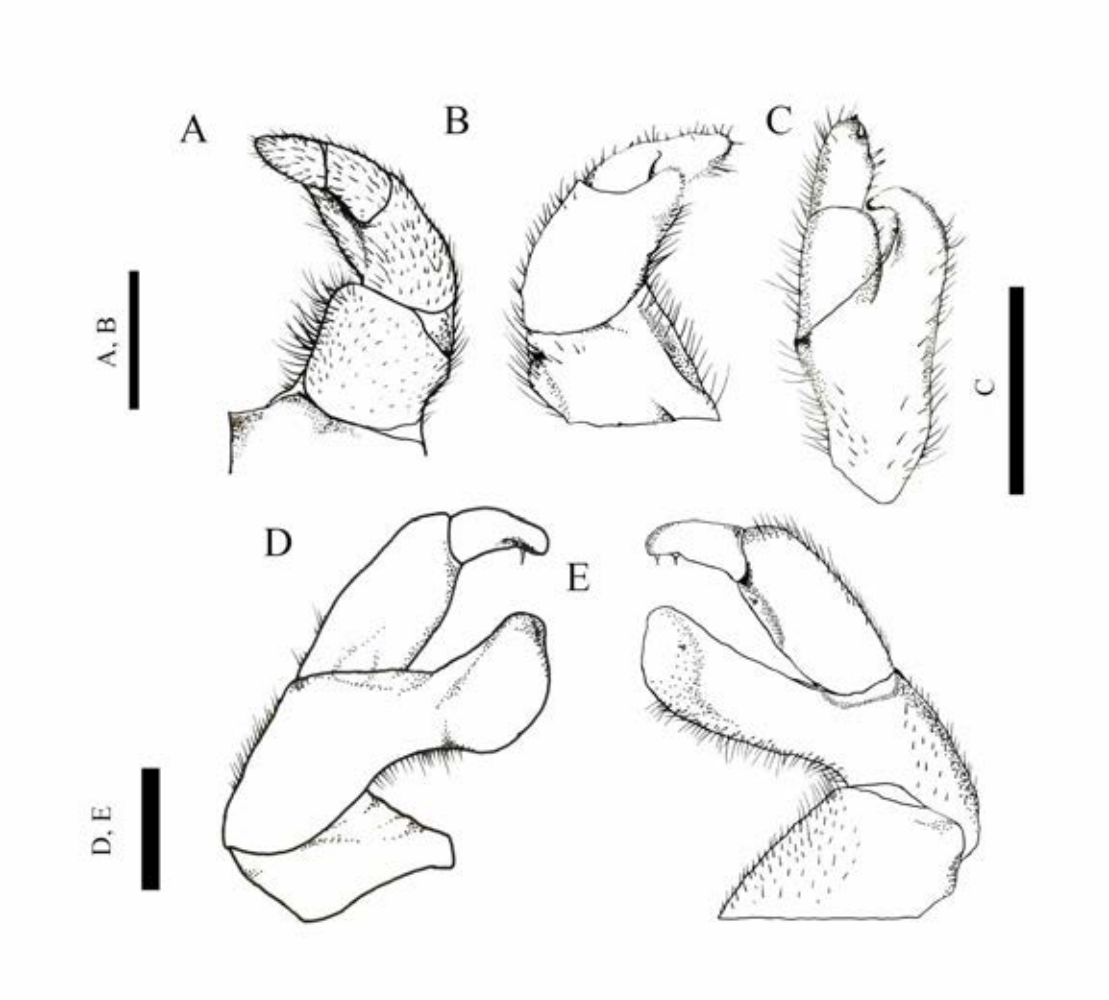

Figure 3.15 *Sphaerobelum* sp.5, drawing, **A**: right anterior telopod, anterior view; **B**: last three podomeres of right anterior telopod, posterior view; **C**: last three podomeres of right anterior telopod, lateral view; **D**: last three podomeres of right posterior telopod, posterior view; **E**: right posterior telopod, anterior view. Scale bars = 1 mm.

Anal shield: Ventral side with one long black locking carina.

Female vulva (Fig. 3.32): Operculum high concaved degree, basal part of operculum surrounding apical part of basal plates, distally protruding above coxa to basal half of prefemur. Vulva covers half (1/2) of coxa width.

Subanal plate (Fig. 3.14G): brown, semicircular with a central shallow notch.

Male gonopore (Figs. 3.14E, F): covered by an undivided sclerotized plate with small penis.

Anterior telopods (Figs. 3.15A-C): telopodite consist of four podomeres, all podomeres covered by long setae. First podomere width equals height. Second podomere with posterior lobe-like, highly curved process with rounded edges; process protruding up to the end of third podomere; anterior side of process without spine. Fourth podomere as long as third podomere, with four sclerotized spines located on small thin sclerotized fields, one spine at apex and the other three spines located on posterior side within two sclerotized fields. Sclerotized teeth are absent.

Posterior telopods: (Figs. 3.15.D, E): telopodite consist of four podomeres. First podomere is parallelogram-shaped. Second and third podomeres dominated by short setae, margins with long setae. Process of second podomere is weakly curved, distally glabrous, posteriorly apically enlarged and swollen, anteriorly apically concave, spatulate, with a single sclerotized spine. Movable finger consist of third podomere and small fourth podomere, slightly curved. Third podomere at inner margin with one small light colored spine, without any crenulated teeth. Fourth podomere is slender without sharped apex, inner margin with two small membranous spines located in single brown sclerotized field.

Unknown Genus

Key to species of the giant pill-millipede in unknown genus

1. Outer zone of endotergum without sparsely spine; male gonopore covered by two sclerotized plate and surrounded by long setae; Second sclerotized plate protruded above gonopore with sharp apex. Second coxa is bearing large penis; subanal plate eliptical……..……..……..Unknown sp.1
- Outer zone of endotergum with sparsely spine; male gonopore covered by two sclerotized plate and surrounded by long setae. Second sclerotized plate protruded above gonopore with slightly sharp apex. Second coxa no bearing large penis; subanal plate semicircle……..……..Unknown sp.2

Unknown sp.1

Material examined: 3 males, **CUMZ 2011.44-46** and 2 females, **CUMZ 2011.47-48**, Thailand, Nan Province, Na Muen District, Na Tanung Sub-district; evergreen forest; latitude: 18.1378, longitude: 100.6629; coll. N. Wongthamwanich; hand collecting; September 9, 2011.

Distribution: Known only from collection locality.

Description:

Measurements: Sizes of volvated male: length 19.1 mm, width 17.2 mm and height 17.8 mm. Sizes of volvated female: length 19.6 mm, width 17.7 mm and height 18.3 mm.

Habitus: overall shape elliptical with minute setae.

Coloration: Reddish-brown.

Endotergum (Figs. 3.16A-D): with a smooth margin (Fig. 3.16B), outer zone with a row of three-fourth (3/4) regular marginal setae of posterior margin height and without sparsely spine (Fig. 3.16B). A single row of small eliptical cuticular impression is presented next to marginal ridge. Intersegmental membrane covered sparsely with dimple and small conical spines (Fig. 3.16C) followed by the area of short setae with small conical spines (Fig. 3.16D).

Anal shield: Ventrally with one short locking carina.

Legs: 9th leg pair with 11 ventral spines and one apical spine on tarsus, femur with one long ridge.

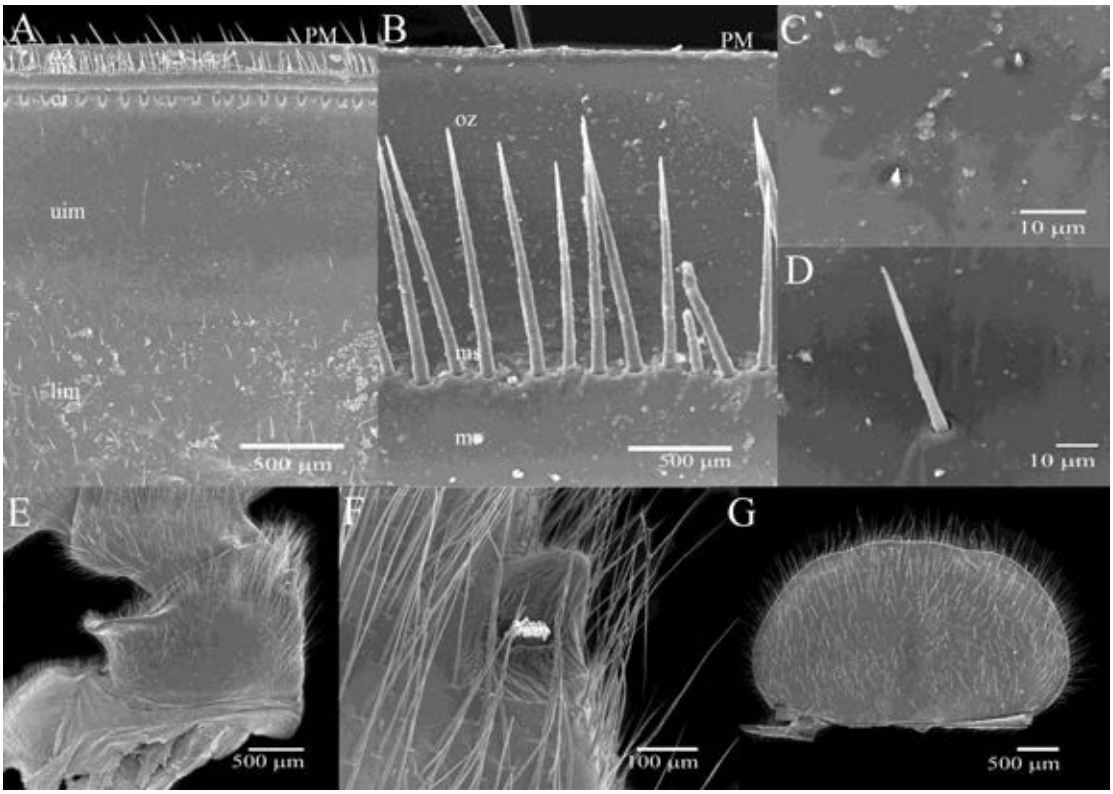

Figure 3.16 Unknown sp.1, male, endotergum, SEM, **A**: overview; **B**: setae of lower intersegmental membrane; **C**: posterior margin of endotergum with marginal setae; D: outer zone spines; **E**: upper intersegmental membrane; **F-G**: male gonopore on second coxa; **H**: female, subanal plate.

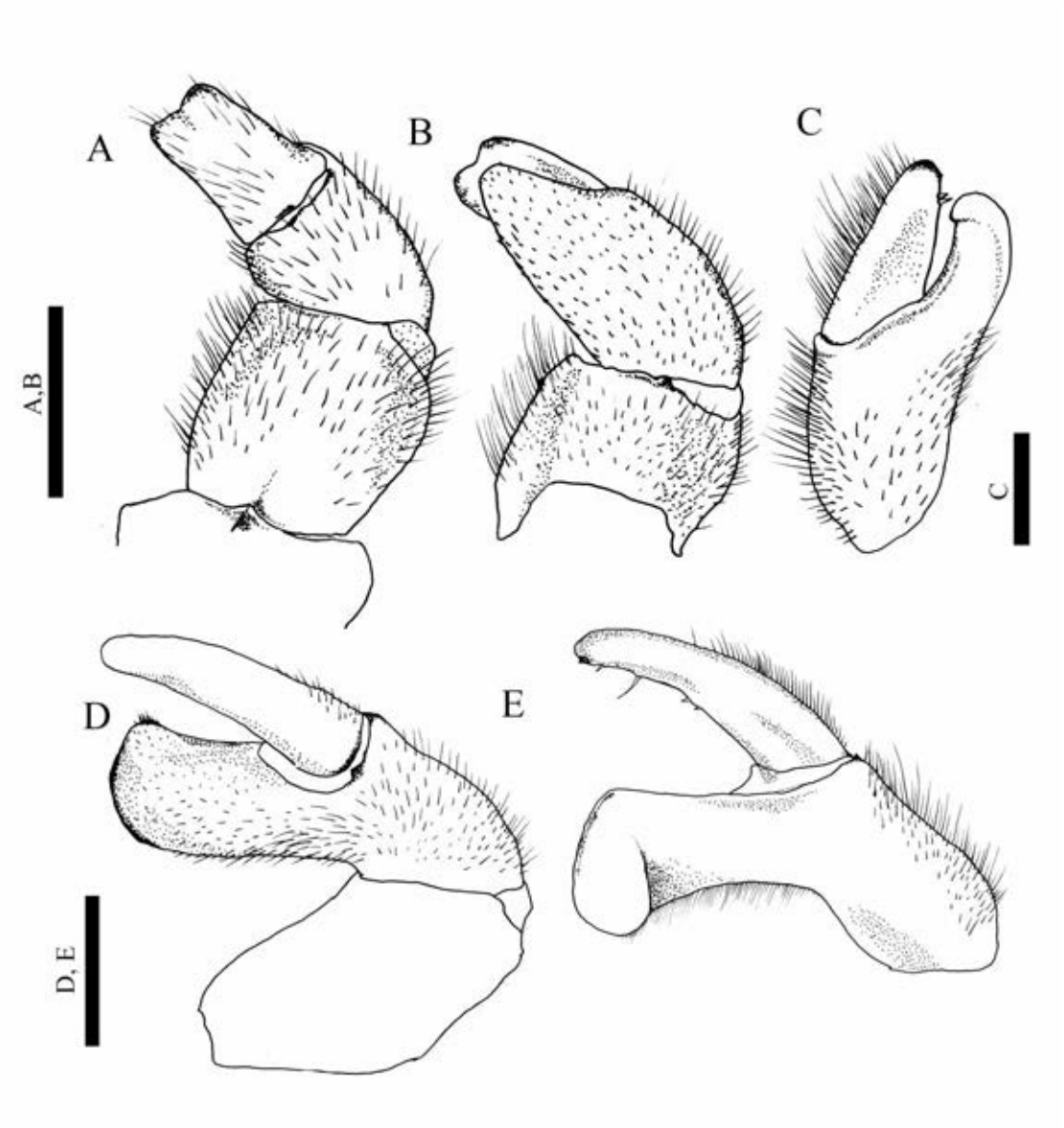

Figure 3.17 Unknown sp.1, drawing, **A**: right anterior telopod, anterior view; **B**: left anterior telopod, posterior view; **C**: last two podomeres of right anterior telopod, lateral view; **D**: right posterior telopod, anterior view; **E**: last two podomeres of left posterior telopod, posterior view. Scale bars = 1 mm.

Stigmatic plate of first leg (Fig. 3.31): rounded, short and weakly curved, but forming a steep angle towards the coxa.

Female vulva (Fig. 3.32): consists of two basal plates which are fused proximally and divided distally. Operculum is steep (ca 45°), basal part of operculum surrounding apical part of basal plates, distally protruding above coxa to basal half of prefemur. Vulva covers one-third (1/3) of coxa width, vulva is one-third (1/3) longer than coxa. Mesal plate height is six time of operculum.

Subanal plate (Fig. 3.16G): elliptical shape.

Male gonopore (Figs. 3.16E, F): covered by two plates and surrounded by long setae. Apical part of first plate is membranous. Second sclerotized plate protruded above gonopore with sharp apex. Second coxa bearing large penis.

Anterior telopods (Figs. 3.17A-C): telopodite consist of three podomeres, all podomeres covered by long setae. First podomere width equals height. Second podomere with posterior lobe-like, curved process with rounded edges; process protruded up to end of third podomere. Third podomere distally concaved with two separated sclerotized spines.

Posterior telopods (Figs. 3.17D, E): telopodite consist of three podomeres and dominated by long setae. First podomere is slightly parallelogram-shaped. Process of second podomere is curved, distally glabrous, posteriorly apically enlarged and swollen, anteriorly apically slightly concave, spatulate, with a single sclerotized spine. Third podomere slightly curved and slender, inner margin with three small sclerotized spines located in separate field, without any crenulated teeth; margins with long setae.

Unknown sp.2

Material examined: 1males, **CUMZ 2011.49** and 2 females, **CUMZ 2011.50-51**, Thailand, Nan Province, Ban Luang District, Suat Sub-district; evergreen forest; 47 Q 2006231 N, 675921 E; coll. N. Wongthamwanich; hand collecting; September 17, 2011.

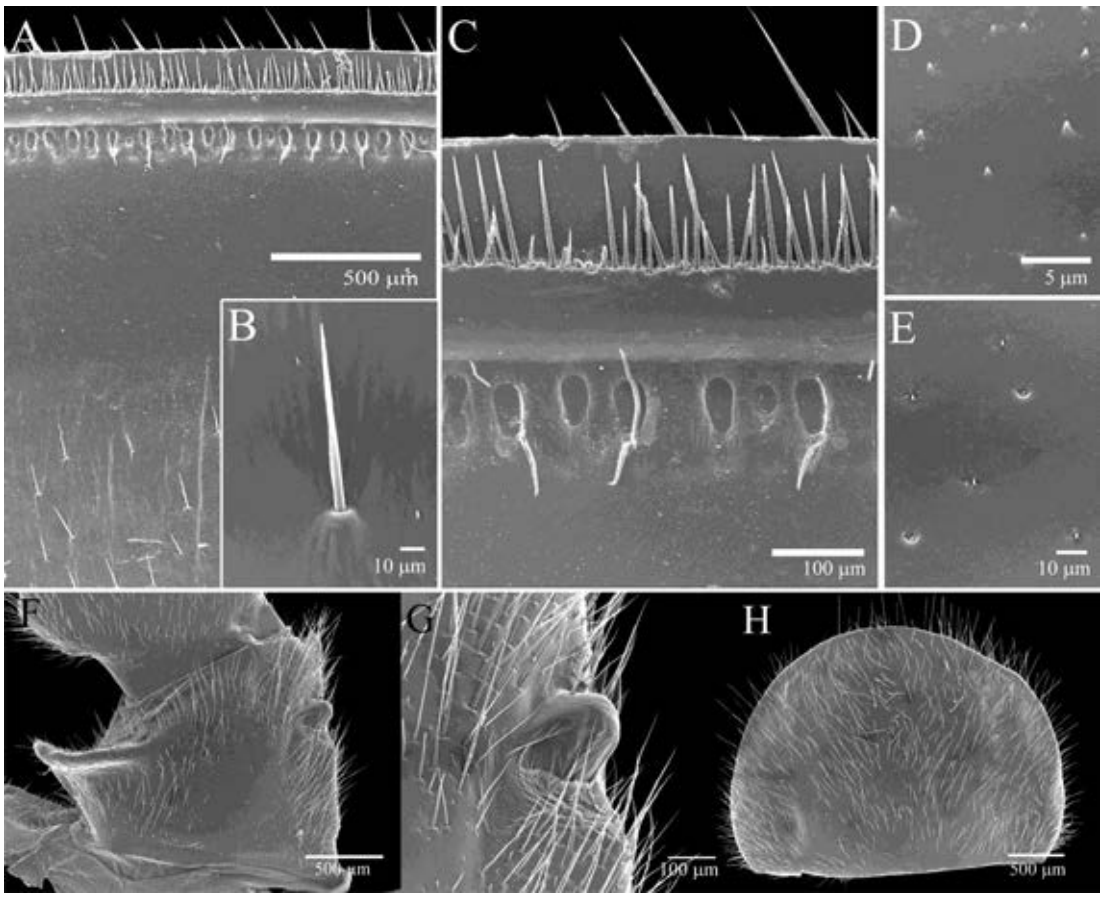

Figure 3.18 Unknown sp.2, male, endotergum, SEM, **A**: overview; **B**: setae of lower intersegmental membrane; **C**: posterior margin of endotergum with marginal setae; D: outer zone spines; **E**: upper intersegmental membrane; **F-G**: male gonopore on second coxa; **H**: female, subanal plate.

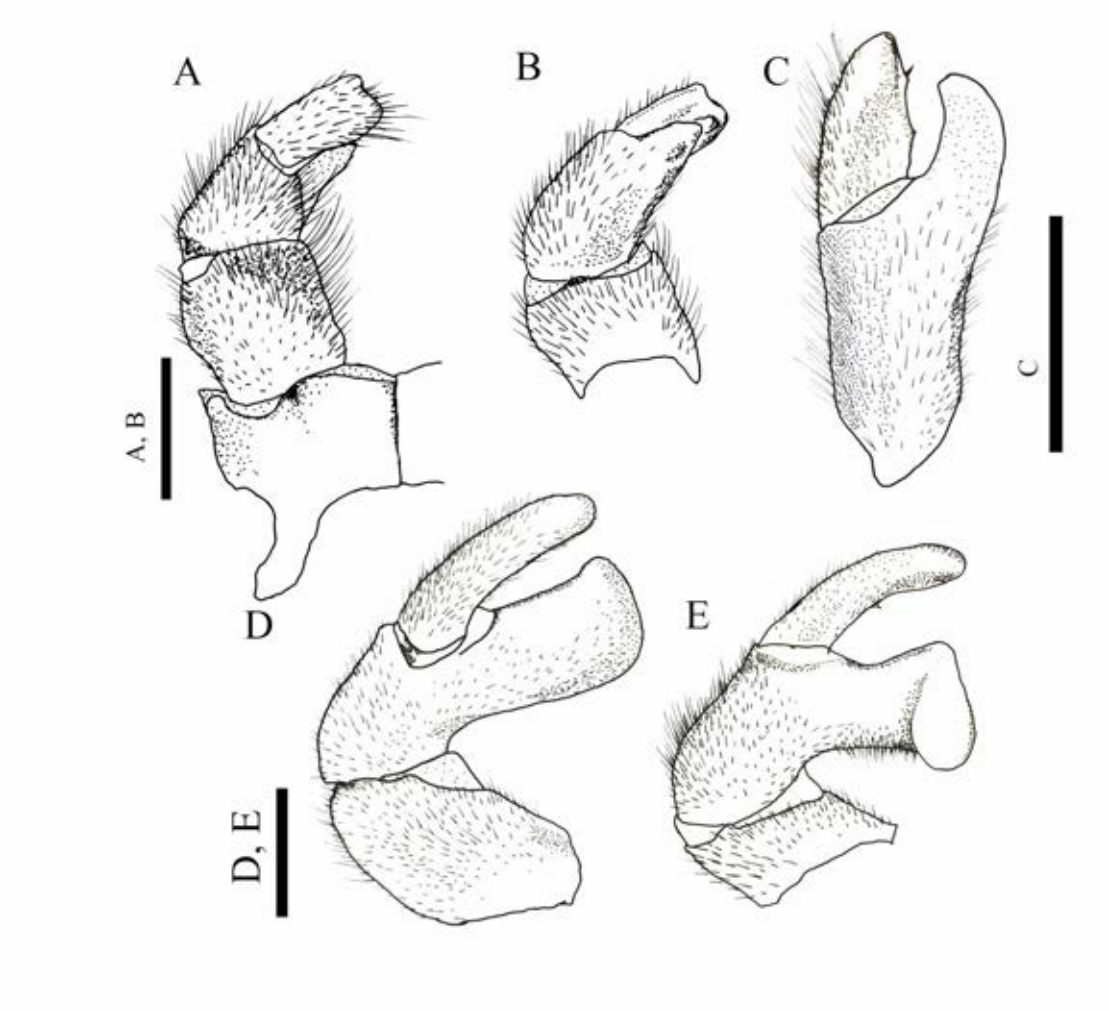

Figure 3.19 Unknown sp.2, drawing, **A**: left anterior telopod, anterior view; **B**: right anterior telopod, posterior view; **C**: last two podomeres of right anterior telopod, lateral view; **D**: left posterior telopod, anterior view; **E**: right posterior telopod, posterior view. Scale bars = 1 mm.

Distribution: Known only from collection locality.

Description:

Measurements: Sizes of volvated male: length 17 mm, width 15.6 mm and height 15.9 mm. Sizes of volvated female: length 18.7 mm, width 16.5 mm and height 17.1 mm.

Habitus: overall shape elliptical with hairy setae.

Coloration: Reddish-brown.

Endotergum (Figs. 3.18A-E): with a smooth margin (Fig. 3.18B), outer zone with a row of three-fourth (3/4) regular marginal setae of posterior margin height and covered by sparsely spines (Fig. 3.18D). A single row of small eliptical cuticular impression is presented next to marginal ridge. Intersegmental membrane covered sparsely with dimple and small conical spines (Figs. 3.18G, E) followed by the area of long setae with small conical spines (Fig. 3.18B).

Anal shield: Ventrally with one short locking carina.

Legs: 9th leg pair with 10 ventral spines and one apical spine on tarsus, femur with one long ridge.

Stigmatic plate of first leg (Fig. 3.31): rounded, short and weakly curved, but forming a steep angle towards the coxa.

Female vulva (Fig. 3.32): consists of two basal plates which are fused proximally and divided distally. Operculum is steep (ca 45°), basal part of operculum surrounding apical part of basal plates, distally protruding above coxa to basal half of prefemur. Vulva covers one-third (1/3) of coxa width, vulva is one-third (1/3) longer than coxa. Mesal plate height is six time of operculum.

Subanal plate (Fig. 3.18H): semicircular.

Male gonopore (Fig. 3.18F, G): covered by two plate. Apical part of first plate is membranous. Second sclerotized plate protruded above gonopore with slightly sharp apex.

Anterior telopods (Figs. 3.19A-C): telopodite consist of three podomeres, all podomeres covered by long setae. First podomere width equals height. Second podomere with posterior lobe-like, curved process with rounded edges; process protruded up to end of third podomere. Third podomere distally concaved with 2 separated sclerotized spines.

Posterior telopods (Figs. 3.19D, E): telopodite consist of three podomeres and dominated by long setae. First podomere is slightly parallelogram-shaped. Process of second podomere is curved, distally glabrous, posteriorly apically enlarged and swollen, anteriorly apically slightly concave, spatulate, with a single sclerotized spine. Third podomere slightly curved and slender, inner margin with three small sclerotized spines located in separate field, without any crenulated teeth; margins with long setae.

Genus Zephronia Gray, 1932

Type species: *Zephronia ovalis* Gray, 1832

Key to species of the giant pill millipede genus *Zephronia* in Nan Province

1. Marginal setae equal or beyond posterior margin……2
- Marginal setae beneath posterior margin …….... ….4
2. Marginal setae with 2 irregular rows; outer zone with sparsely single spines ….....…3
- Marginal setae with 1 irregular row; outer zone with sparsely single spines……*Z.* sp.4
3. Upper intersegmental membrane with regular setae, more than 6 rows of setae; setae length up to 110 μm ……..…….……*Z.* sp.1
- Upper intersegmental membrane with irregular setae, less than 6 rows of setae; setae length ca. 90 μm ……..……...……*Z.* sp.3
4. Endotergum without marginal ridge ……..*Z.* sp.2
- Endotergum with marginal ridge…….……5
5. Marginal setae 1 regular or irregular row, length ½ to ¾ time of outer zone……..…...6
- Marginal setae 2 irregular rows, length ½ of outer zone ……..….*Z.* sp.7
6. Marginal setae irregular, socket close to each other; lower intersegmental membrane with setae length ca. 90 μm up to 4 rows …….……*Z.* sp.5
- Marginal setae regular, socket separate to each other; lower intersegmental membrane with setae length ca. 70 μm less than 4 rows ……..……...*Z.* sp.6

Zephronia sp.1 (*Z.*cf. *viridescens*, Attem 1936)

Material examined: 5 males CUMZ 2010.20-24, and 5 females CUMZ 2010.25-29, Thailand, Nan Province, Wiang Sa District, Lai-Nan Sub-district, Chulalongkorn University Forestry and Research Station; deciduous forest; 47 Q 2053452 N, 690270 E; coll. N. Wongthamwanich; hand collecting, July 29, 2010.

Distribution: Only known from deciduous forest, Nan province

Description:

Measurements: Sizes of volvated male: length 19.4 mm, width 16.6 mm and height 17.5 mm. Sizes of volvated female: length 22.5 mm, width 18.5 mm and height 20.1 mm.

Habitus: elliptical shape, tapering slightly from 7 or 8 tergites towards the head and anal shield.

Coloration: collum dark brown, thoracic shield and anal shield red-brown, tergites brown. Thoracic shield border along anterior and posterior margins, tergite border along posterior margin dark brown. Coxa and prefemur light brown mixed with green, the remaining part of leg green.

Endotergum (Figs. 3.20A-E): posterior margin of tergite 9, outer zone with few small conical spines, followed by two rows of irregular marginal setae beyond tergite margin (Figs 3.20C-D). Single row of large elliptical cuticular impression forming a marginal ridge. Inner area with smooth zone, followed by a zone dominated by few long setae (Fig. 3.20A).

Anal shield: Ventral side with one medium black locking carina.

Legs: 9th leg pair provided with 9-11 ventral spines and five apical spines.

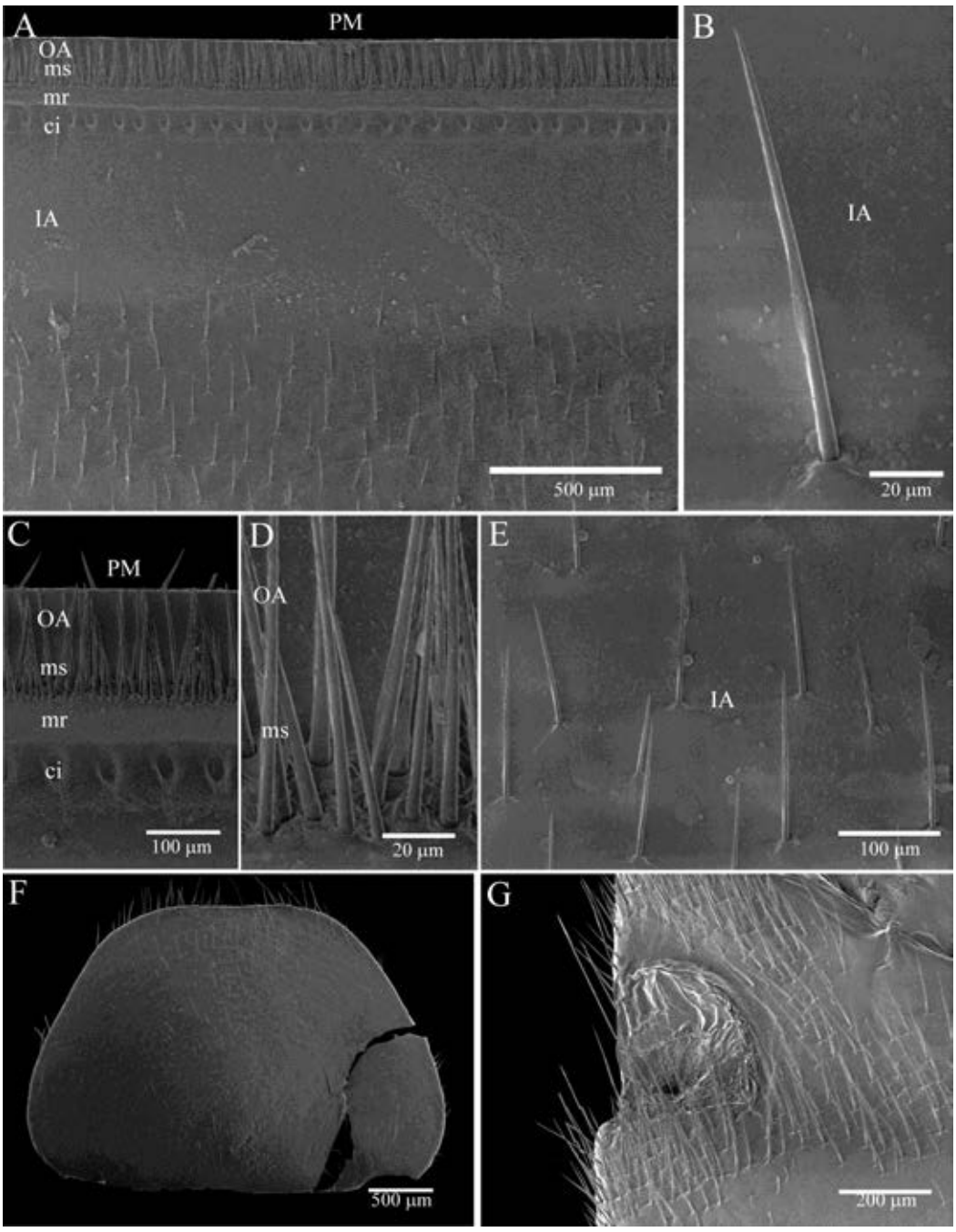

Figure 3.20 *Zephronia* sp.1 (*Z.* cf. *viridescens*), endotergum, SEM, **A**: overview; **B**: setae on lower intersegmenatal membrane; **C**: outer zone to cuticular impression area; **D**: outer zone of endotergum margin; E: inner area of endotergum; **F**: female subanal plate; G: male gonopore on second coxa. Abbreviations: **PM** = posterior margin; **oz** = outer zone; **ms** = marginal setae; **mr** = marginal ridge; **ci** = cuticular impressions; **im** = intersegmental membrane.

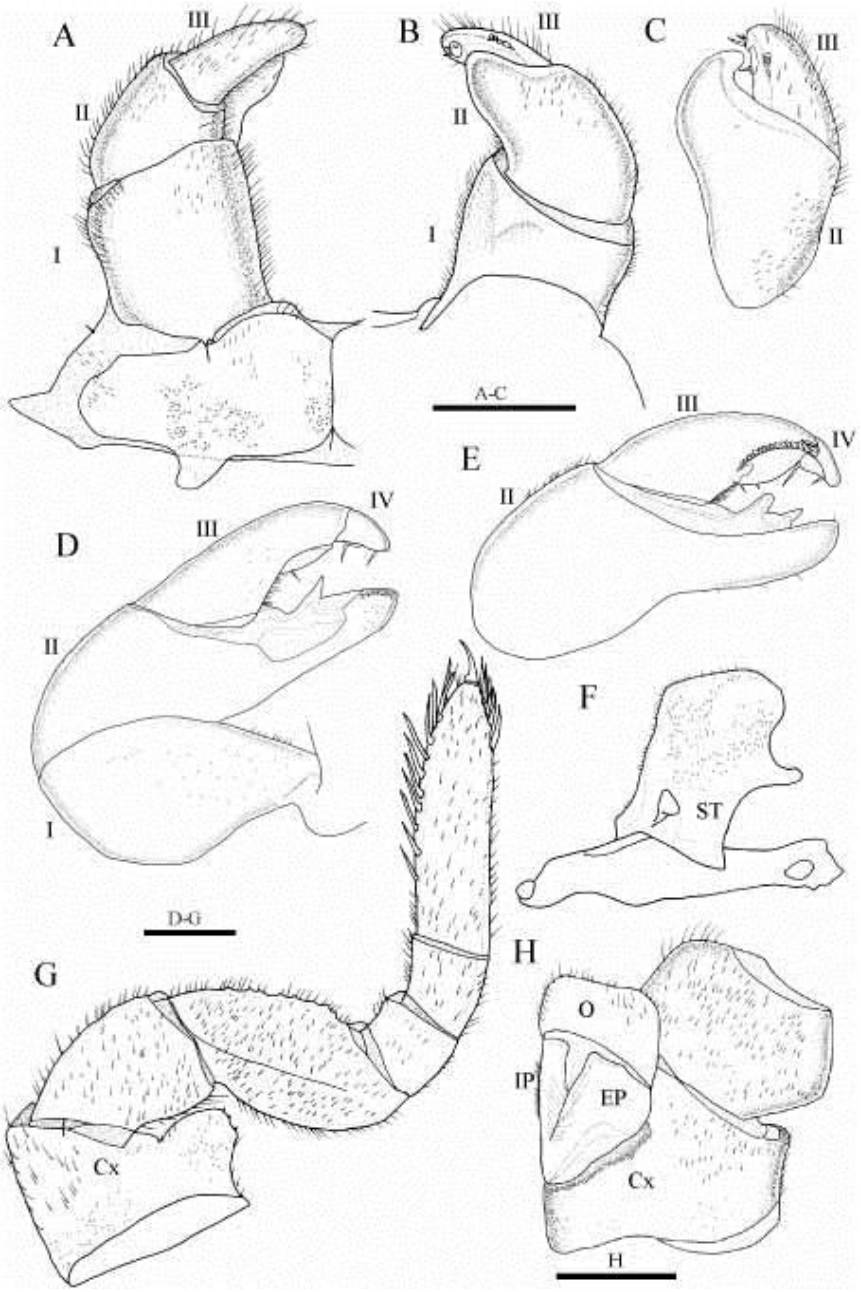

Figure 3.21 *Zephronia* sp.1 (*Z.* cf. *viridescens*), drawing, **A**: left anterior telopod, anterior view; **B**: last three podomeres of left anterior telopod, posterior view; **C**: last two podomeres of left anterior telopod, lateral view; **D**: last three podomeres of left posterior telopod, anterior view; **E**: last three podomeres of right posterior telopod, posterior view; **F**: stigmatic plate of 9th left leg; **G**: 9th left leg, posterior view; **H**: second left coxa with vulva, posterior view. Abbreviations: **Cx** = coxa; **ST** = stigmatic plate; **O** = operculum; **EP** = external plate of vulva; **IP** = mesal plate of vulva. Roman numbers refer to number of podomere. Scale bars = 1 mm.

Stigmatic plate of first leg: rounded, moderate and weakly curved, but forming a slightly steep angle towards the coxa, located next to cardo of mandible, carrying long setae.

Female vulva (Fig. 3.21H): consists of two basal plates, fused proximally and divided distally. Operculum truncate, basal part of operculum surrounding apical part of basal plates and distally protruding above coxa to basal half of prefemur. Vulva covers two-fifth (2/5) of coxa width, vulva is one-third (1/3) longer than coxa.

Subanal plate (Fig. 3.20F): brown, trapezoid nearly rounded shape, without stridulation ribs.

Gonopore (Fig 3.20G): semi-round gonopore with an undivided plate. Gonopore covered by semicircle sclerotized, apical part of membranous plate.

Anterior telopods (Figs 3.21A-C): Syncoxa with few small spines scattered with 3 podomeres, all covered by numerous long setae. First podomere strong, width as long as height. Second podomere with posterior process, process lobe-like and curved with rounded edges, protruding up to 2/3rd of third podomere. Third podomere short, on posterior side with 5 crenulated teeth located at inner margin. Two membranous lobes, first one with 3 spines next to tip of third podomere and another lobe with 1 spine below crenulated teeth.

Posterior telopods (Figs. 3.21D, E): with 4 podomeres. First podomere is parallelogram shape. Anterior and posterior sides of second podomere are glabrous except outer edge with short setae. Fixed finger weakly curved, with 2 large membranous lobes and small elliptical granules at posterior margin of fingertip. Movable finger slightly curved, consist of third podomere and small forth podomere. Third podomere at inner margin on posterior side with 16-18 sclerotized crenulated teeth and 1 or 2 small light colored spines. Forth podomere with 2 small membranous spines. Inner horns with sharp-edged tips, slightly curved backwards.

Zephronia sp.2

Material examined: 1 male CUMZ 2010.30, and 2 females CUMZ 2010.31-32, Thailand, Nan Province, Wiang Sa District; mixed deciduous forest; 47 Q 2050077 N, 676166 E; coll. N. Wongthamwanich; hand collecting, June 6, 2010.

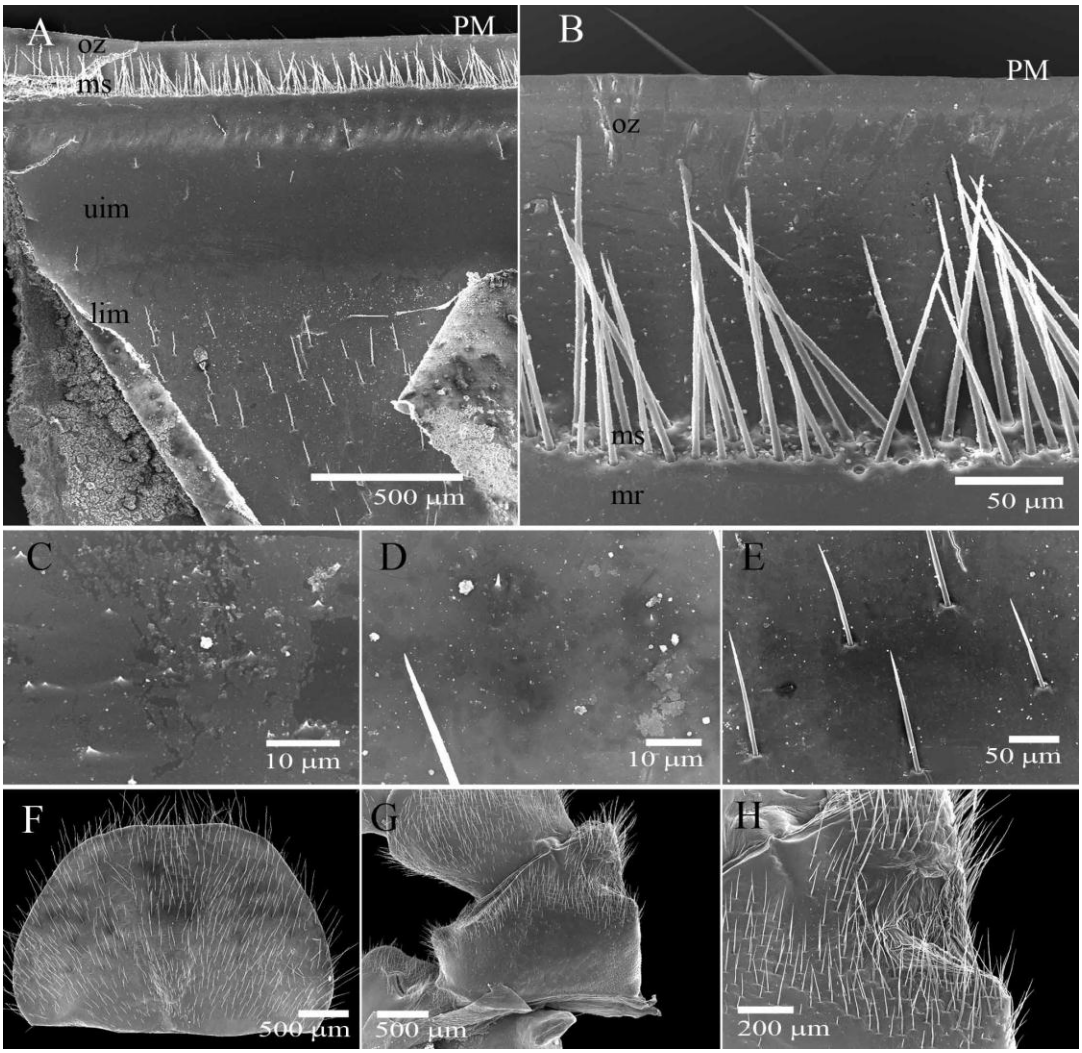

Figure 3.22 *Zephronia* sp.2, male, endotergum, SEM, **A**: overview; **B**: posterior margin of endotergum with marginal setae; **C**: outer zone spines; **D**: upper intersegmental membrane **E**: setae of lower intersegmental membrane; **F**: female, subanal plate. **G-H**: male gonopore on second coxa;

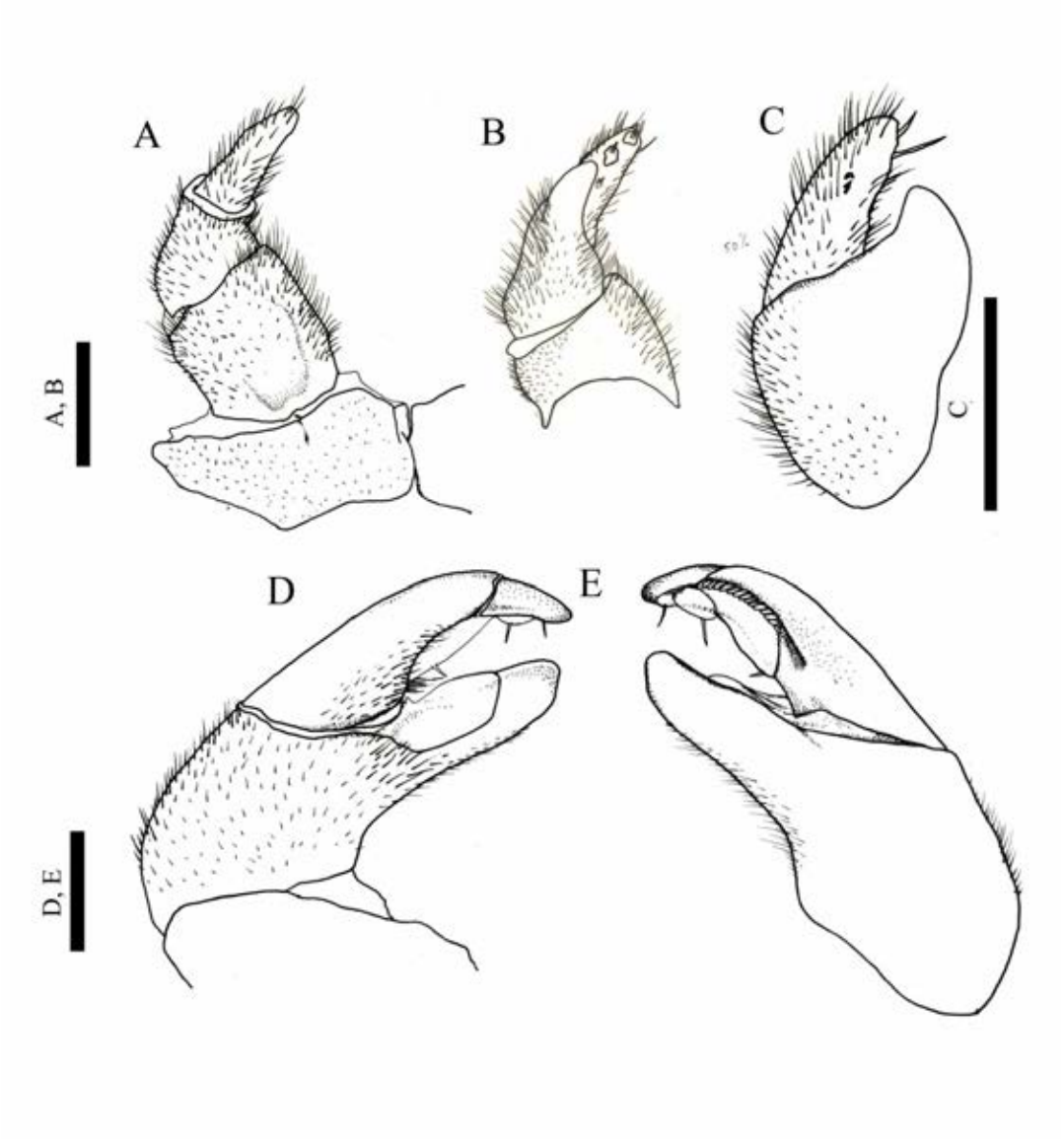

Figure 3.23 *Zephronia* sp.2, drawing, **A**: left anterior telopod, anterior view; **B**: right anterior telopod, posterior view; **C**: last two podomeres of right anterior telopod, lateral view; **D**: last three podomeres of left posterior telopod, anterior view; **E**: last three podomeres of left posterior telopod, posterior view.; Scale bars = 1 mm.

Distribution: Only known from collection locality

Description:

Measurements: Sizes of volvated male: length 16.9 mm, width 14.2 mm and height 15mm. Sizes of volvated female: length 21.4 mm, width 17.6 mm and height 19.1 mm.

Habitus: elliptical shape, tapering slightly from 7 or 8 tergites towards the head and anal shield.

Coloration: over all brown, blackish posterior margin.

Endotergum (Figs. 3.22A-E): outer zone covered by sparsely spines, dominated by two rows of irregular marginal setae, length half time of outer zone (Figs 3.22C-D). Single row of large circular cuticular impression forming a marginal ridge. Intersegmental membrane covered with sparsely minute spines at the upper area, followed by a zone of few long setae at lower intersegmental membrane (Fig. 3.22A).

Anal shield: Ventral side with one short black locking carina.

Legs: 9th leg pair provided with seven ventral spines and three apical spines.

Stigmatic plate of first leg (Fig. 3.31): rounded, moderate and weakly curved, but forming a slightly steep angle towards the coxa.

Female vulva (Fig. 3.32): consists of two basal plates, fused proximally and divided distally. Operculum truncate, basal part of operculum surrounding apical part of basal plates and distally protruding above coxa to basal half of prefemur. Vulva covers two-fifth (2/5) of coxa width, vulva is one-third (1/3) longer than coxa.

Subanal plate (Fig. 3.22F): brown, trapezoid nearly rounded shape, without stridulation ribs.

Gonopore: semi-round gonopore with an undivided plate. Gonopore covered by semicircle sclerotized, apical part of membranous plate.

Anterior telopods (Figs 3.23A-C): telopodite consist of three podomeres, all podomeres covered by long setae. First podomere strong, width equals height. Second podomere with posterior lobe-like, curved process with rounded edges; process protruding up to 2/3rd of third podomere. Third podomere short, on posterior side with 3 crenulated teeth located at inner margin. Three membranous lobes with 3 spines separated field, one spine at apex and other located on posterior side.

Posterior telopods (Figs. 3.23D, E): telepodite consist of 4 podomeres. First podomere is parallelogram shape. Second and third podomeres covered with long setae, except posterior view of second podomere is glabrous. Process of second podomere weakly curved, with 2 large membranous lobes and small elliptical granules at posterior margin of fingertip. Movable finger slightly curved, consist of third podomere and small forth podomere. Third podomere at inner margin on posterior side with 13 sclerotized crenulated teeth and 1 small light colored spine. Forth podomere have 2 small membranous spines.

Zephronia sp.3

Material examined: 1 female CUMZ 2010.36, Thailand, Nan Province, Chiang Klang District, Puea Sub-district; deciduous forest; 47 Q 2136627 N, 700833 E; coll. N. Wongthamwanich; hand collecting, July 26, 2010.

Distribution: Only known from collection locality

Description:

Measurements: Sizes of volvated female: length 18.2 mm, width 15.5 mm and height 16.4 mm.

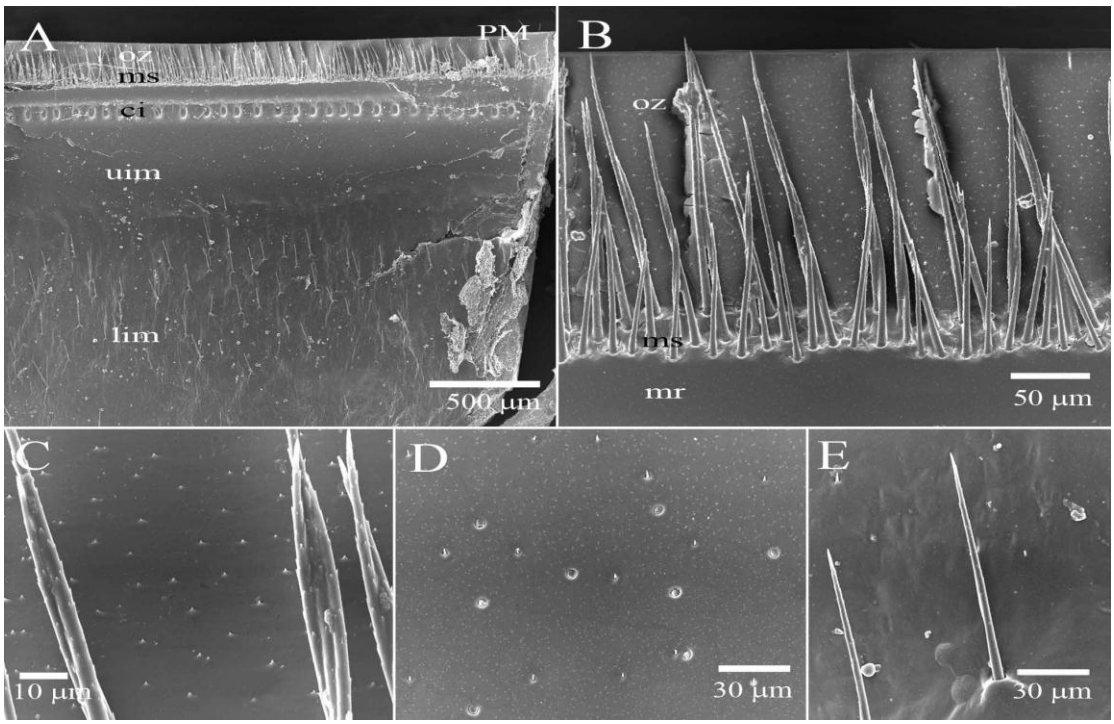

Figure 3.24 *Zephronia* sp.3, female, endotergum, SEM, A: overview; B: posterior margin of endotergum with marginal setae; C: outer zone spines; D: upper intersegmental membrane E: setae of lower intersegmental membrane.

Habitus: elliptical shape, tapering slightly from 7 or 8 tergites towards the head and anal shield.

Coloration: over all brown, posterior margin black.

Endotergum (Figs. 3.24A-E): outer zone covered by sparsely single spines; dominated by two rows of regular marginal setae, length equal outer zone height (Figs 3.24C-D). Single row of large eliptical cuticular impression forming a marginal ridge. Intersegmental membrane covered with sparsely minute spines and dimple at the upper area, followed by a zone of few long setae at lower intersegmental membrane (Fig. 3.24A).

Anal shield: Ventral side with one short black locking carina.

Legs : 9th leg pair provided with nine ventral spines and three apical spines.

Female vulva (Fig. 3.32): consists of two basal plates, fused proximally and divided distally. Operculum truncate, covered by long setae; basal part of operculum surrounding apical part of basal plates and distally protruding above coxa to basal half of prefemur. Vulva covers two-fifth (2/5) of coxa width, vulva is one-third (1/3) longer than coxa.

Subanal plate: rounded with a central shallow notch.

Zephronia sp.4

Material examined: 2 males CUMZ 2010.37-38, and 12 females CUMZ 2010.39-50, Thailand, Nan Province, Phu Phiang District, Nam Kian Sub-district; deciduous dipterocarp forest; 47 Q 2074360 N, 696000 E; coll. N. Wongthamwanich; hand collecting, July 31, 2010.

Distribution: Only known from collection locality

Description:

Measurements: Sizes of volvated male: length up to 19.7 mm, width 16.9 mm and height 17.6 mm. Sizes of volvated female: length up to 23.0 mm, width 19.3 mm and height 20.6 mm.

Habitus: elliptical shape, tapering slightly from 7 or 8 tergites towards the head and anal shield.

Coloration: over all brown, posterior margin dark-brown.

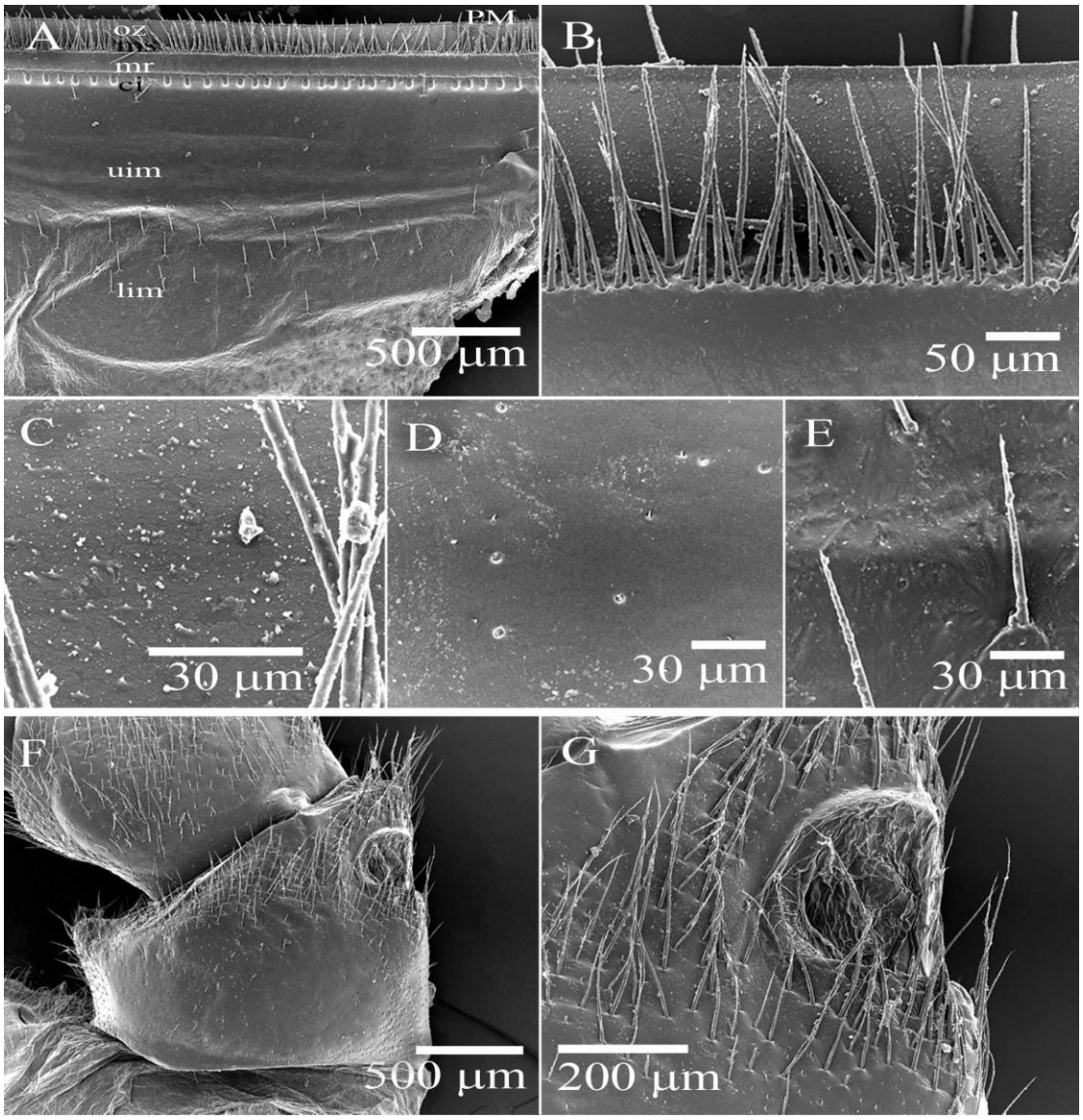

Figure 3.25 *Zephronia* sp.4, male, endotergum, SEM, **A**: overview; **B**: posterior margin of endotergum with marginal setae; **C**: outer zone spines; **D**: upper intersegmental membrane **E**: setae of lower intersegmental membrane; **F-G**: male gonopore on second coxa.

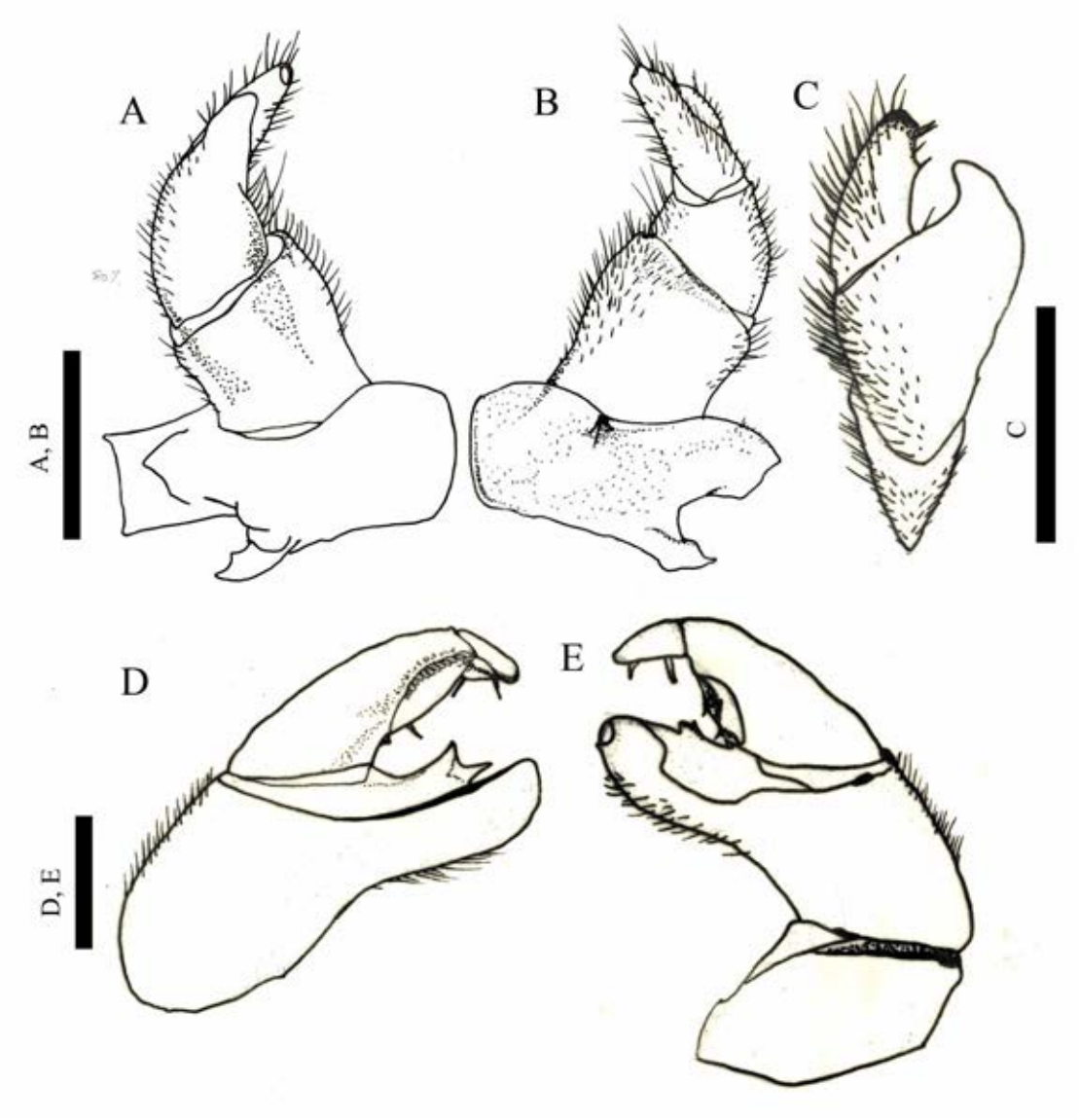

Figure 3.26 *Zephronia* sp.4, drawing, **A**: right anterior telopod, posterior view; **B**: right anterior telopod, anterior view; **C**: last two podomeres of right anterior telopod, lateral view; **D**: last three podomeres of right posterior telopod, posterior view; **E**: last three podomeres of right posterior telopod, anterior view. Scale bars = 1 mm.

Endotergum (Figs. 3.25A-E): outer zone covered by sparsely single spines; dominated by two rows of irregular marginal setae beyond posterior margin (Figs 3.25B-C). Single row of large eliptical cuticular impression forming a marginal ridge. Intersegmental membrane covered with sparsely minute spines and dimple at the upper area, followed by a zone of few long setae at lower intersegmental membrane (Fig. 3.25A).

Anal shield: Ventral side with one medium black locking carina.

Legs: 9th leg pair provided with 9 spines and four apical spines.

Stigmatic plate of first leg (Fig. 3.31): rounded, moderate and weakly curved, but forming a slightly steep angle towards the coxa.

Female vulva (Fig. 3.32): consists of two basal plates, fused proximally and divided distally. Operculum truncate, basal part of operculum surrounding apical part of basal plates and distally protruding above coxa to basal half of prefemur. Vulva covers two-fifth (2/5) of coxa width, vulva is one-third (1/3) longer than coxa. Coxal lobe presented.

Subanal plate: brown, trapezoid nearly rounded shape, without stridulation ribs.

Male gonopore (Fig 3.25F, G): covered by undivided plate. Sclerotized semicircular-plate located upper gonopore and covered by membranous plate.

Anterior telopods (Figs 3.26A-C): telopodite consist of three podomeres, all podomeres covered by long setae. First podomere strong, width equals height. Second podomere with posterior lobe-like, curved process with rounded edges; process protruded up to 2/3rd of third podomere. Third podomere short, sclerotized apex, on posterior side without crenulated teeth located at inner margin. Three membranous lobes with 2 spines separated field located on posterior side.

Posterior telopods (Figs. 3.26D, E): telepodite consist of 4 podomeres. First podomere is parallelogram shape. Second and third podomeres are glabrous, except lateral side of podomere covered with long setae. Process of second podomere weakly curved, with 2 large membranous lobes and small elliptical granules at posterior margin of fingertip. Movable finger slightly curved, consist of third podomere and small forth podomere. Third podomere at inner margin on posterior side with 14 sclerotized crenulated teeth and 1 small light colored spine. Forth podomere have 2 small membranous spines.

Zephronia sp.5

Material examined: 1 male CUMZ 2010.51, and 2 females CUMZ 2010.52-53, Thailand, Nan Province, Na Noi District, Sathan Sub-district; deciduous dipterocarp forest; 47 Q 2018653 N, 680264 E; coll. N. Wongthamwanich; hand collecting, August 8, 2010.

Distribution: Only known from collection locality

Description:

Measurements: Sizes of volvated male: length 16 mm, width 13.6 mm and height 14.3 mm. Sizes of volvated female: length 18.3 mm, width 15.5 mm and height 16.3 mm.

Habitus: elliptical shape, tapering slightly from 7 or 8 tergites towards the head and anal shield.

Coloration: over all brown, blackish posterior margin.

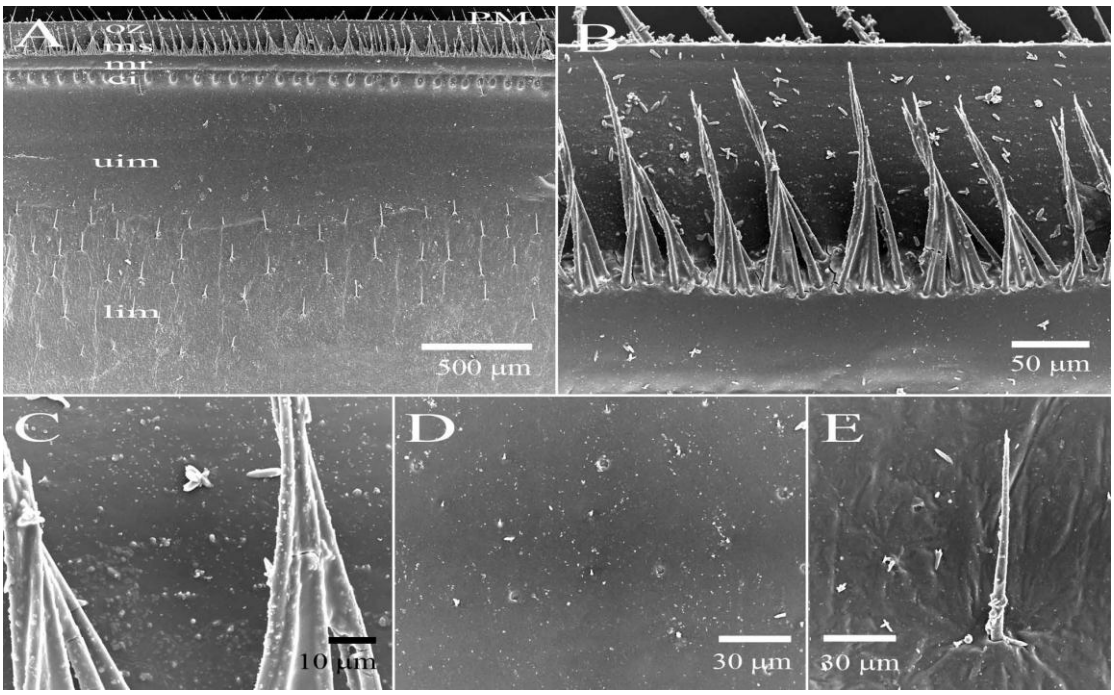

Figure 3.27 *Zephronia* sp.5, male, endotergum, SEM, **A**: overview; **B**: posterior margin of endotergum with marginal setae; **C**: outer zone spines; **D**: upper intersegmental membrane **E**: setae of lower intersegmental membrane.

Endotergum (Figs. 3.27A-E): outer zone covered by single sparsely spines, dominated by two rows of irregular marginal setae, length four-fifth (4/5) of outer zone height (Figs 3.27C-D). Single row of large eliptical cuticular impression forming a marginal ridge. Intersegmental membrane covered with sparsely minute spines and dimple at the upper area, followed by a zone of few long setae with nodule at lower intersegmental membrane (Fig. 3.27A).

Anal shield: Ventral side with one short black locking carina.

Legs: 9th leg pair provided with 11 ventral spines and three apical spines.

Zephronia sp.6

Material examined: 10 juveniles CUMZ 2011.52-61, Thailand, Nan Province, Thung Chang District; mixed deciduous forest; 47 Q 2144663 N, 699576 E; coll. N. Wongthamwanich; hand collecting, September 3, 2011.

Distribution: Only known from collection locality

Description:

Measurements: Sizes of volvated juvenile: length 13.6 mm, width 11.3 mm and height 12 mm.

Habitus: elliptical shape, tapering slightly from 7 or 8 tergites towards the head and anal shield.

Coloration: over all brown, posterior margin dark-brown.

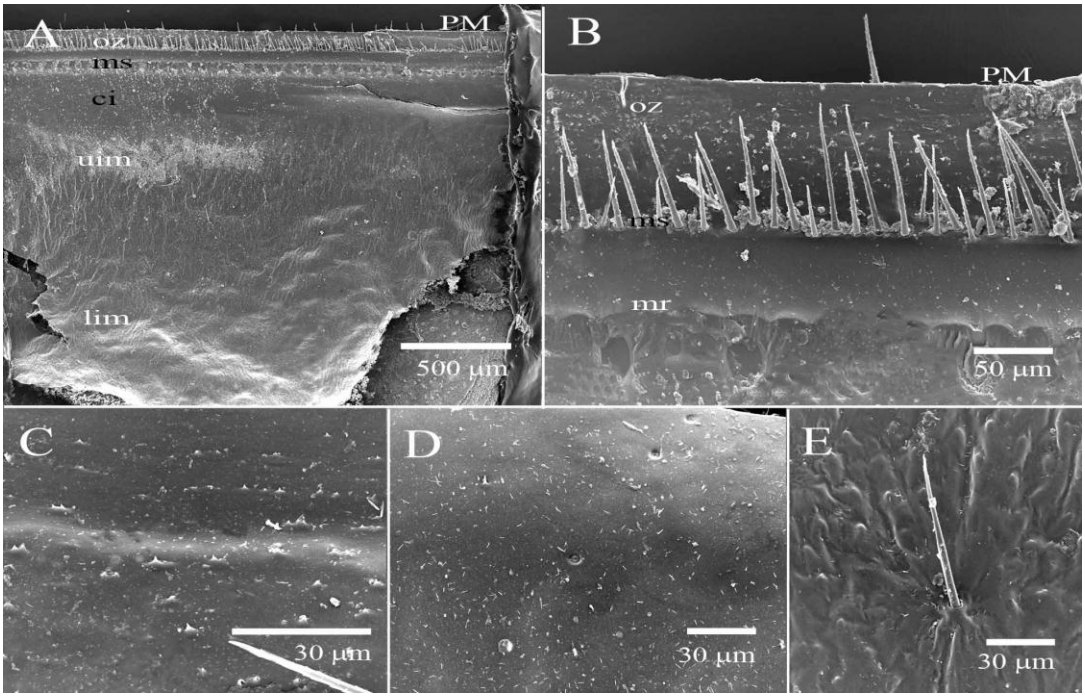

Figure 3.28 *Zephronia* sp.6, endotergum, SEM, **A:** overview; **B:** posterior margin of endotergum with marginal setae; **C:** outer zone spines; **D:** upper intersegmental membrane **E:** setae of lower intersegmental membrane.

Endotergum (Figs. 3.28A-E): outer zone densely covered by single or double sparsely spines, dominated by a row of regular marginal setae, length half time of outer zone (Figs. 3.28B-C). Single row of large circular cuticular impression forming a marginal ridge. Intersegmental membrane covered with sparsely minute spines at the upper area, followed by a zone of few long setae at lower intersegmental membrane (Fig. 3.28A).

Anal shield: Ventral side with one short black locking carina.

Zephronia sp.7

Material examined: 1 male CUMZ 2011. 62, Thailand, Nan Province, Wiang Sa District; dry evergreen forest; 47 Q 2035759 N, 709777 E; coll. N. Wongthamwanich; hand collecting, September 18, 2011.

Distribution: Only known from collection locality

Description:

Measurements: Sizes of volvated male: length 18.3 mm, width 16 mm and height 16.7 mm.

Habitus: elliptical shape, tapering slightly from 7 or 8 tergites towards the head and anal shield.

Coloration: over all brown, blackish posterior margin.

Endotergum (Figs. 3.29A-E): outer zone covered by sparsely double or triple spines, dominated by two rows of spreadly regular marginal setae, length half time of outer zone (Figs 3.29B, C). Single row of large circular cuticular impression forming a marginal ridge. Intersegmental membrane covered with sparsely minute spines at the upper area, followed by a zone of few long setae at lower intersegmental membrane (Fig. 3.29A).

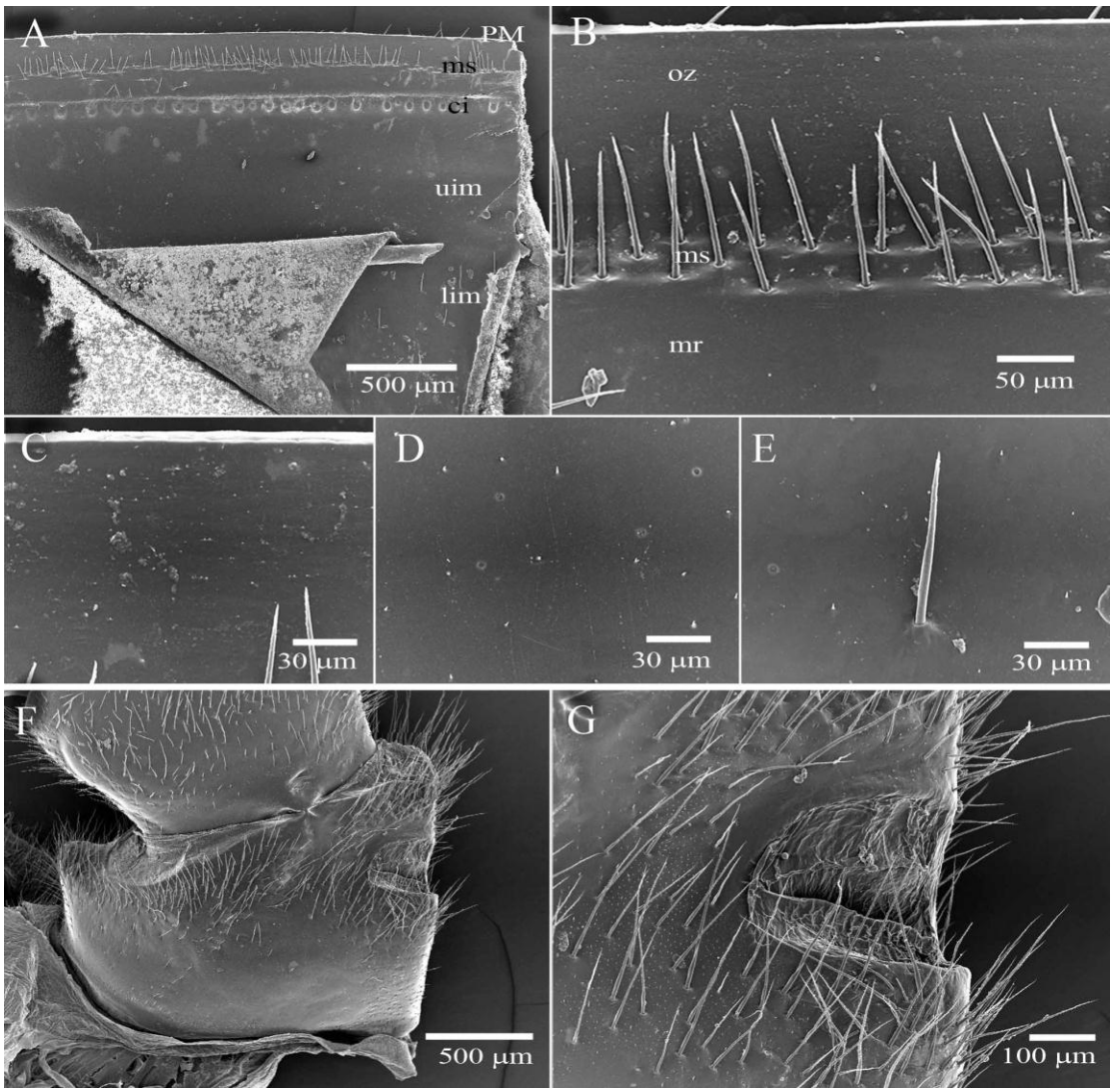

Figure 3.29 *Zephronia* sp.7, endotergum, SEM, **A**: overview; **B**: posterior margin of endotergum with marginal setae; **C**: outer zone spines; **D**: upper intersegmental membrane **E**: setae of lower intersegmental membrane; **F-G**: male gonopore on second coxa.

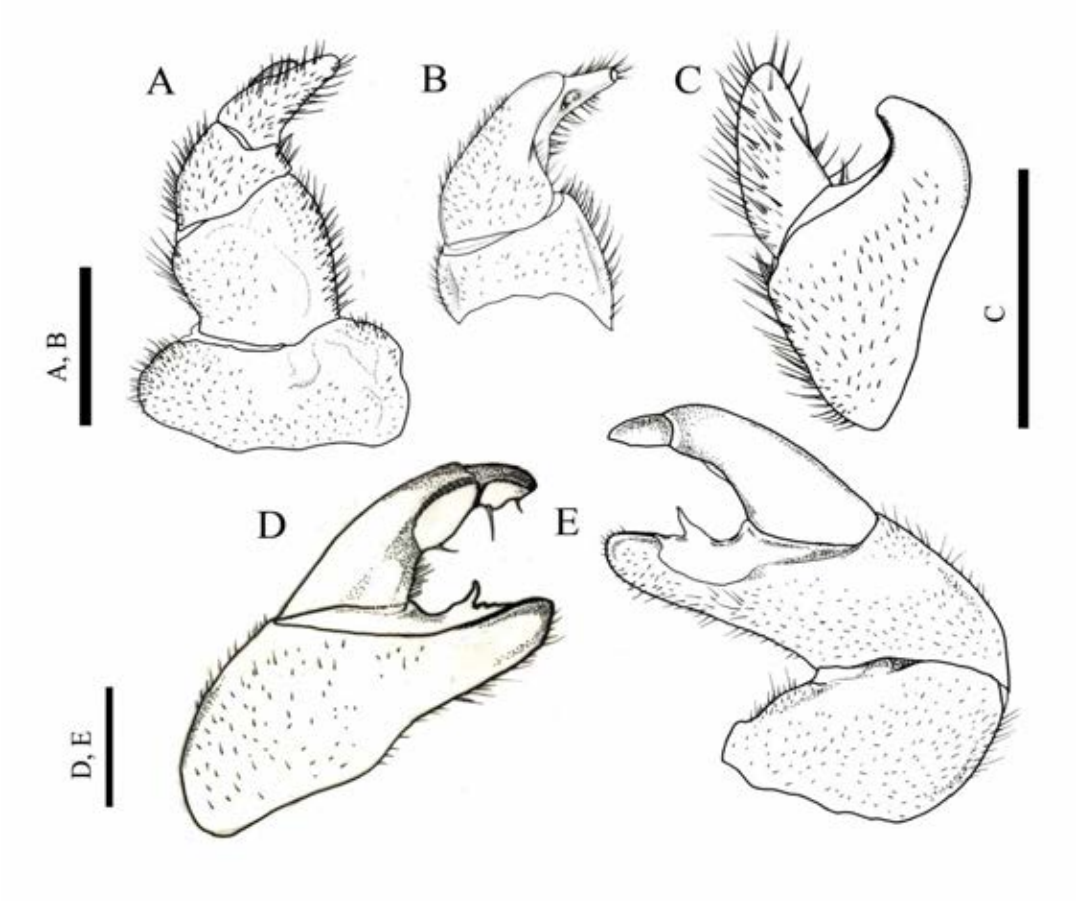

Figure 3.30 *Zephronia* sp.7, drawing, **A**: left anterior telopod, anterior view; **B**: anterior telopod, posterior view; **C**: last two podomeres of left anterior telopod, lateral view; **D**: last three podomeres of left posterior telopod, posterior view; **E**: last three podomeres of left posterior telopod, anterior view. Scale bars = 1 mm.

Anal shield: Ventral side with one short black locking carina.

Legs: 9th leg pair provided with seven ventral spines and one apical spine.

Stigmatic plate of first leg (Fig. 3.31): rounded, moderate and weakly curved, but forming a slightly steep angle towards the coxa.

Male Gonopore (Fig 3.29F, G): semicircular gonopore with divided plates. Gonopore covered by two sclerotized plates and apical part with membranous plates.

Anterior telopods (Figs 3.30A-C): telopodite consist of three podomeres, all podomere covered by long setae. First podomere strong, width equals height. Second podomere with posterior lobe-like, curved process with rounded edges; process protruding up to 2/3rd of third podomere. Third podomere short, on posterior side with 3 crenulated teeth located at inner margin. Three membranous lobes with 3 spines separated field, one spine at apex and the others located on posterior side.

Posterior telopods (Figs. 3.30D, E): telepodite consist of 4 podomeres. First podomere is parallelogram shape. Second and third podomeres covered with long setae, except posterior view of second podomere is glabrous. Process of second podomere weakly curved, with 2 large membranous lobes and small elliptical granules at posterior margin of fingertip. Movable finger slightly curved, consist of third podomere and small forth podomere. Third podomere at inner margin on posterior side with 12 sclerotized crenulated teeth and 1 small light colored spine. Forth podomere have 2 small membranous spines.

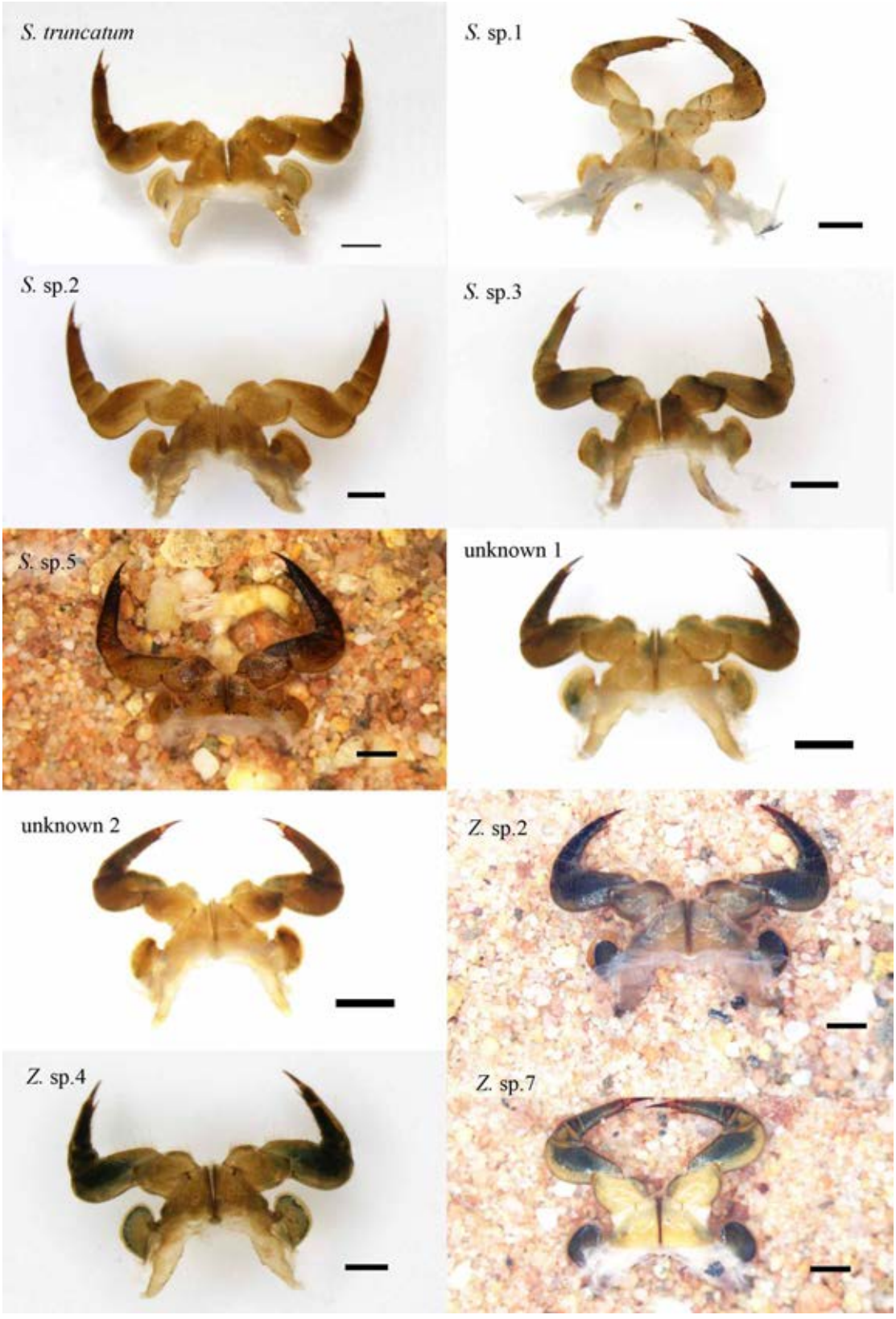

Figure 3.31 Stigmatic plates of first leg, digital photographs. Scale bar = 1 mm.

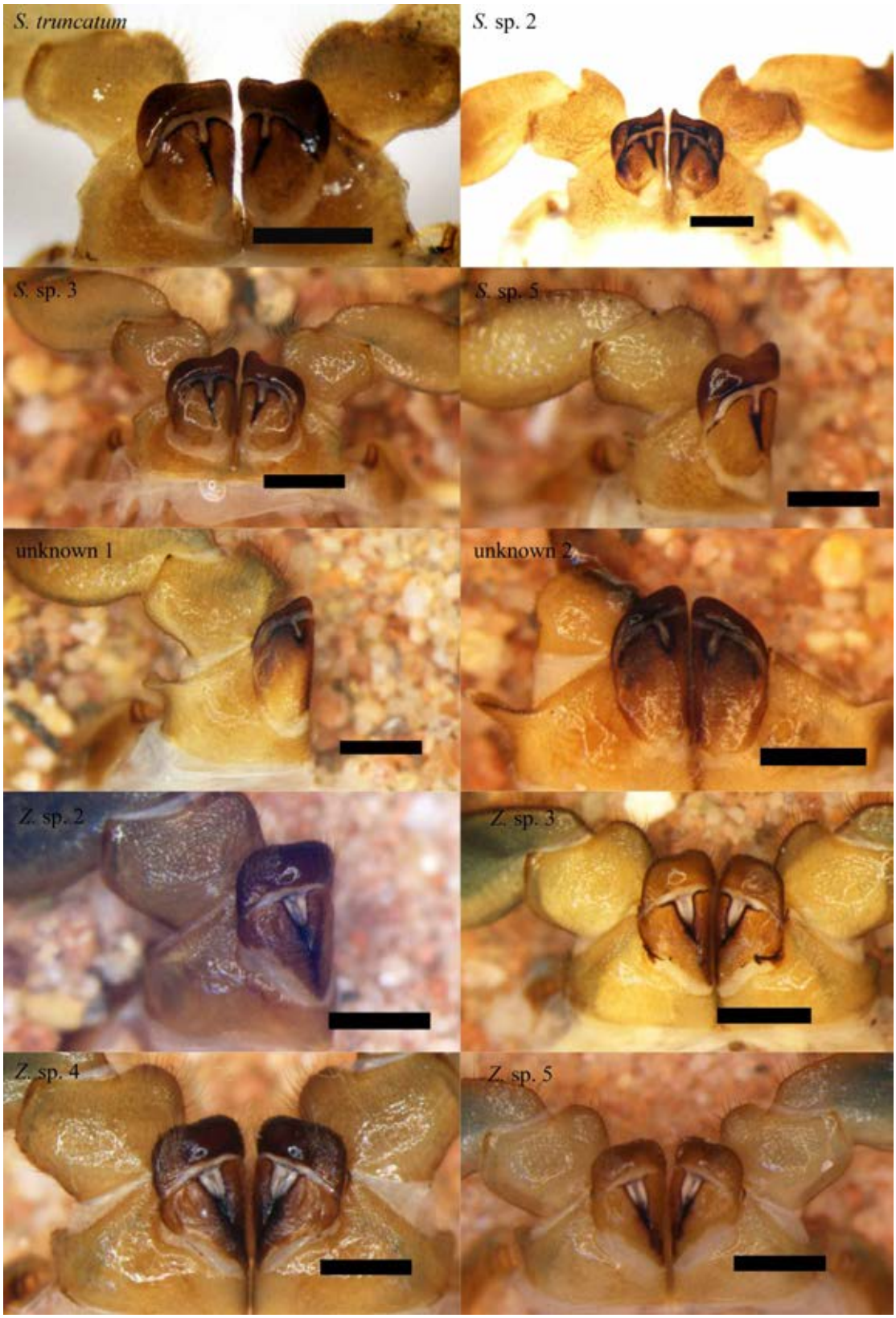

Figure 3.32 Vulva on second coxa of the giant pill-millipede, digital photographs. Scale bar = 1 mm.

Table 3.3 Morphological characters of giant pill-millipedes from Nan Province. Abbreviations: MS = marginal setae; n.a. = not available.

Characters	*Sphaerobelum*					Unknown			*Zephronia*						
	S. truncatum	*S.* sp.1	*S.* sp.2	*S.* sp.3	*S.* sp.4	*S.* sp.5	Unknown sp.1	Unknown sp.2	*Z.* sp.1	*Z.* sp.2	*Z.* sp.3	*Z.* sp.4	*Z.* sp.5	*Z.* sp.6	*Z.* sp.7
Tergite															
-Color	black	black	brown	black	black	black	reddish-brown	reddish-brown	brown	brown	brown	brown	brown	brown	brown
Endotergum															
-Margin	square-wavy	smooth	smooth	square-wavy	square-wavy	serrate	smooth	smooth	smooth	smooth	smooth	smooth	smooth	smooth	smooth
-Rows of MS	3	2	4	3	2	3	1	1	2	2	2	1	1	1	2
-MS length	beneath margin	beneath margin	beyond margin	beneath margin	beneath margin	beneath margin	beneath margin	beneath margin	beyond margin	not reach margin	equal margin	beyond margin	beneath margin	beneath margin	beneath margin
-Marginal ridge	present	present	present	absent	present	present	present	present	present	absent	present	present	present	present	present
Locking carina															
-Length	long	long	long	long	long	long	long	long	short	short	short	short	short	short	short
9th leg															
-Ventral spines	7	10	6	9	n.a.	9	11	10	9	7	9	9	11	n.a.	7
-Apical spines	1	1	1	1	n.a.	1	1	1	5	3	3	4	3	n.a.	1
1st stigmatic plate															
-Shape	rounded	rounded	rhomboidal	rounded	n.a.	rounded	rounded	rounded	rounded	rounded	n.a.	rounded	n.a.	n.a.	rounded
Operculum															
-Shape	concave	n.a.	concave	concave	n.a.	high concave	steep	steep	truncate	truncate	truncate	truncate	truncate	n.a.	n.a.
Subanal plate															
-Shape	semi-circular	n.a.	semi-elliptical	sem-circular	n.a.	semi-circular	elliptical	semi-circular	trapezoid	trapezoid	rounded	trapezoid	trapezoid	n.a.	n.a.
Gonopore															
-Covered by	undivided plate	undivided plate	undivided plate	undivided plate	n.a.	undivided plate	divided plates	divided plates	undivided plate	undivided plate	n.a.	undivided plate	n.a.	n.a.	divided plate
Anterior telopods															
-No. of podomeres	4	4	4	4	n.a.	4	3	3	3	3	n.a.	3	n.a.	n.a.	3
-Membranous lobe	absent	absent	absent	absent	n.a.	absent	absent	absent	absent	present	n.a.	present	n.a.	n.a.	present
Posterior telopods															
-No. of podomeres	4	4	4	4	n.a.	4	3	3	4	4	n.a.	4	n.a.	n.a.	4
-Membranous lobe	absent	absent	absent	absent	n.a.	absent	absent	absent	present	present	n.a.	present	n.a.	n.a.	present

Discussion

In this study, one new species and 14 morphospecies of the giant pill-millipede have been found. Seven morphospecies belong to genus *Zephronia*, five morphospecies of *Sphaerobelum* including *S. truncatum* Wongthamwanich, 2012 and two morphospecies of unknown genus occurred in various habitat types. Most of *Zephronia* morphospecies were found in deciduous dipterocarp forest and mixed deciduous forest, the member of *Sphaerobelum* occurred in evergreen forest and two morphospecies of the same unknown genus were found in moist mixed deciduous forest. Therefore, the distribution of some giant pill-millipede species might be specific with the forest types. All morphospecies of giant pill-millipedes were found only from collecting locality which is a small area (less than 100 m^2). Therefore, it can be concluded that the millipedes of family Zephroniidae in Nan Province are the micro-endemic species which are similar to many species of the Malagasy giant pill-millipedes (Wesener, 2009).

The new species belongs to genus *Sphaerobelum, S. truncatum* n. sp., including five morphospecies were found in high moisture forests of Nan Province. These five morphospecies showed very clear difference comparing with the five previous known species of giant pill-millipedes in genus *Sphearobelum* Verhoff, 1924: *S. clavigerum* Verhoeff, 1924, *S. hirsutum* Verhoeff, 1924, *S. bicorne* Attem, 1938, *S. separatum* Attems, 1953 and *S. truncatum* Wongthamwanich, 2012. Thus, these morphospecies would be the new species from Nan Province.

The endotergum of each morphospecies from Nan Province was investigated and it was found that endotergum was taxonomic character of the giant pill millipede as found in Van den Spiegel *et al*. (2002). The special attention character of family Zephroniidae should be done at spines on outer zone of endotergum wich is the first notice of the difference between morphospecies. However, to classify species, this character including endotergum character from Van den Spiegel *et al*. (2002) work should be combined with other taxonomic characters such as telopods to get more clarify data to determine species. Moreover, in the future work, molecular genetics should be used to confirm the difference between morphospecies and their relationship.

The posterior telopod of the giant pill-millipede showed the high potential for classification of millipede genera of the family Zephoniidae. The millipedes in genus *Sphaerobelum* from the previous description showed four podomeres on posterior telopods and the club-shaped on the second podomere (the unique character of genus *Sphaerobelum*), while the unknown genus was also found the swollen at the distal of second podomere, but present only three podomeres on the posterior telopods. This data indicate that the unknown genus might be the new genus in the world.

CHAPTER IV

POPULATION ECOLOGY OF *Zephronia* cf. *viridescens*

Introduction

The life patterns of animals including millipedes are induced by environmental factors such as temperature changes, rainfall, day length and food availability (Campbell *et al*., 1999). Most of the millipede fauna are active on soil surface for feeding, searching mate and mating during rainy season (Banerjee, 1967a; Ashwini and Sridhar, 2006), while during dry season they disappear from soil surface. These phenomena are influenced by ecological cues such as moisture and temperature (Dangerfield and Telford, 1991). However, where and how they survive across critical period in dry season had a few data.

The giant pill-millipedes belong to order Sphaerotheriida. Their distribution has occurred in South Africa, Madagascar, India, Southeast Asia, Australia and New Zealand (Jeekel, 1974; Hoffman, 1982; Shelley, 1999; Wesener and Van den Spiegel, 2009). The members of the order Sphaerotheriida are more than 300 species (Sierwald and Bond, 2007; Wesener *et al*., 2010; Wongthamwanich *et al*., 2012). The giant pill-millipedes molt to increase their body segment and legs, including body weight and size until they have 13 segments of which this first stage of growth is called anamorphosis stadia. After that, they molt continuously to increase their body weight and size, but not for their body segment and legs in the second stage of growth form juvenile to adult; this stage is called epimorphosis stadia (Enghoff *et al*., 1993). The exoskeleton of each millipede after molting is weak and risky for their survival. However, both the molting process and growth of the giant pill-millipede are little known.

Population density, dispersion, diet, diapause, molting and growth are important for their survival and reproduction. These data of the giant pill-millipedes are needed to

know for their conservation and management in the future. Therefore, this research focused on population ecology of the giant pill-millipede in deciduous forest.

Materials and Methods

Identity of the studied species

The giant pill-millipedes of Thailand are very poorly known. Although several species obviously exist, only one has been recorded, viz., *Zephronia siamensis* Hirst, 1907, from the Si Chang Island in the Gulf of Thailand, Chonburi Province and from Chantaburi Province (Enghoff, 2005). According to the original description (Hirst, 1907) and after comparison to our unpublished studies on topotypical material of *Z. siamensis*, the species studied in this research was not that species. Instead, the studied species was very similar to *Zephronia viridescens* Attems, 1936, as described from a specimen from Dawei, southeastern Myanmar (Attem, 1936; Jeekel, 2001). However, because of some differences, we refer to the studied species in this report as *Zephronia* cf. *viridescens.*

Study area

The main area of this study was Chulalongkorn University Forestry and Research Station, located between N2051960 – 2054260 and E0688400 – 0693060 in UTM zone 47Q at Nam Wa Sub-watershed, Lai-Nan Sub-district, Wiang Sa District, Nan Province (Fig. 4.1). The elevation ranges from 200-260 meters above mean sea level. The area is covered by broad leaf forest, including secondary deciduous dipterocarp forest and mixed deciduous forest within 340 ha in size. The average temperature in rainy season and dry season are range from 23.1–35.1 ^{o}C and 39.8–15.8 ^{o}C, respectively. The average precipitation in rainy season is highest in August, 264 mm and lowest, 8.33 mm in dry season (Fig. 4.2). The differences of precipitation and temperature between rainy season and dry season winter and summer) are the cause of shedding leave of most

trees in the forest in dry season. The forest floor is covered by saplings and seedlings, including a leaf litter at up to 3 cm depth throughout the year. The deciduous dipterocarp forest is dominated by *Dipterocarpus obtusifolius*, *D. tuberculatus*, *Shorea obtusa*, *S. siamensis*, *Pterocarpus macrocarpus* (Dumrongrojwatthana *et al*., 2009) in sandy soil, while mixed deciduous forest is dominated by *Gigantochloa albociliata* in silt soil.

Population density and dispersion

Previous studies showed that active searching method was likely to provide more accurate data on species diversity and abundance of giant-pill millipedes (Mesibov *et al*., 1995; Druce *et al*., 2004). Giant pill-millipedes were sampling in twenty systematic 2 × 2 m^2 plots every month for one year from January to December 2009. Number of the giant pill-millipedes was recorded and population density was estimated.

Vertical dispersion were sampling in plot size of 30 × 30 × 30 m^3 inside of 2 × 2 m^2, excavated soil along with litter were transferred to the tray. Number of the giant pill millipede and distance from soil surface to the millipede were mapped and recorded for interpreting vertical dispersion.

Diapause of giant pill-millipede

Forest floors such as plain area, tree base, termite mound, bamboo clump, dry waterway, under log and etc. in deciduous dipterocarp forest and mixed deciduous forest were randomly sampling to search for diapause area every month during dry season in 2009-2011. The locality, diameter and depth of diapause chamber from soil surface were recorded.

Molting of giant pill-millipede

The molting sites of giant pill-millipedes were observed in their habitat. Molting was observed mainly in the habitat and some were observed in plastic box in the laboratory.

Figure 4.1 Study area of *Zephronia* cf. *viridescens* activities in Chulalongkorn University Forestry and Research Station.

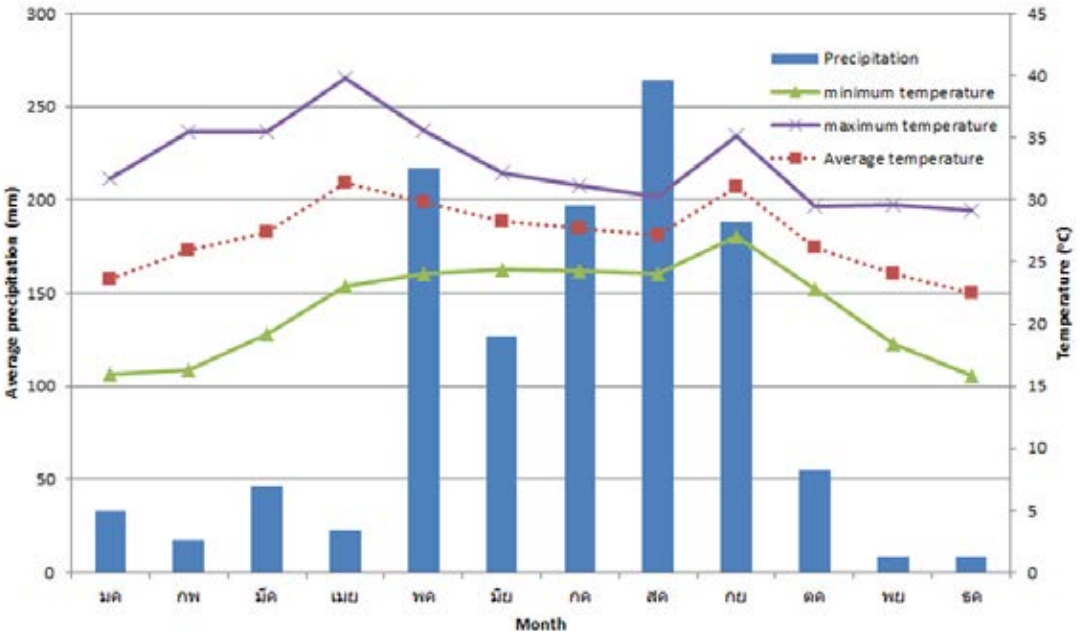

Figure 4.2 Average precipitation and temperature in Chulalongkorn University Forestry and Research Station from July 2009 to December 2011.

Growth of giant pill-millipede

The giant pill-millipedes were collected from their habitat in the rainy season of 2009 to 2011. Growth of anamorphosis stadia millipede was observed in plastic box in laboratory at room temperature. Data on length and height were measured from digital photo individually. Some specimens were preserved in 70% alcohol for counting number of tergite, plurite and leg pairs of them. Growth of epimorphosis stadia millipede was observed in 30 × 30 × 30 cm^3 enclosure embedded 10 cm in the soil of mixed deciduous forest. Data on body weight, length, height and width were measured individually every 2 weeks. Data on the rate and pattern of development and weight were recorded at successive molts up to maturity.

Thirty adult males and 30 adult females were studied on their sexual dimorphisms. Their body segment morphology such as width, length and height were measured, including number of sensory cone on antenna. The means of each morphological character between sexes were compared by t-test.

Results

Population density

The giant pill-millipede, *Zephronia* cf. *viridescens*, presented on the soil surface during rainy season of 2009 between April to September, but it was not found in dry season between January to March and between October to December of the year. The number of *Z.* cf. *viridescens* was highest in June and July of 2009 with approximately 1,500 and 1,125 individual/ha, respectively (Figs. 4.3, 4.4). Then, the millipede number declined in September before the end of rainy season. Spearman correlation coefficient showed that the relationship between density and precipitation was at 0.611 (P = 0.035), whilst the relationships between density and average temperature and between density and minimum temperature were at 0.74 (P=0.006) and 0.80 (P=0.02), respectively.

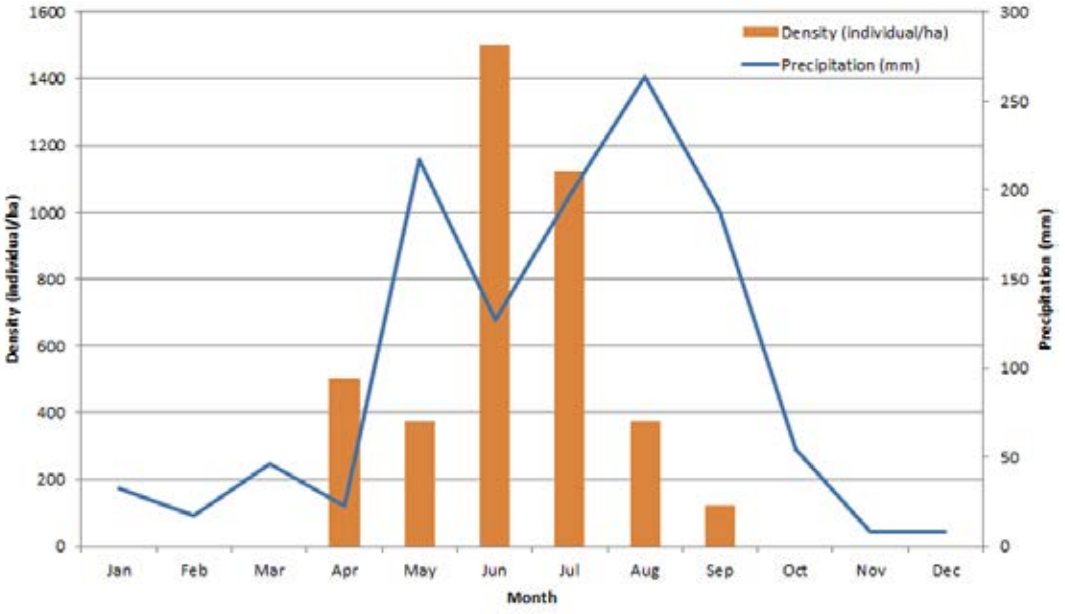

Figure 4.3 Population densities of *Zephronia* cf. *viridescens* in deciduous forest of Chulalongkorn University Forestry and Research Station during rainy season of 2009 in relation to year-round precipitation.

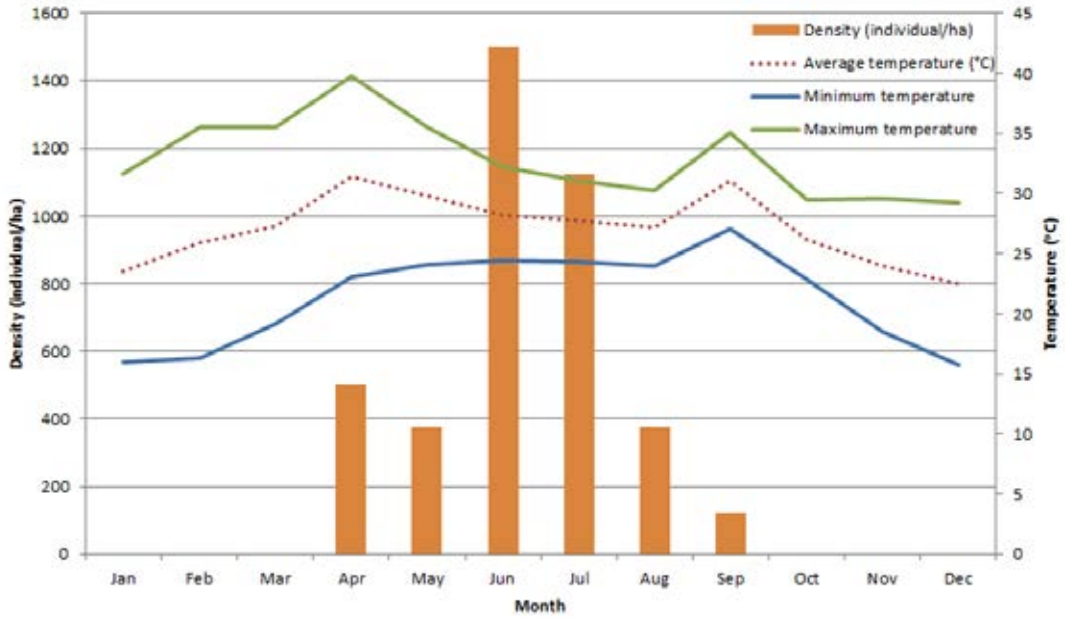

Figure 4.4 Population densities of *Zephronia* cf. *viridescens* in deciduous forest of Chulalongkorn University Forestry and Research Station. Data were recorded during rainy season of 2009 in relation to temperature.

Diapause

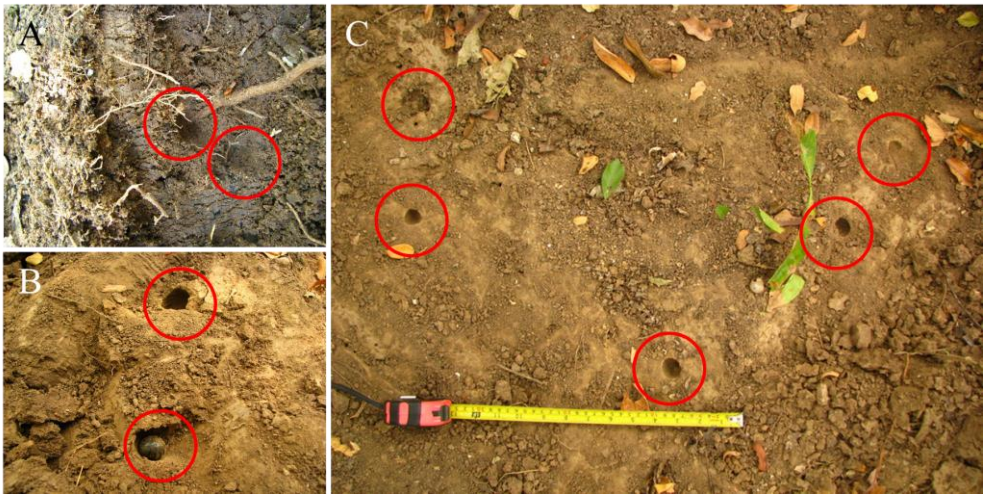

Figure 4.5 A-C: Dispersion of *Zephronia* cf. *viridescens* in deciduous forest during dry season at Chulalongkron University Forest Research Station, Nam Wa Sub-watershed, Lai-Nan Sub-district, Wiang Sa District, Nan Province.

Figure 4.6 Diapause area of *Zephronia* cf. *viridescens* during dry season; A-B: deciduous dipterocarp forest, C-D: mixed deciduous forest.

For the vertical dispersion study, only two individuals of the giant pill-millipede were found. One was found in December 2008 at 3 cm below the soil surface and another one was found at 3 cm in March 2009. With the small sample size, therefore, dispersion pattern cannot be interpreted.

The millipedes entered diapause in the same area not far from each other. Thus, their dispersion in dry season was clumped (Figs. 4.5A-C).

Diapause area in deciduous dipterocarp forest (Figs. 4.6A, B): A great numbers of the giant pill-millipede were found around the base of termite mound which was covered by large tree(s) or bamboo clump(s) with seedlings and saplings. A couple of wrinkled millipedes were found in the areas covered with little plant materials and exposed largely to sunlight. Moreover, a few individuals were found dead in the chamber at this area during dry season of 2010.

Diapause area in mixed deciduous forest (Figs. 4.6C, D): A huge numbers of the giant pill-millipedes were found around bamboo clumps and some of them were found near the tree base with 70-80% of forest crown cover.

Diapause chamber (Fig. 4.7A): The diameters of diapause chambers were approximately 2.5 – 3 cm, bigger than the millipede individual. The characters of the soil chamber were spherical shape and compact. The inner surface was smooth and harder than the soil particle surrounding it.

Figure 4.7 Soil chambers of the giant pill-millipede. A: diapause chamber; B: molting chamber.

Molting

During late dry season (March-April) the freshly exoskeleton giant pill-millipedes were found with their old exoskeleton in diapause chamber. Normally in rainy season, the giant pill-millipede molted in a spherical soil chamber which was similar to a diapause chamber. However, molting chamber was looser, softer and shallower than diapause chamber. The durations of molting process were estimated by the millipede disappearances from soil surface in rainy season. The data showed that the giant pill-millipede spent 2-4 weeks for molting process. Before molting, the millipede body was swollen, after that the old exoskeleton, including head and collum were splitted by new one. The giant pill-millipede then moved towards the crack, causing their tergites had trait similar to tattoo. Then, its legs and body was separated from the old exoskeleton. The new exoskeleton was weak and lighter than the old one. The millipede rotated in its chamber several times for rearrangement their body. Their exoskeleton became hard after several days and also changed to the natural colors in its chamber before emerging to the soil surface.

Growth

Mode of growth in giant pill-millipedes, including *Z*. cf. *viridescens* is called hemianamorphosis consisted of anamorphosis stadia and epimorphosis stadia. The results of both stadia are shown as followed:

Anamorphosis stadia (Fig. 4.8): The specimens were collected from under leave litter surrounded by seedlings of bamboo in mixed deciduous forest during late rainy season (August-September 2011). This is a second species of the giant pill millipede reported on anamorphosis development.

The giant pill-millipede, *Zephronia* cf. *viridescens*, tended to pass through eight anamorphosis stadia to become epimorphosis stadia (Table 1). The smallest size of observed anamorphosis millipede had six tergites (6 + (1+A)) and five pleurites with six leg pairs followed by the millipedes which had seven tergites and 6 pleurites with 10 leg pairs. Next stadium had eight tergites and 7 pleurites with 12 leg pairs. The larger had nine tergites millipedes and eight pleurites with 14 leg pairs. All of stadia from II to V had a certain number of leg pairs, while the leg pair in VI to VIII stadia had various numbers (n, n+1).

Moreover, some morphological characters of anamorphosis stadia also changed after molting such as an increasing of ocelli number and number of sensory cone on the antennae, including anal shield socket on latero-ventral side of thoracic shield. When the giant pill-millipede had body segment less than 10 + (1+A) in stadia II-V, the collum was not completely held by anal shield and the sockets were available (Figs. 4.9A, B) and compatible with its anal shield. Whilst the giant pill-millipede had body segment at least 10 + (1+A) in stadia VI, the collum was completely held by anal shield and the sockets were reduced (Figs. 4.9C, D).

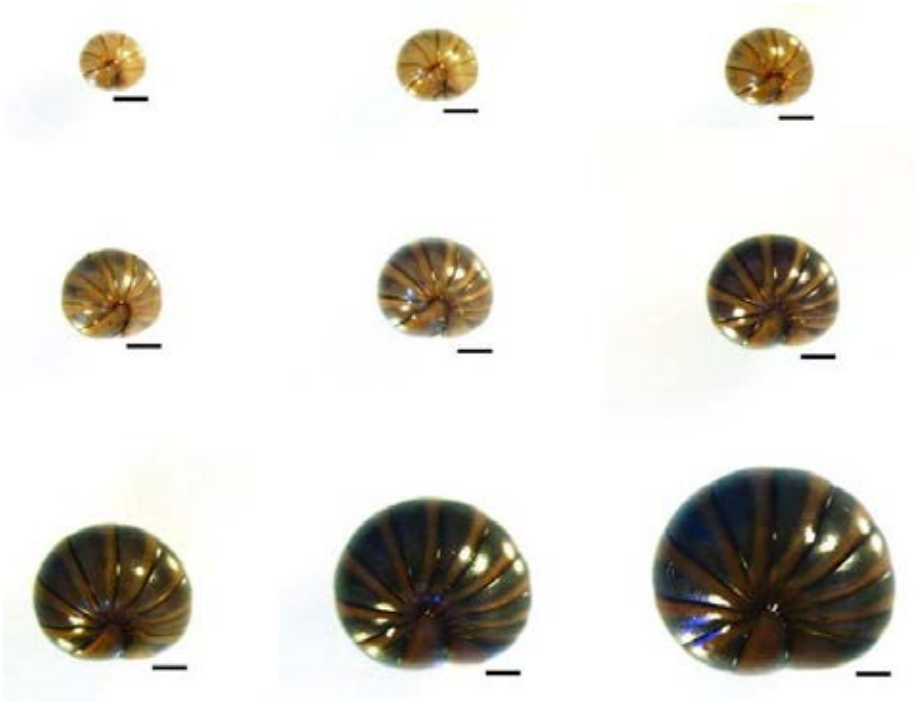

Figure 4.8 Anamorphosis in the giant pill-millipede *Z.* cf. *viridescens.* Scale bars = 1 mm.

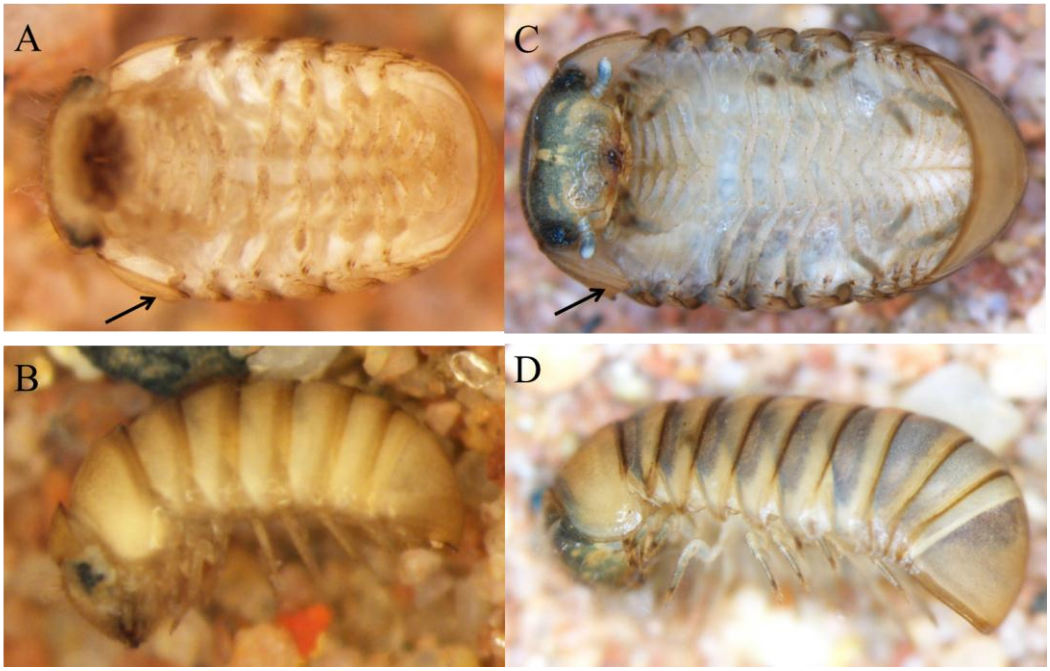

Figure 4.9 Reduction of anal shield socket in anamorphosis stadia. A, B = stadium III; C, D = stadium VI.

Remark: Up to now, egg laying site of *Z*. cf. *viridescens* is still unknown. However, the soil sample with millipede fecal pallets from the upper soil surface in this area was collected before these anamorphosis stadia specimens were found from the field. The four juvenile pill-millipedes in III stadium then were found after one month had passed. It might be possible that the upper soil surface or fecal pellet was egg laying site of *Z*. cf. *viridescens*.

Table 4.1 Anamorphosis stadia of *Zephronia* cf. *viridescens* from Nan Province. Abbreviation: n.a. = not available

stadiium	*I	II	III	IV	V	VI	VII	VIII
leg pairs	n.a.	6	10	12	14	16, 17	n.a.	20, 21
tergites	n.a.	6 + (1+A)	7 + (1+A)	8 + (1+A)	9 + (1+A)	10 + (1+A)	n.a.	12 + (1+A)
pleurites	n.a.	5	6	7	8	9	n.a.	11
no. of spms	n.a.	1	21	10	26	10, 3	n.a.	1, 1

*According to Dohle (1992), pupoid stage of the giant pill-millipede genus *Cyliosoma* has 3 pair of legs and the first known of free living stage has six tergites with 5 leg pairs. The giant pill-millipede, *Z*. cf. *viridescens*, with six tergites was assumed as second anamorphosis stadium (II).

Epimorphosis stadia: The data of epimorphosis growth of each individual could not be collected completely from juvenile to adult stages in this study because *Z.* cf. *viridescens* has long life span. This is the pilot study on epimorphic growth of the giant pill-millipede in the field. Length increments in one year for six millipedes were 3.5-5 mm and the molting frequency in smaller size was more than in larger size (Fig. 4.10). An estimation of molting numbers in *Z.* cf. *viridescens* from 34 different sizes of molting individuals in the enclosure by combining their size data was approximately at least 20 times. Preliminary data and graph were provided in Appendix 1 and Appendix 2, respectively.

At first stage of epimorphosis stadia, the giant pill millipede was in juvenile stage. Their telopod, gonopore (male) and vulva (female) developed every molting. They became adult when their volvated sizes were more than 16.4 mm (ca 8 epimorphosis stadia in male) and 15.3 mm (ca 7 epimorphosis stadia in female). The minimum size of the male giant pill-millipede which searched for mate in the field was 18.4 mm in volvated length.

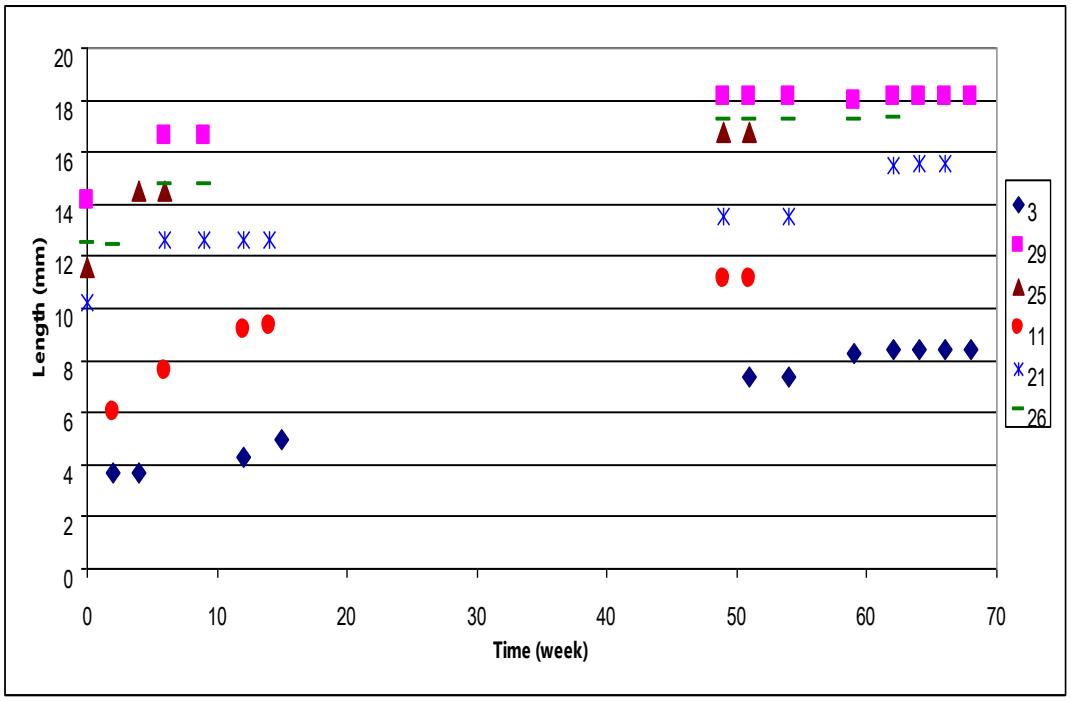

Figure 4.10 Yearly length increment of *Z.* cf. *viridescens*.

Sexual dimorphism

Z. cf. *viridescens* had no sexual size dimorphism. The dominant morphological characters showed in male were thoracic shield, ninth, tenth, eleventh, twelfth body segment, anal shield and sensorial cone number of the antennae. However, body sizes such as weight, length, height and width were not significantly different between sexes ($P < 0.05$). Summary of morphological differences was presented in Table 4.2. Moreover, the anal shield shape at horizontal line was concave in male while female had convex shape.

Table 4.2 Morphological differences between males and females

Morphological characters	Male (Mean ± SE)	Female (Mean ± SE)	p-value
Volvated length/volvated height	1.118 ± .002	1.129 ± .001	.000
No. of sensory cone on right antenna	70.70 ± 1.662	52.07 ± 1.097	.000
No. of sensory cone on right antenna	68 ± 2.308	53.23 ± 1.113	.000
Thoracic shield length/ volvated length	0.200 ± .002	0.192 ± .002	.008
Thoracic shield width/volvated width	0.952 ± .001	0.948 ± .001	.038
9 tergite width/ volvated width	0.988 ± .001	0.985 ± .001	.000
10 tergite width/ volvated width	0.968 ± .001	0.962 ± 0.001	.016
11 tergite width/ volvated width	0.941 ± .001	0.933 ± .001	.000
12 tergite width/ volvated width	0.907 ± .002	0.894 ± .001	.000
Anal shield length/ volvated width	0.510 ± .002	0.499 ± .001	.000
Anal shield width/ volvated width	0.810 ± .003	0.789 ± .003	.000

Discussions

Population density

An appearance of the giant pill-millipede, *Z.* cf. *viridescens* occurred only in rainy season between April to September of the year which related with precipitation and temperature. The population was highest in June and July and decline at the late of rainy season in September. The end of giant pill-millipede activity was before the end of rainy season similar to Julid millipede in Zimbabwe (Dangerfield and Telford, 1991). Therefore, precipitation may not be the only one factor which effected with its presentation. The increasing of temperature might be another factor which related with its appearance.

Year round life pattern

Figure 4.11 Year–round life pattern of *Zephronia* cf. *viridescens* in deciduous forest at Chulalongkron University Forest Research Station in at Nam Wa Sub-watershed, Lai-Nan Sub-district, Wiang Sa District, Nan Province.

According to the result of the activities of giant pill-millipedes *Z.* cf. *viridescens* in Chapter V and in this Chapter especially on diapause, molting and growth of them, it can be summarized in Figure 4.11 and can be concluded that the giant pill-millipedes dug into the soil and constructed the diapause chambers in late rainy season. They lived in the chamber individually throughout dry season. The millipedes molted one time in late dry season before emerging to soil surface in early wet season. In rainy season, adult millipedes spent most of the time feeding, searching for mate and mating, while juvenile millipedes spent most of the time feeding and molting. Molting of juveniles occurred one or a few times depending on their sizes. Each molting occurred in molting chamber and emerged to soil surface for feeding. After that, they entered diapause in soil chamber again in late rainy season.

The above life pattern shows a part of millipede adaptation in deciduous forest of tropical zone. Their activities are limited only in rainy season when natural resources such as diet are available for their survival and growth. Each individual emerges to the soil surface since it is a time for mate pairing. In contrast, during the dry season natural resources are limited especially precipitation which directly affect to other environmental factors. Therefore, millipedes did not active during dry season.

Diapause

Diapause area is important for survival of giant pill-millipedes in dry season. A huge number of individually diapause chambers of giant pill-millipede were found in the microhabitats such as base of termite mound and bamboo clump, dominated by 70-80% crown cover. Thus, these microhabitats should be suitable for diapause in dry season because they tend to have higher soil moisture than plain area. On the other hand, a few wrinkled millipedes and a dead millipede were found in the areas covered with little plant materials and exposed largely to sunlight. Therefore, this area is not suitable for diapausing. The difference in number of the millipedes between microhabitats shows that the millipedes have habitat selection for diapausing where they can have minimum transpiration rate across dry season. The duration to enter diapause of the giant pill-millipede occurred before dry season and diapausing period was similar to Lewis (1974) study which stated that most flat-back millipede species survive through the dry season in soil chambers. The spherical diapause chamber of the giant pill-millipede was constructed under the silt-soil surface from 3-10 cm in depth. This data showed that the giant pill-millipede has high potential for burrowing. The inner surface of the chamber was compact, smooth and harder than the soil particle surrounding it. Hopkin *and* Read (1992) stated that secretion glands in the millipede rectum involved in the building of chamber. Thus, it could decrease transpiration rate of millipede in dry season. Moreover, the giant pill-millipedes can roll into a complete ball (volvation), which is a good mechanism not only for protection of water loss but also for enemies. For example, volvation in genus *Sphaerotherium* provided an effective protection from

predators, such as ants, birds and mice (Eisner and Davis, 1967). In addition to defence from predators and water loss, volvation also could decrease energy, air and food requirements in the dry season (Lawrence, 1984; Hopkin and Read, 1992).

Molting

Molting of *Z.* cf. *viridescens* occurred at least 20 times during the period of epimorphosis stadia. Generally, the mature millipedes molted one time per year in diapause chamber during late dry season (March-April) before emerging, while the juvenile millipedes molted one time in diapause chamber and at least one time in rainy season depended on their size. The frequency of molting in matures and juveniles are similar to *Glomeris* millipede (Heath *et al*., 1974). The difference in molting frequency might be because of the negative correlation between metabolic rate and millipede size.

In rainy season, the giant pill-millipede naturally molted in a spherical soil chamber which supported new exoskeleton and protected them form external environment including their predators. Shape of molting chamber in *Z.* cf. *viridescens* was similar to Verhoeff (1928) report which stated that many pill-millipedes in genus *Glomeris* revolved themselves under soil surface to construct molting chambers with smoothly internal surface. This action has some similarities with diapause chamber construction in *Z.* cf. *viridescens* in Chapter V. Comparing to molting chamber in a closest group as pill-millipede in order Glomerida (Evans, 1910; Heath *et al*., 1974), the characters of *Z.* cf. *viridescens* chamber are similar to Glomerida such as a loosely simple soil chamber. Moreover, it also molted on mineral soil surface as found in other species. The molting chamber of *Z.* cf. *viridescens* was looser, softer and shallower than diapause chamber. The differences between characters of these chambers might be coincided with environmental factors such as soil water content and air moisture. Molting process of the giant pill-millipede occurred in rainy season which has higher moisture content, causing lower transpiration rate in the millipede than in dry season. Thus, it is not necessary to construct compact, strong and deep chamber as a diapause

chamber, which uses higher energy. This notion was supported by the study in laboratory of Heath *et al*. (1974) who reported that *Glomeris marginata* normally constructed loose soil and simple chamber but it also constructed thick soil chamber at 2-3 cm below the soil surface when soil moisture was low.

The duration of molting process in *Z.* cf. *viridescens*, estimated by the millipede disappearance from soil surface in rainy season, was approximately 2-4 weeks for molting in epimorphosis stadia. Molting period of them closely related to the molting period of *Glomeris* millipede which was between 2 to 3 weeks in laboratory (Helkka, 1958; Vannier, 1966; Verhoeff, 1937), from 2 to 4 weeks in tyerylene net bags placed in the field and could be less than 2 to 4 weeks for smaller millipedes (Heath *et al*., 1974).

The body weight of *Z*. cf. *viridescens* had decreased before entering the chamber for molting, which is similar to other arthropods, because at that time the animals do not feed. According to the previous studies in millipede molting process (Halkka, 1958; Verhoeff, 1928), *Z*. cf. *viridescens* has some similarities with cylindrical and flat-back-millipede. Their body was swollen before molting. Comparing to the old exoskeleton after molting, the new exoskeleton was softer and lighter. They spent several days changing the characters of their exoskeleton to come back to normal stage. However, molting process between the giant pill-millipede and other forms of millipedes are different. In the giant pill-millipede, split occurred at anterior part between head and collum, while in cylindrical and flat-back millipedes, a longitudinal split occurred along the mid ventral line and laterally above the legs (Hopkin *and* Read, 1992).

Growth

Egg laying site of *Z*. cf. *viridescens* is still unknown. However, four giant pill-millipedes of III stadium were found in the soil samples with millipede fecal pallets after one month had passed. Dohle (1992) found one egg and two pupoid larvae of the giant pill-millipede *Cyliosoma* sp. under rotten logs. This egg was surrounded by rotten wood

material. Therefore, it might be possible that upper soil surface or fecal pellet is egg laying site of *Z*. cf. *viridescens*.

Many other morphological characters changed during the millipede development. Some characters reduced within anamorphosis stadia such as the anal shield sockets on latero-ventral side of thoracic shield. Some characters increased after molting since anamorphosis stadia such as the number of ocelli and number of sensory cone on the antennae. Some characters developed within epimorphosis stadia.

The sockets on thoracic shield were found since the first known stadia and disappeared when the giant pill-millipede had 10 + (1+A) segments in stadia VI. At first period, the millipede's collum was not completely held by anal shield, the millipede had a few number of tergites, and also had a few locking carinae on latero-ventral tergites. These are probably not high potential enough for locking and protecting themselves from environmental factors. In the second period, their collum was completely held by the anal shield and also other characters were more developed, having a higher potential for rolling into a complete ball. This socket was not only found in Zephroniidae but also found in other order such as Madagascar giant pill-millipede from Wesener's study (unpublished data). Thus, the present of the sockets in the first period to increase their volvation efficiency when the millipede had a few tergites might be the adaptation for protecting themselves from environmental factors.

Anamorphosis stadia: Dohle (1992) stated that pupoid stage of the giant pill-millipede in genus *Cyliosoma* presented 3 leg pairs and first free living stage has 5 leg pairs. If the pattern of *Zephronia* cf. *viridescens* growth was similar to *Cyliosoma*, it has to pass 8 molting times or at least 1 to 2 years to be epimorphosis stadia. However, the number of leg pattern between species was different.

Epimorphosis stadia: The giant pill-millipedes are long life span animal. Therefore, the combination of each molting observed millipedes was chosen to apply in this study. Juvenile stage was found not only in anamorphosis stadia but also found in

epimorphosis stadia. At first stage of epimorphosis stadia, the secondary sexual characters of males and females did not function but they developed at each molting stage. Length increment per year of giant pill millipedes was approximately 3.5-5.0 mm. Thus, the minimum sizes of mature millipede were more than in 7-8 of epimorphosis stadium could be spent time at least 4 years and the giant pill-millipede life span could be at least 5 years.

The difference between sexes of *Z.* cf. *viridescens* was not found in size. The dominant morphological characters showed in male were thoracic shield, ninth, tenth, eleventh, twelfth body segment, anal shield and sensorial cone number of the antennae. Moreover, the anal shield shape at horizontal line was concave in male while female had convex shape. Some of these are difficult to observe. Therefore, the special attention should go to the shape of anal shield which easy to determine sex in field when the millipede volvating. This character might relate to mate pairing, including with the higher number of sensory cones on antenna may be used for detection female before mating. Both characters also dominate in other genera of family Sphaerotheriida (Verhoeff, 1928; Van den Spiegel *et al*., 2003, Wesener, 2005a; 2009)

CHAPTER V

DAILY ACTIVITY OF *Zephronia* cf. *viridescens*

Introduction

The number of described millipede species has been reported from 7,753 (Shear, 2011) to 12,000 with an estimated of 80,000 extant species in the world (Hoffman, 1979; Sierwald and Bond, 2007), including approximately 325 described species of giant pill-millipedes (order Sphaerotheriida) (Wesener *et al*., 2010). Giant pill-millipedes occur in discontinuous geographical areas (Jeekel, 1974; Hoffman, 1982; Shelley, 1999;, Wesener and VandenSpiegel, 2009), and have been separated into four families: Sphaerotheriidae in South Africa, Procyliosomatidae in Australia and New Zealand, Arthrosphaeridae in Southern India and Madagascar, and Zephroniidae in Southeast Asia and the Sunda Islands (Wesener and VandenSpiegel, 2009).

Activity patterns in most animals, including feeding and reproduction, are influenced by environmental factors, such as temperature changes, rainfall, day-length and food availability. For example, peak activity of the cylindrical millipede *Ommatoiulus moreletii* (order Julida) in South Australia occurs during autumn to early winter when adults are actively searching for food, mates and oviposition sites (Baker, 1979). The activities of cylindrical millipedes (superorder Juliformia) in Zimbabwe were found to increase rapidly after emergence from the soil at the beginning of the rainy season and then to decline a couple of weeks later (Dangerfield and Telford, 1991). In southern India, the abundance and biomass of the giant pill-millipede *Arthrosphaera magna* were positively correlated with rainfall during the monsoon season (Ashwini and Sridhar, 2006).

Previous studies have not monitored activities of millipedes directly throughout the day in their habitats. Most studies were conducted in laboratory or using indirect

observation methods such as pitfall traps or quadrat sampling (Cloudsley-Thompson, 1951; Banerjee, 1967b; Bano and Krishnamoorthy, 1979; Boccardo and Penteado, 1995; Koilraj *et al*., 1999, 2000; Tuf *et al*., 2006; Kadamannaya and Sridhar, 2009). To date, only a few observations on the ecology of the millipedes in family Zephroniidae have been reported, although it is the biggest family of giant pill-millipedes. The present study focuses on daily activities, daily movement and some other aspects of behavior of a zephroniid millipede species in a deciduous forest in northern Thailand, which is a part of the Indo-Burma biodiversity hotspot (Myers *et al*., 2000).

Material and Methods

Identity of the studied species

The giant pill-millipedes of Thailand are very poorly known. Although several species obviously exist, only one has been recorded, viz., *Zephronia siamensis* Hirst, 1907, from the Si Chang Island in the Gulf of Thailand, Chonburi Province and from Chantaburi Province (Enghoff, 2005). According to the original description (Hirst, 1907) and after comparison with newly collected topotypical material of *Z. siamensis*, the species studied here is not that species. Instead, it is very similar to *Z. viridescens* Attems, 1936, described from a specimen from Dawei, southeastern Myanmar (Attems, 1936; Jeekel, 2001). However, because of some differences, we refer to the studied species as *Zephronia* cf. *viridescens*.

Study area

Daily activities of *Z.* cf. *viridescens* were investigated during the rainy season in July–September 2009 and May–September 2010 in Chulalongkorn University Forestry and Research Station. The area covers 340 ha in size and is located between N2051960 – 2054260 and E0688400 – 0693060 in UTM zone 47Q at Nam Wa sub-watershed, Lai-Nan Sub-district, Wiang Sa District, Nan Province (Fig. 5.1). The elevation ranges from

200–260 meters above mean sea level. This area is covered by secondary deciduous dipterocarp forest and mixed deciduous forest dominated by *Dipterocarpus obtusifolius*, *D. tuberculatus*, *Shorea obtusa*, *S. siamensis*, *Pterocarpus macrocarpus* (Dumrongrojwatthana *et al*., 2009) and bamboo (*Gigantochloa albociliata*). The forest floor is covered by saplings and seedlings, including a leaf litter of up to 3 cm in depth throughout the year.

Figure 5.1 Study area of *Zephronia* cf. *viridescens* activities in Chulalongkorn University Forestry and Research Station.

Observation of activities

Sixteen males and 23 females of *Z.* cf. *viridescens* were collected. Each millipede was sexed and weighed, and its length, width and height were measured while it was in the rolled up ball shape (Wongthamwanich *et al*., 2012). Then it was marked with acrylic color on the anal shield and released back to its original habitat. Every 30 minutes over 24 hours, it was recorded whether the millipede was feeding, walking, mating or resting. Any other types of behavior were recorded as well. The positions of the millipede at each sampling time were marked by small flags. A small stick was used to open the leaf litter during each observation when the millipede was under the cover. A flashlight covered with red cellophane was used for nighttime observation in order to minimize disturbance. The number of changed positions observed at each recording time within one day was counted for evaluation of the frequency of movement. The accumulated distances from the initial to the final positions were determined for estimating the daily distance moved, while the distance between the starting and end points was determined for the daily linear displacement.

Relative humidity, air temperature at 130 cm above the ground in the shade and soil temperature at 5 cm depth were recorded. The 24 hours observation period was subdivided based on these physical factors (Fig. 5.2). The proportions of feeding, walking and resting were plotted against time. Differences between activities of males and females were compared in relation to daytime versus nighttime periods or to physical factors, using Chi-square tests. Differences in daily movements between males and females were compared using the Mann-Whitney U tests.

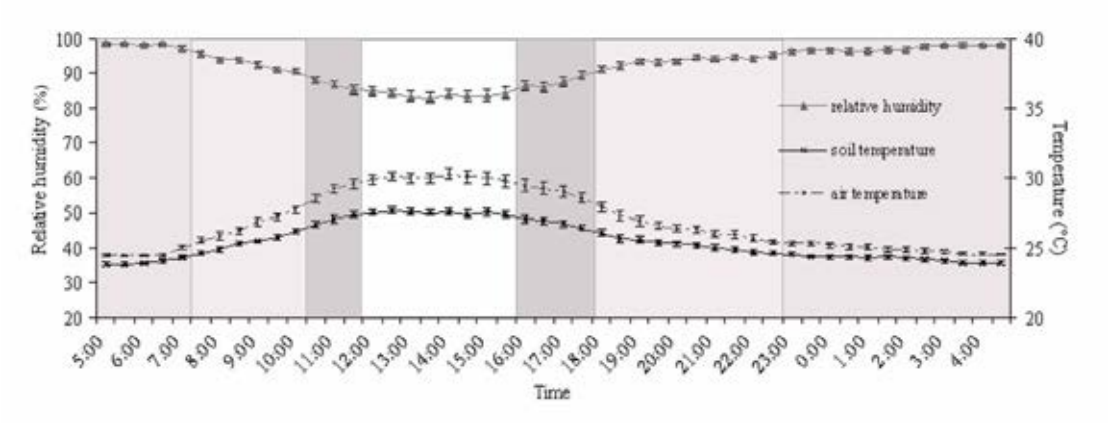

Figure 5.2 Daily variation in physical factors (Mean ± SE) within the study area during the study period. The shadows indicate periods with similar environmental factors: white = time at lowest humidity and highest temperature (LestH, HestT), dark gray = time at low humidity and high temperature (LH, HT), light gray = time at high humidity and low temperature (HH, LT) and gray = time at highest humidity and lowest temperature (HestH, LestT).

Result

Daily activities

The total numbers of *Z.* cf. *viridescens* millipedes observed in each time period are summarized in Table 1. The proportions of the three key daily activities of these 39 specimens (16 male, 23 females) are shown in Figures 5.3 and 5.4. Overall, over the 24 hour period, the millipedes spent an average of 57.4% of their time feeding, followed by resting, and with walking the lowest of the three at 12.1% (Fig. 5.3). Mating activity was not found in any of the 39 marked millipedes during the survey period, even though it was observed in other specimens in the area.

Table 5.1 Number of marked *Z.* cf. *Viridescens* specimens observed in the rainy season of 2009 and 2010 at Lai-Nan forest, Nam Wa sub-watershed, Lai-Nan Sub-district, Wiang Sa District, Nan.

Sex	Jul-09	Aug-09	Sep-09	May-10	Jun-10	Jul-10	Aug-10	Sep-10	Total number observed
Male	3	3	3	0	2	4	1	0	16
Female	3	3	3	4	4	0	1	5	23
Total	6	6	6	4	6	4	2	5	39

The proportion of individuals observed walking is shown in Figure 5.4A. The males had a significantly higher walking activity than females during daytime (Table 5.2; χ^2 = 15.8, df = 1, P ~ 0.000), nighttime (Table 5.2; χ^2 = 26.6, df = 1, P ~ 0.000), and also throughout the 24 hour period (Table 5.2; χ^2 = 40.2, df = 1, P ~ 0.000). The walking activity of male millipedes seemed to have three peaks per day (Fig. 5.4A), coinciding with the high humidity and the low temperature period (7:30–8:00 hrs and 20:30 to 23:00 hrs) and the lowest humidity and the highest temperature period (14:30 hrs). In these periods, walking activity of males was also significantly higher than females (Table 5.3; $\chi^2_{HH,LT}$ = 21.1, df = 1, P ~ 0.000; $\chi^2_{LestH,HestT}$ = 13.3, df = 1, P ~ 0.000). However, there were small peaks during the night, at dawn, at dusk and during daytime. The female's walking frequency tended to be higher during daytime than during nighttime with peak in the morning, ranging from broadly 5:00 to 11:00 hrs (but with no activity at 7:30 hr). There was no significant difference in walking between daytime and nighttime in either sex (Table 5.2; χ^2_{male} = 0.2, df = 1, P = 0.657; χ^2_{female} = 2.6, df = 1, P = 0.108). The mobility of females was low at night, whilst the mobility of males peaked at this time. The high level of male walking activity tended to coincide with a low (80% RH) or high (100% RH) relative humidity (Table 5.4; χ^2 = 10.6, df = 4, P = 0.031)

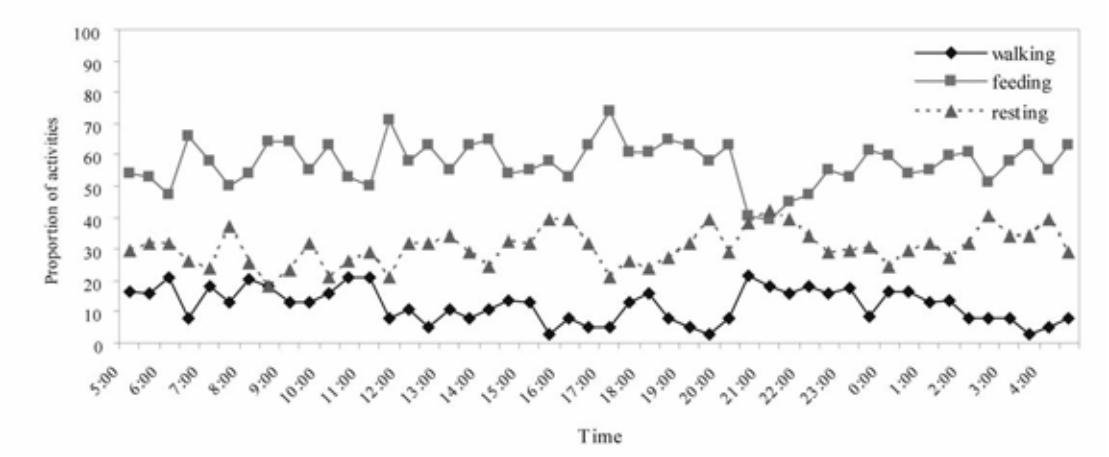

Figure 5.3 Proportion of *Z.* cf. *viridescens* individuals engaged in each type of activity over a 24-hour time interval. Data are from 39 individual millipedes (Table 5.1).

The proportion of individuals observed feeding over the 24 hour period (Fig. 5.4B) was not significantly different between males and females (Table 5.2; χ^2 = 1.8, df = 1, P = 0.175). However, it was significantly higher in females than in males during daytime (Table 5.2; χ^2 = 4.9, df = 1, P = 0.027), related to the lowest humidity and the highest temperature period at 12:00–15:30 hrs (Table 5.3; χ^2 = 7.1, df = 1, P = 0.008). Feeding activity in males seemed to be high in the evening (17:00 and 18:30–20:00 hrs), with smaller peaks of activity in the morning (6:30 and 9:00–9:30 hrs). However, there was no significant difference between daytime and nighttime in male feeding activity (Table 5.2; χ^2 = 0.2, df = 1, P = 0.660). The feeding activity in females tended to peak slightly at 6:30–7:30 and 8:30–10:00 hrs, with more significant peaks at 11:30–12:30, 13:30–14:30 and 17:00 hrs, and decrease during 20:30–22:00 hrs. Indeed, females mainly fed during daytime (Table 5.2; χ^2 = 5.5, df = 1, P = 0.019). There were no significant sexual differences in feeding in relation to environmental factors; however, females tended to feed more when humidity was low (Table 5.4; χ^2 = 9.1, df = 4, P = 0.059)

Table 5.2 The activity level (%) of *Z.* cf. *viridescens* over a 24 hour period, daytime and nighttime, during the rainy season in 2009 and 2010 at Nam Wa Sub-watershed, Lai-Nan Sub-district, Wiang Sa District, Nan Province, with the number of observations in parentheses.

Analysis period	Sex		%Walking	%Feeding	%Resting
[a]Total 24 hours	Male (716)		18.2 (130)	55.4 (397)	26.4 (189)
	Female (1096)		8.2 (90)	58.7 (643)	33.1 (363)
		χ^2	40.2***	1.8	9.2**
[b]Daytime	Male (420)		17.6 (74)	54.8 (230)	27.6 (116)
	Female (643)		9.3 (60)	61.6 (396)	29.1 (187)
		χ^2	15.8***	4.9*	0.3
[c]Nighttime	Male (296)		18.9 (56)	56.4 (167)	24.7 (73)
	Female (453)		6.6 (30)	54.5 (247)	38.9 (176)
		χ^2	26.6***	0.3	16.2***
[d]Daytime-nighttime	Male	χ^2	0.2	0.2	0.8
	Female	χ^2	2.6	5.5*	11.5***

[a-c]Comparison of the activity level (%) between males and females for [a] the 24 hour period, [b]daytime (5:00 - 18:30 hrs), and [c]nighttime (19:00 - 4:30 hrs) only.

[d]Comparison of the activity levels between daytime and nighttime

Levels of statistical significance at * $P \leq 0.05$, ** $P \leq 0.01$ and ***$P \leq 0.001$

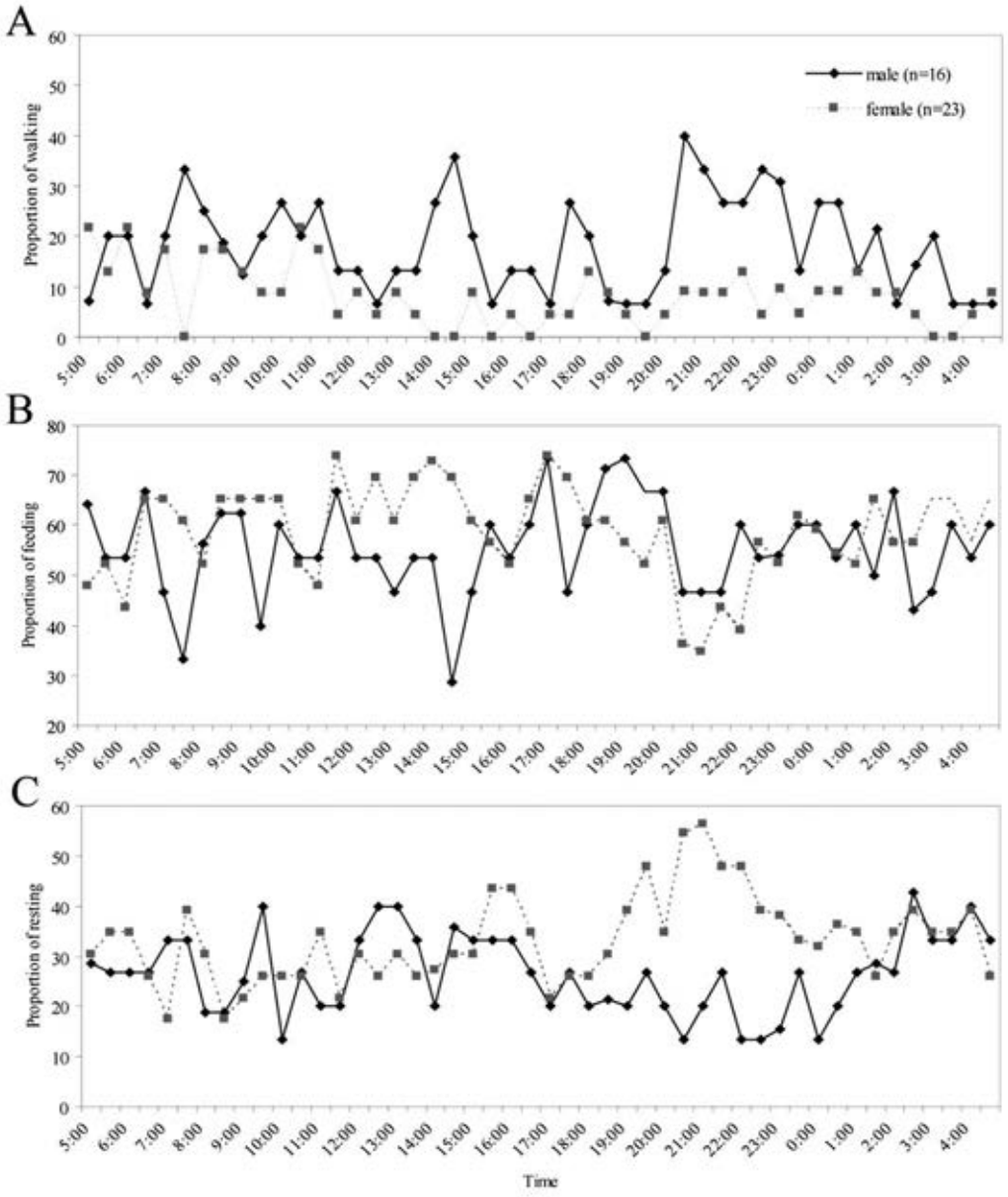

Figure 5.4 Comparison between male and female *Z.* cf. *viridescens* over a 24-hour period for the proportion of individuals (A) walking, (B) feeding and (C) resting. Data are derived from 16 male and 23 female individuals (Table 5.1).

Table 5.3 The activity level (%) of *Z.* cf. *viridescens* over a 24 hour period, specified according to environmental factors during the rainy season in 2009 and 2010 at Nam Wa Sub-watershed, Lai-Nan Sub-district, Wiang Sa District, Nan Province, with the number of observations in parentheses.

Analysis period	Sex	%Walking	%Feeding	%Resting
[a]Highest humidity (HestH),	Male (250)	15.6 (39)	56.0 (140)	28.4 (71)
lowest temperature (LestT)	Female (385)	9.6 (37)	57.9 (223)	32.5 (125)
	χ^2	5.2*	0.2	1.2
[b]High humidity (HH),	Male (242)	21.9 (53)	56.6 (137)	21.5 (52)
low temperature (LT)	Female (367)	8.7 (32)	54.8 (201)	36.5 (134)
	χ^2	21.1***	0.2	15.5***
[c]Low humidity (LH),	Male (105)	17.1 (18)	58.1 (61)	24.8 (26)
high temperature (HT)	Female (161)	8.1 (13)	62.1 (100)	29.8 (48)
	χ^2	5.1*	0.4	0.8
[d]Lowest humidity (LestH),	Male (119)	16.8 (20)	49.6 (59)	33.6 (40)
highest temperature (HestT)	Female (183)	4.4 (8)	65.0 (119)	30.6 (56)
	χ^2	13.3***	7.1**	0.3

[a-d]Comparison of the activity level (%) between males and females for [a]time at highest humidity and lowest temperature (23:00 – 7:00 hrs), [b]time at high humidity and low temperature (7:30 – 10:00 hrs and 18:00 – 22:30 hrs), [c]time at low humidity and high temperature (10:30 – 11:30 hrs and 16:00 – 17:30 hrs) and [d]time at lowest humidity and highest temperature (12:00 – 15:30 hrs).

Levels of statistical significance at * $P \leq 0.05$, ** $P \leq 0.01$ and ***$P \leq 0.001$

Table 5.4 The activity level (%) of *Z.* cf. *viridescens,* specified according to environmental factors, with the number of observations in parentheses, during the rainy season in 2009 and 2010 at Nam Wa Sub-watershed, Lai-Nan Sub-district, Wiang Sa District, Nan Province.

Analysis factor		%Walking		%Feeding		%Resting	
		Male	Female	Male	Female	Male	Female
T_{air} (°C)	24	17.7 (17)	12.5 (21)	54.2 (52)	58.3 (98)	28.1 (27)	29.2 (49)
	25	21.7 (39)	11.3 (23)	58.3 (105)	54.2 (110)	20.0 (36)	34.5 (70)
	26	25.4 (30)	7.8 (9)	53.4 (63)	56.9 (66)	21.2 (25)	35.3 (41)
	27	12.2 (10)	6.5 (10)	54.9 (45)	54.2 (84)	32.9 (27)	39.4 (61)
	28	10.5 (6)	7.9 (6)	56.1 (32)	57.9 (44)	33.3 (19)	34.2 (26)
	29	9.8 (4)	7.8 (7)	53.7 (22)	63.3 (57)	36.6 (15)	28.9 (26)
	30	17.9 (7)	8.8 (5)	46.2 (18)	70.2 (40)	35.9 (14)	21.1 (12)
	χ^2	11.7	5.3	2.3	6.7	12.7*	8.9
T_{soil} (°C)	23	9.7 (3)	9.8 (8)	48.4 (15)	62.2 (51)	41.9 (13)	28.0 (23)
	24	21.3 (43)	10.3 (25)	59.4 (120)	55.0 (133)	19.9 (39)	34.7 (84)
	25	22.6 (37)	12.9 (22)	57.3 (94)	57.1 (97)	20.1 (33)	30.0 (51)
	26	15.0 (17)	5.1 (10)	50.4 (57)	57.9 (114)	34.5 (39)	37.1 (73)
	27	13.1 (11)	9.2 (13)	52.4 (44)	59.2 (84)	34.5 (29)	31.7 (45)
	28	10.5 (2)	9.4 (3)	36.8 (7)	62.5 (20)	52.6 (10)	28.1 (9)
	χ^2	7.8	7.1	6.2	1.9	25.7***	3.8
%RH	80	25.0 (2)	12.5 (1)	50.0 (4)	75.0 (6)	25.0 (2)	12.5 (1)
	85	11.3 (6)	6.8 (8)	50.9 (27)	63.6 (75)	37.7 (20)	29.7 (35)
	90	7.5 (3)	7.8 (6)	70.0 (28)	66.2 (51)	22.5 (9)	26.0 (20)
	95	14.0 (20)	7.7 (15)	53.8 (77)	50.5 (99)	32.2 (46)	41.8 (82)
	100	22.2 (82)	10.9 (51)	54.5 (201)	57.5 (268)	23.3 (86)	31.5 (147)
	χ^2	10.6*	3.3	4.2	9.1	8.0	11.2*

Levels of statistical significance at * $P \leq 0.05$ and ***$P \leq 0.001$

In this study, resting was observed in addition to walking and feeding (Fig. 5.4C). The proportion of individuals resting was not significantly different between females and males during daytime (Table 5.2; χ^2 = 0.3, df = 1, P = 0.605), but during nighttime females rested significantly more than males (Table 5.2; χ^2 = 16.2, df = 1, P ~ 0.000), coinciding with the high humidity and low temperature period (Table 5.3; χ^2 = 15.5, df = 1, P ~ 0.000). Females spent most of the time resting between 19:00 and 23.00 hrs, time during which males rested the least. Resting in males was rather sporadic throughout the 24-hour period, with no significant difference between nighttime and daytime (Table 5.2; χ^2 = 0.8, df = 1, P = 0.337), while in females it was significantly higher during nighttime (Table 5.2; χ^2 = 11.5, df = 1, P = 0.001). The high level of resting in females tended to coincide with a high humidity of 95% RH (Table 5.4; χ^2 = 11.2, df = 4, P = 0.024), while that in males tended to coincide with a high air temperature (Table 5.4; χ^2 = 12.7, df = 6, P = 0.048) and low (23 °C) or high (28 °C) soil temperatures (Table 5.4; χ^2 = 25.7, df = 5, P ~ 0.000).

Daily movement

The daily movement of the millipedes, segregated by sex, is summarized in Table 5.5 The daily distance moved by males was significantly higher than in females (Mann-Whitney U Test: Z = -2.46, P = 0.014), whilst the longest daily distance movement in males (3,690 cm) was some 3.3-fold greater than that in females (1,121 cm). In addition, the displacement in male millipedes was significantly higher than that in females (Mann-Whitney U Test: Z = -2.11, P = 0.035), with the longest displacement in males (1,014 cm) being 1.3-fold longer than that in females (768 cm). However, the frequencies of movement of males and females were not significantly different (Mann-Whitney U Test: Z = -1.26, P = 0.208).

Table 5.5 Mass, size and daily movement of *Z.* cf. *viridescens* observed during the rainy season in 2009 and 2010 at Nam Wa Sub-watershed, Lai-Nan Sub-district, Wiang Sa District, Nan Province.

Parameters	Males (n = 16) Mean ± SE	Females (n = 23) Mean ± SE
Mass (g)	2.3 ± 0.2	3.3 ± 0.2
Length in ball shape (mm)	17.9 ± 0.7	20.5 ± 0.5
Mean distance moved in a day (cm)	1,080 ± 226	486 ± 59
Median distance moved in a day (cm)*	898	475
Range of distance moved in a day (cm)	193 – 3,690	23 – 1,121
Mean displacement in a day (cm)	403 ± 62	269 ± 32
Median displacement in a day (cm)*	428	261
Range of displacement moved in a day (cm)	120 – 1,014	18 – 768
Mean frequency moved in a day (time)	15 ± 3	10 ± 1
Median frequency moved in a day (time)	13	10
Range of frequency moved in a day (time)	2 – 34	1 – 23

*Significantly different at $P \leq 0.05$.

Notes on types of behavior

Walking (Fig. 5.5A): *Z.* cf. *viridescens* were observed walking randomly using the sensorial cones on their antenna tips to touch objects above the ground surface as they moved from one position to another to search for resources, such as food and shelter. They were also observed walking from an open area exposed to the sunlight, with or without leaf litter, to a shaded area. Walking speed was observed to be faster in exposed area than in shaded area.

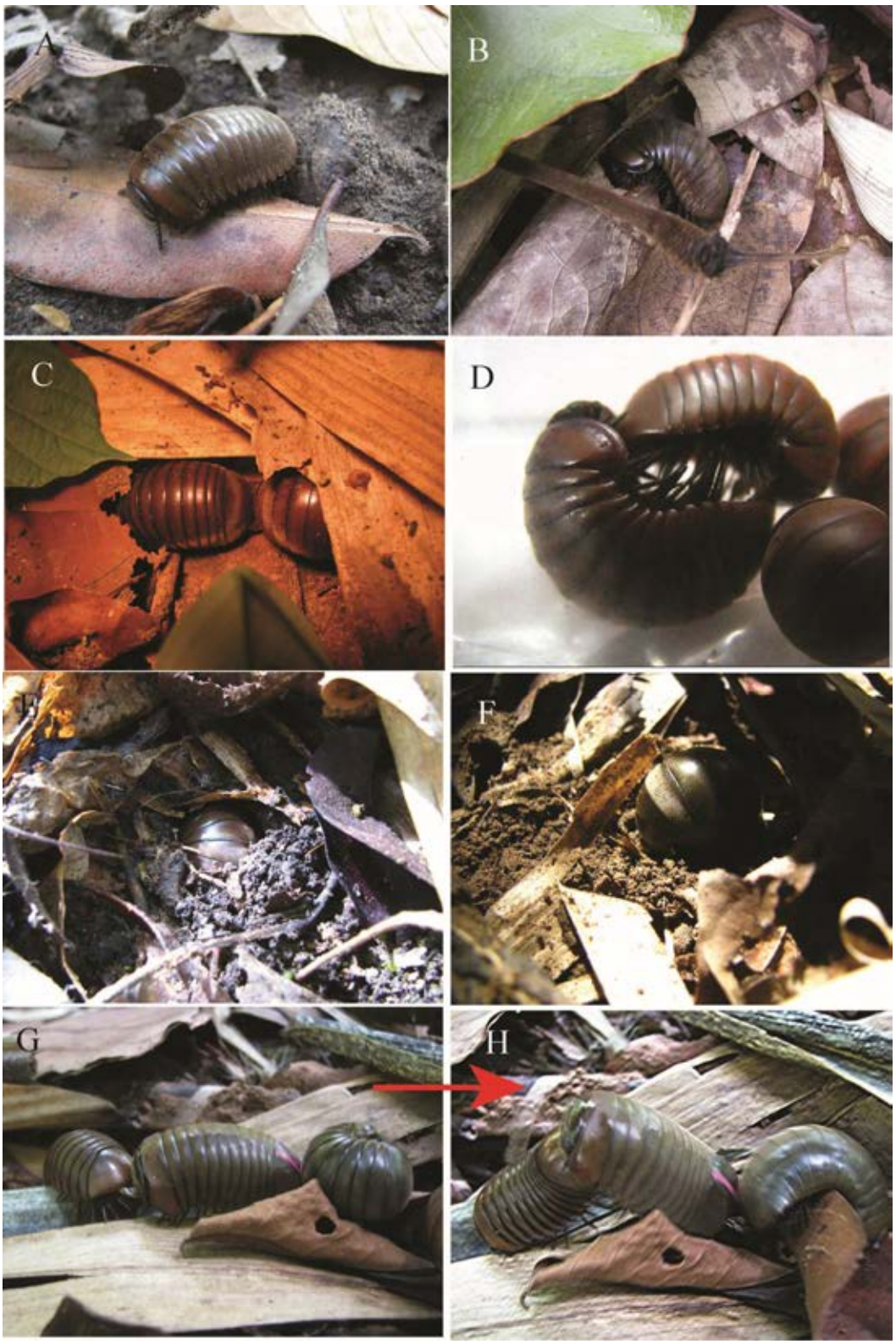

Figure 5.5 *Z.* cf. *viridescens* behaviors, **Digital photographs**, **A**: Walking; **B**: Feeding; **C-D**: Mating; **E-F**: Resting; **G-H**: Guarding.

Feeding (Fig. 5.5B): The millipedes usually spent most of the time feeding under the leaf litter. They un-rolled, curved themselves a little bit and moved their anterior parts to feed. Their feet were used to control the direction of the leaf litter. They could feed continuously for more than one hour, and a few millipedes fed throughout the 24-hour period. When they encountered a dry leaf with low moisture, they took a shorter time, less than five minutes, for feeding and then went on searching for another food item. Their diets in the study area consisted of leaf litter and soil particles. Most of the leaf litter was from *Gigantochloa albociliata*, *Bauhinia* spp. and *Pterocarpus macrocapus*, with a moisture content of more than 90% (w/w).

Mating (Figs. 5.5C, D): Some un-marked male millipedes were observed to approach marked females. The walking routes of males were similar to those of females. Males used their sensorial cones on the antenna tips to search not only for food, but also for finding mates. When the female did not allow the male to mate, the male then attempted to continuously follow the same female throughout the night. Upon approaching a female, the male walked slowly backwards and turned his anal shield to the female, extending his telopods to the female's anal shield as much as possible. When the female was un-rolled, the male used his telopod to raise the posterior part of the female, which caused the female to turn over. Then, the male walked rapidly backwards to the ventral side of the female. If the female rolled into a ball shape, the male tended to wait for her to unroll, which was sometimes more than 20 minutes later. Moreover, the male used his telopod to raise another male that was walking near the female (Fig. 5.4G, H).

Resting (Fig. 5.5E, F): Giant pill-millipedes roll themselves into a ball shape for resting. This was mostly seen to occur after feeding on leaf litter in the same position between the soil surface and under the leaf litter or among litter strata (Fig. 5.5F). Two individuals were observed to burrow a few centimeters at the soil surface to rest underneath the litter (Fig. 5.5E). Other two individuals were also seen resting between litter strata at a bamboo clump throughout the cloudy day. In this case the average soil

surface temperature and average relative humidity were 26.4 °C and 87.9%, respectively.

Other activities: Besides the above three behaviors, some other activities were observed, such as defecation and burrowing. After feeding, some millipedes were in a C-shape, and then rotated for a minute before defecating. However, most of the observed defecations occurred whilst feeding. During the late rainy season, in September 2009, a male millipede was observed burrowing into the soil layer under a tree. Soil particles were subsequently sent from the anterior to the posterior feet and then to the ground surface. This millipede then rotated itself around the soil and continually burrowed into a deep soil layer. Twenty-four hours later, the millipede was found at 5 cm depth below the soil surface.

Discussion

Daily activities

The present study revealed that the two most frequently observed activities of *Z.* cf. *viridescens*, namely feeding and walking, occurred throughout the day. However, earlier works have reported that most millipedes in the tropical zone show a higher level of movement at dusk or nighttime (Cloudsley-Thompson, 1951; Banerjee, 1967b; Bano and Krishnamoorthy, 1979; Boccardo and Penteado, 1995; Koilraj *et al*., 1999, 2000; Tuf *et al.,* 2006; Kadamannaya and Sridhar, 2009). Although *Z.* cf. *viridescens* have ocelli for detecting light, they spend most of the daytime and nighttime doing activities under leaf litter. Therefore, light may not be an important factor influencing their activity. The difference between the result of this study on *Z.* cf. *viridescens* and those of other studies may be due to the different habitat types, because the transpiration rate of millipedes, temperature, humidity and precipitation in various habitats are different. This notion is supported by previous data which reported that the distribution of millipedes

was closely correlated to their transpiration (Haacker, 1968) and the nocturnal habits of tropical arthropods are presumably related to their high transpiration rate in the daytime, which is dependent upon the amount of moisture content in the atmosphere (Cloudsley-Thompson, 1959). Webb and Telford (1995) explained that the transpiration rate was positively correlated with oxygen consumption level in the juliform millipede *Alloporus bilobatus*. Here, the resting behavior during the daytime could decrease their metabolic rate, oxygen consumption and transpiration rate. Moreover, the lower temperature during nighttime was described as a trigger for activities (Cloudsley-Thompson, 1951). For *Z*. cf. *viridescens*, the microclimate in their habitat (Fig. 5.2) changed a few degrees between daytime and nighttime with high relative humidity (more than 80 %) throughout the day. Thus, transpiration rate may not be high enough to influence their daytime activities. Moreover, the millipedes could reduce their transpiration rate during the daytime by walking rapidly from sun-exposed to shady areas and spend more time feeding between the soil and the leaf litter or litter strata.

The proportion of *Z*. cf. *viridescens* individuals feeding throughout the 24 hour period was not significantly different between the sexes. Therefore, it is possible that males need broadly similar amounts of energy in their diet as females in the rainy season. The feeding of *Z*. cf. *viridescens* males tended to be high in the morning hours (6:30, 7:30–8:00 hrs) and at dusk (17:00–17:30 and 18:00–20:00 hrs) is somewhat consistent with a previous investigation of giant pill-millipedes in India (Kadamannaya and Sridhar, 2009). In the afternoon (12:00 to 13:30 hrs), males of *Z*. cf. *viridescens* tended to rest when the temperature was highest with a lowest relative humidity, which is similar to that reported for *Arthrosphaera dalyi* and *A. davisoni* in a plantation in India (Kadamannaya and Sridhar, 2009). Thus, temperature and humidity could influence millipede activity, in accordance with previous reports (Perttunen, 1953; Banerjee, 1967b; Tuf *et al*., 2006). Although female *Z*. cf. *viridescens* spent a relatively high proportion of their time feeding from morning until dusk, they rested at moderately high levels in late afternoon for a short period of time (Fig. 5.4C).

The amount of time spent on walking, and more so for male than female, is also similar to that reported for juliformian and flat-backed millipedes (Dangerfield *et al.,* 1992; Rowe, 2010). The proportion of walking in *Z*. cf. *viridescens* males was highest during nighttime (20:30–23:00 hrs). This could be explained by males using their energy and time to search for females. In contrast, the proportion of females resting was higher than that for males throughout the day and it was highest during nighttime (20:30–22:00 hrs). This would potentially serve the purpose of decreasing the metabolic rate and so accumulating energy in the rainy season to invest in egg maturation. Therefore, from the movement of males and females, the mating behavior in *Z*. cf. *viridescens* may well occur at nighttime more frequently than in the daytime.

Distance moved and displacement

No previous study has reported on the daily movement of millipedes on the ground surface. In this study, daily distance moved and daily displacement were higher in males than in females of *Z*. cf. *viridescens*. The higher mobility in male millipedes may increase their opportunity for mate finding and mating, whilst the lower movement in females may increase the available time for feeding and resting to accumulate energy for egg reproduction in the breeding season. This idea was supported by previous studies (Wise, 1975; Ballinger, 1977; Boggs and Ross, 1993), which showed that fecundity was positively related with food and energy availability.

Other adaptations for survival and reproduction

The behavior of *Z*. cf. *viridescens* in a deciduous forest during the rainy season was dominated by feeding, in accordance with other millipedes studied previously (Dangerfield *et al.,* 1992; Kadamannaya and Sridhar, 2009). Feeding appears to be the most important activity, presumably for accumulating and storing energy reserves for the forthcoming dry season, as well as for reproduction in terms of either future reserve allocation to egg production in the more sedentary females, or investing in walking in the

more active males for mate finding and mating. In addition, Lawrence (1984) stated that the intestine of giant pill-millipedes in relation to body length is longer than in most other millipede groups and bends in an 'N' shape for storing enough food material to supply the large body size, a potential adaptation for diapause during the dry season.

In a deciduous forest, food components like leaf litter and soil particles are not limiting because they remain numerous on the soil surface throughout the year. The mobility of *Z.* cf. *viridescens* in part reflects its optimal foraging strategy, where walking to new areas assists in searching for a high quality diet within their habitat; this is consistent with previous studies on *Julus scandinavius* (order Julida) (Kheirallah, 1979) and *Alloporus uncinatus* (order Spirostreptida) (Dangerfield and Telford, 1993). Sakwa (1974) mentioned that the important factors that affect food acceptance for millipedes include the nitrogen content, sugar levels and moisture content of the leaf litter. Therefore, dietary selection could result from nutrition requirement, food availability, food type and microhabitat of millipede species. However, no theoretical approaches such as optimal foraging or game theory based models have evaluated the foraging strategy of millipedes in heterogeneous habitats, nor has the quality of the habitat been assessed.

In this study, *Z.* cf. *viridescens* walks and uses sensorial cones on the antennae to make contact with the surrounding area (Fig. 5.5A). Since male *Z.* cf. *viridescens* can find females in their habitat whilst walking, it is possible that females secrete sex pheromone(s) onto the forest floor to attract males in the breeding season. This notion is supported by the studies on other millipede species such as *Glomeris marginata* (order Glomerida) and *Ommatoiulus moreletii* (order Julida), which produce pheromone to attract each other over very short distances (Hopkin and Read, 1992). Moreover, in many other millipede species, males could not mate successfully if they did not have their antennae (Haacker, 1974), suggesting chemical involvement in mate finding, recognition and acceptance.

In contrast to the courtship behavior of pill-millipedes in the genus *Sphaerotherium* (Haacker, 1974; Wesener *et al*., 2011), *Z.* cf. *viridescens* males did not

produce any sound but used body contact and waited for females to unroll (Fig. 5.5C). However, the mating behavior of *Z.* cf. *viridescens*, such as the male's backward walk to the female and their reversed copulation position with their ventral sides adjacent to each other (Fig. 5.5D), is similar to that of other pill-millipedes (Haacker, 1974; Wesener *et al*., 2011). In addition, a male *Z.* cf. *viridescens* was observed to follow a female and attack another male who came close to her (Figs. 5.5G, H). If supported by further future observation, this is of interest as there are no previous reports on precopulatory mate guarding in millipedes. Postcopulatory mate guarding which was not observed in *Z.* cf. *viridescens* has been reported in *Alloporus uncinatus* (order Spirostreptida) (Telford and Dangerfield, 1990), and *Nyssodesmus python* (order Polydesmida) (Adolph and Geber, 1995). Both types of mate guarding can increase mating success and fitness of the male (Parker, 1974; Waage, 1979).

During the rainy season, some *Z.* cf. *viridescens* were observed to burrow into the shallow layer of the upper soil surface to rest (Fig. 5.5E), which is similar to the burrowing behavior for resting reported in European millipedes (Haacker, 1967, 1968) and Indian giant pill-millipedes (Kadamannaya and Sridhar, 2009). The burrowing behavior for diapause of *Z.* cf. *viridescens* was also observed at the end of September in the late rainy season. The result is similar to the observation on other millipede species, such as the paradoxosomatids and gomphodesmids (order Polydesmida), which enter chambers at the same time for diapause (Lewis, 1974).

CHAPTER VI

CONCLUSION AND RECOMMENDATION

Conclusion

Thailand is located in Indo-Burma biodiversity hotspot which has high forest destruction and habitat lost. However, there are few data in taxonomy and ecology of many organisms including the giant pill-millipedes. This work is the first step of the giant pill-millipede study in Thailand focused on species diversity and ecology of the giant pill-millipedes in Nan Province where many mountains including various forest habitats exist. Therefore, this area has been expected to have high diversity of the giant pill-millipedes. For the species diversity of the giant pill-millipede in family Zephroniidae, the specimens were collected in rainy season during 2009-2011. Two genera, genus *Sphaerobelum* Verhoeff, 1924 and genus *Zephronia* Gray, 1832 in family Zephroniidae were dominated in Nan Province. Generally, genus *Sphaerobelum* presented in higher moisture habitats such as moist deciduous forest and evergreen forest, while genus *Zephronia* presented in drier habitats in mixed deciduous forest and dry deciduous dipterocarp forest. Each morphospecies of the giant pill-millipedes was found only in its collected locality. Therefore, it can be concluded that the millipedes of family Zephroniidae in Nan Province are the micro-endemic species which is similar to many species of the Malagasy giant pill-millipedes.

Population ecology of the giant pill-millipede *Zephronia* cf. *viridescens* was studied in deciduous forest of Chulalongkorn University Forestry and Research Station, Nam Wa Sub-watershed, Lai-Nan Sub-district, Wiang Sa District, Nan Province. Population density, dispersion, daily activities, diet and growth were investigated in the field.

Population density of the giant pill millipede *Zephronia* cf. *viridescens* was studied in 2009. Twenty of 2×2 m^2 quadrats were sampling randomly each month for one year. Abundance of *Z*. cf. *viridescens* was highest on soil surface in rainy season during June to July, while it was absent in dry season. Two of *Z*. cf. *viridescens* were found under soil surface at 3 cm in dry season in a sampling plot of December, 2008 and March, 2009.

The daily activities of *Z*. cf. *viridescens* such as walking, resting, feeding and mating were recorded every 30 minutes throughout the day during rainy season of 2009-2010. The result showed that they spent most of the time, daytime and nighttime, under leaf litter for feeding. Another major activity of both sexes occurred mainly at nighttime, resting in female and walking in male, was for the purpose of mating. Diets of giant pill millipedes were observed in the field and parts of plants were collected for identification. It was found that the millipedes fed more than 20 species of plants. The major litter species was *Gigantochloa albociliata* and *Bauhinia* spp.

According to *Z*. cf. *viridescens* digging into the soil in late wet season, this is the evidence of preparing solitary diapause chamber for dry season. The giant pill millipedes aggregated in their spherical chambers, 3-10 cm in the soil around the bamboo clump, termite nest and mound. They molted in compact diapause chamber in late dry season (March-April, 2010). Normally, the small sizes of millipedes molted one or two times based on their sizes in loose soil chamber during rainy season.

Growth of giant pill millipedes was studied during rainy season of 2009-2011. Samples of *Z*. cf. *viridescens* were collected and placed in enclosures within their habitat. Their body sizes; weight, length, height, and width in ball shape were measured individually every 2 weeks. It was found that the body weights of these specimens decreased before molting and increased after molting which is similar to other arthropods. The development from juvenile to adult was more than 4 years and their life spans were estimated to be more than 5 years. In addition, the frequency of molting in small millipedes was more than large millipedes.

Thirty males and 30 females were collected for comparing the differences in morphology between sexes. The dominant morphological characters of males were thoracic shield, ninth segment, tenth segment, eleventh segment, twelfth body segment, anal shield and sensorial cone number of the antennae. These morphologies represent the high performance for mating and reproduction.

Recommendation

There are at least 14 morphospecies of giant pill-millipedes based on field surveys of species diversity in Nan Province. It is expected that all of them are new species. Therefore, numerous species of the giant pill-millipedes are waiting for discovery not only in Nan Province but also in Thailand and Southeast Asia. However, this region is at risk for habitat lost and forest destruction, thus taxonomic works and ecological studies of the giant pill millipedes should be conducted urgently before some of them will be lost in the near future. The number of millipede species in family Zephroniidae is more than in other families and this family is problematic because the type specimen from genus Zephronia is losing. Therefore, urgent works for this family should be done especially the selection of the neotype. Moreover, their biology, ecology, behavior and molecular evolution should be conducted in the future.

The ecological study of *Z.* cf. *viridescens* is the case study in a deciduous forest habitat. Normally, its population lives in mixed deciduous forest and deciduous dipterocarp forest. In rainy season, they are highly active on soil surface, while they disappear from soil surface in dry season. According to their diapausing data, millipede samples were found in higher soil moisture areas such as at bamboo base, termite nest and mound covered by seedlings, saplings and had crown cover more than 70%. The high potential areas for conserving water content belong to the mixed deciduous forest. To maintain millipede diversity, their natural habitat should be conserved.

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APPENDICES

Appendix A

Epimorphic growth of the giant pill-millipedes, *Z.* cf. *viridescens* in enclosures in mixed deciduous forest at Chulalongkorn University Forestry and Research Station, Nan Province during 2009-2011.

Individual	Date	Weight	Long	Height	Width
1	27/6/2010	0.08	6.3	5.6	5
1	16/7/2010				
1	28/7/2010				
1	16/8/2010	0.13	7.3	6.4	5.7
1	7/9/2010	0.14	7.3	6.4	5.7
2	21/7/2009	0.60	6.45	5.65	4.80
2	6/8/2009	1.00	6.50	5.70	5.20
2	20/8/2009	1.00	6.70	5.80	5.25
2	4/9/2009				
2	18/9/2009	1.60	7.75	6.50	5.85
2	1/10/2009				
2	25/10/2009	1.80	7.65	6.65	6.10
3	27/6/2010	0.02	3.7	3.3	3
3	16/7/2010	0.01	3.7	3.3	3
3	28/7/2010				
3	16/8/2010				
3	7/9/2010	0.03	4.3	3.75	3.35
3	19/9/2010				
3	30/9/2010	0.04	5	4.4	4
3	22/5/2011				
3	5/6/2011	0.15	7.4	6.45	5.8
3	26/6/2011	n.a.	7.4	6.45	5.8
3	31/7/2011	0.2	8.3	7.3	6.6
3	20/8/2011	0.23	8.4	7.3	6.6
3	2/9/2011	0.21	8.4	7.3	6.6
3	19/9/2011	0.21	8.4	7.3	6.6
3	3/10/2011	0.21	8.4	7.3	6.6
4	21/7/2009	0.70	6.55	5.85	5.20
4	6/8/2009	1.00	6.75	6.00	5.30
4	20/8/2009	1.5	7.65	6.65	5.90
4	4/9/2009	1.50	7.65	6.65	5.90
4	18/9/2009	1.80	7.65	6.65	5.90
4	1/10/2009	1.80	7.65	6.65	6.10
4	25/10/2009	2.50	8.80	7.65	6.80

Appendix A (Cont.)

Individual	Date	Weight	Long	Height	Width
5	16/8/2010	0.07	6	5.3	4.8
5	7/9/2010	0.07	6	5.3	4.8
5	19/9/2010				
5	30/9/2010				
5	22/5/2011				
5	5/6/2011	0.24	9.2	8.1	7.2
5	26/6/2011		9.2	8.1	7.2
5	31/7/2011	0.31	9.1	8.1	7.2
5	20/8/2011	0.3	9.2	8	7.3
5	2/9/2011				
6	6/8/2009	2.20	8.60	7.40	
6	20/8/2009	2.20	8.50	7.45	6.80
6	4/9/2009				
6	18/9/2009	3.50	9.90	8.70	7.80
6	1/10/2009	3.60	9.90	8.70	7.90
6	25/10/2009				
7	19/6/2009	1.60	8.20	7.15	n.a.
7	2/7/2009	4.00	10.20	8.90	
8	15/6/2010	0.27	9.4	8.1	7.3
8	27/6/2010	0.32	9.3	8.2	7.3
8	16/7/2010	0.28	9.4	8.3	7.3
8	28/7/2010				
8	16/8/2010	0.32	9.8	8.65	7.8
8	7/9/2010				
9	27/6/2010	0.28	9.3	8.2	7.4
9	16/7/2010	0.25	9.3	8.2	7.4
9	28/7/2010	0.29	9.3	8.2	7.4
9	16/8/2010				
9	7/9/2010	0.44	10.85	9.6	8.6
9	19/9/2010	0.45	10.9	9.6	8.6
9	30/9/2010	0.46	10.9	9.6	8.6
10	27/6/2010	0.06	6	5.2	4.7
10	16/7/2010				
10	28/7/2010	0.16	7.6	6.75	5.8
10	16/8/2010				
10	7/9/2010	0.27	9.2	8.15	7.2
10	19/9/2010	0.29	9.3	8.15	7.2
10	30/9/2010				
10	22/5/2011	0.49	11.1	9.8	8.9
10	5/6/2011	0.48	11.1	9.8	8.9

Appendix A (Cont.)

Individual	Date	Weight	Long	Height	Width
11	8/6/8/2009	3.20	10.00	8.65	
11	8/20/8/2009	3.40	9.90	8.70	8.00
11	9/4/9/2009	4.10	11.30	9.90	9.00
12	19/6/2009	2.90	9.70	8.50	n.a.
12	2/7/2009	4.40	11.90	10.45	n.a.
12	17/7/2009	6.10	12.00	10.50	n.a.
12	6/8/2009	6.30	12.00	10.60	9.70
12	20/8/2009	6.2	12.00	10.60	9.70
12	4/9/2009	5.80	12.10	10.60	9.70
12	18/9/2009	6.5	12.00	10.60	9.70
12	1/10/2009				
12	25/10/2009	7.50	12.50	10.95	10.40
13	6/19/2009	4.60	11.60	10.35	n.a.
13	2/7/2009	6.10	11.50	10.30	n.a.
13	17/7/2009	7.50	12.90	11.50	n.a.
14	15/6/2010	0.6	12.8	11.4	10.6
14	27/6/2010	0.88	13.4	11.8	10.7
14	16/7/2010	0.77	13.4	11.8	10.7
14	28/7/2010	0.83	13.4	11.8	10.7
15	19/9/2010	0.41	10.55	9.25	8.35
15	30/9/2010	0.41	10.55	9.25	8.35
15	22/5/2011				
15	5/6/2011	0.88	14.3	12.7	11.3
15	26/6/2011	n.a.	14.3	12.7	11.3
15	31/6/2011	1.1	14.3	12.6	11.4
15	20/8/2011	1.15	14.3	12.7	11.3
16	19/6/2009	0.88	13.85	12.40	n.a.
16	2/7/2009	1.07	14.30	12.80	n.a.
17	19/9/2010	0.76	12.2	10.7	9.8
17	30/9/2010	0.64	12.2	10.7	9.8
17	22/5/2011	1.28	15.1	13.5	12.6
17	5/6/2011	1.29	15.1	13.5	12.6
17	26/6/2011	n.a.	15.1	13.5	12.6
17	31/7/2011	1.47	15.1	13.6	12.6

Appendix A (Cont.)

Individual	Date	Weight	Long	Height	Width
18	15/6/2010	0.62	12	10.5	9.8
18	27/6/2010	0.64	12	10.5	9.8
18	16/7/2010				
18	28/7/2010	0.89	13.3	11.75	11
18	16/8/2010	0.93	13.3	11.75	11
18	7/9/2010				
18	19/9/2010				
18	30/9/2010				
18	22/5/2011	1.34	15.4	13.5	12.6
18	5/6/2011	1.33	15.4	13.5	12.6
18	26/6/2011	n.a.	15.4	13.5	12.6
18	31/7/2011	1.4	15.4	13.5	12.6
18	20/8/2011	1.4	15.4	13.55	12.6
18	2/9/2011	1.39	15.4	13.6	12.6
18	19/9/2011	1.39	15.4	13.6	12.6
19	15/6/2010	0.83	13.25	11.7	10.9
19	27/6/2010				
19	16/7/2010				
19	28/7/2010	1.18	15.6	13.7	12.7
20	15/6/2010	0.38	10.2	8.95	8.2
20	27/6/2010				
20	16/7/2010				
20	28/7/2010	0.75	12.65	11.2	10.4
20	16/8/2010	0.85	12.65	11.2	10.4
20	7/9/2010	0.74	12.65	11.2	10.4
20	19/9/2010	0.77	12.65	11.2	10.4
20	30/9/2010				
20	22/5/2011	1.02	13.5	12	11.3
20	5/6/2011				
20	26/6/2011	n.a.	13.5	12	11.4
20	31/7/2011				
20	20/8/2011	1.38	15.5	13.8	13
20	2/9/2011	1.35	15.6	13.9	13
20	19/9/2011	1.37	15.6	13.9	13

Appendix A (Cont.)

Individual	Date	Weight	Long	Height	Width
21	19/9/2010	0.74	12.7	11.3	10.4
21	30/9/2010	0.76	12.7	11.3	10.4
21	22/5/2011	1.09	14.3	12.7	11.9
21	5/6/2011	1.1	14.3	12.8	11.9
21	26/6/2011	n.a.	14.3	12.8	11.9
21	31/7/2011				
21	20/8/2011	1.38	15.6	14.1	13.1
21	2/9/2011	1.28	15.6	14.1	13.1
22	5/6/2011	1.02	14.4	12.7	11.8
22	26/6/2011	n.a.	15.8	14.1	13.3
22	31/7/2011	1.59	15.6	14	13.3
23	27/6/2010	0.81	14	12.2	11.6
23	16/7/2010	1.03	14	12.3	11.5
23	28/7/2010				
23	16/8/2010				
23	7/9/2010				
23	19/9/2010	1.43	15.7	13.9	12.9
23	30/9/2010	1.45	15.7	13.9	12.9
24	15/6/2010	0.54	11.6	10.1	9.5
24	27/6/2010				
24	16/7/2010	0.84	14.5	12.7	11.6
24	28/7/2010	1.09	14.5	12.8	11.6
24	16/8/2010				
24	7/9/2010				
24	19/9/2010				
24	30/9/2010				
24	22/5/2011	1.54	16.8	14.8	13.6
24	5/6/2011	1.52	16.8	14.8	13.6
25	15/6/2010	0.67	12.5	10.9	10.1
25	27/6/2010	0.78	12.4	10.9	10.1
25	16/7/2010				
25	28/7/2010	1.16	14.7	13	12
25	16/8/2010	1.24	14.7	13	12
25	7/9/2010				
25	19/9/2010				
25	30/9/2010				
25	22/5/2011	1.84	17.2	15	14.2
25	5/6/2011	1.86	17.2	15.1	14.2
25	26/6/2011		17.2	15.1	14.2
25	31/7/2011	2.08	17.2	15.1	14.2
25	20/8/2011	2	17.3	15.25	14.2

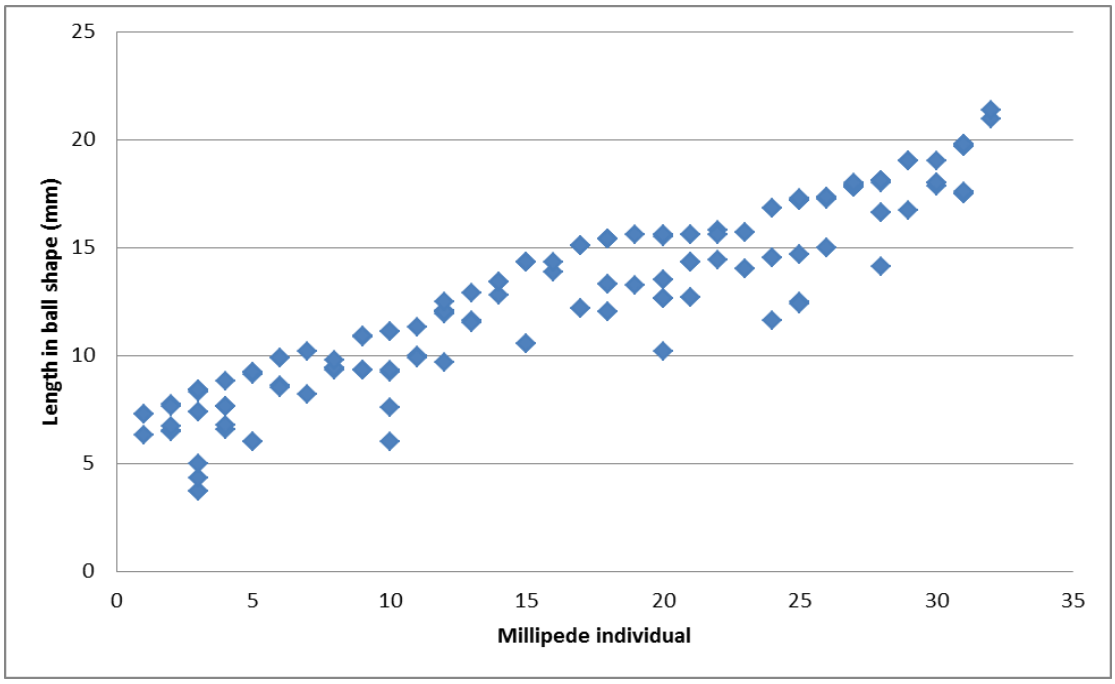
Appendix A (Cont.)

Individual	Date	Weight	Long	Height	Width
26	15/6/2010	1.18	15	13.2	12
26	27/6/2010	1.3	15	13.2	12
26	16/7/2010				
26	28/7/2010	1.82	17.25	15.4	14.2
26	16/8/2010	1.63	17.3	15.4	14.2
26	7/9/2010	1.41	17.35	15.4	14.2
26	19/9/2010	1.71	17.35	15.4	14.2
26	30/9/2010	1.68	17.35	15.4	14.2
27	9/5/2011	1.36	17.8	15.7	14.7
27	5/6/2011	1.23	17.8	15.7	14.7
27	26/6/2011	n.a.	17.8	15.7	14.7
27	31/7/2011	2.22	17.8	15.7	14.7
27	20/8/2011	2.25	17.9	15.7	14.7
27	2/9/2011	2.07	17.9	15.7	14.7
27	19/9/2011	2.05	17.9	15.7	14.7
27	3/10/2011	2.31	18	16	14.6
28	15/6/2010	1.04	14.1	12.5	11.8
28	27/6/2010				
28	16/7/2010				
28	28/7/2010	1.72	16.6	14.6	13.9
28	16/8/2010	1.82	16.6	14.6	13.9
28	7/9/2010				
28	19/9/2010				
28	30/9/2010				
28	22/5/2011	1.97	18.1	16.1	15.1
28	5/6/2011	2.21	18.1	16.1	15.1
28	26/6/2011	n.a.	18.1	16.1	15.1
28	31/7/2011	2.46	18	16.1	15.2
28	20/8/2011	2.42	18.1	16	15.1
28	2/9/2011	2.27	18.1	16	15.1
28	19/9/2011	2.35	18.1	16	15.1
28	3/10/2011	2.32	18.1	16	15.1
29	15/6/2010	1.78	16.7	14.7	13.9
29	27/6/2010				
29	16/7/2010				
29	28/7/2010	2.45	19	17	15.75
29	16/8/2010	2.36	19	17	15.75
29	7/9/2010	1.99	19	17	15.75

Appendix A (Cont.)

Individual	Date	Weight	Long	Height	Width
30	21/7/2009	1.87	17.85	16.15	15.40
30	6/8/2009	2.34	18.00	16.20	15.50
30	20/8/2009	2.28	18.00	16.20	15.50
30	4/9/2009	2.42	18.00	16.25	15.50
30	18/9/2009	2.82	19.00	17.00	15.40
31	15/6/2010	1.96	17.5	15.7	14.9
31	27/6/2010	2.3	17.5	15.7	14.9
31	16/7/2010	2.07	17.5	15.7	14.9
31	28/7/2010	2.21	17.6	15.7	14.9
31	16/8/2010				
31	7/9/2010				
31	19/9/2010				
31	30/9/2010				
31	22/5/2010	2.94	19.7	17.6	16.2
31	5/6/2011	2.8	19.7	17.6	16.2
31	26/6/2011	n.a.	19.7	17.6	16.2
31	31/7/2011	3.06	19.8	17.7	16.2
31	20/8/2011	3.11	19.8	17.7	16.3
31	2/9/2011	2.96	19.8	17.7	16.3
31	19/9/2011	2.97	19.8	17.7	16.3
31	3/10/2011	3.03	19.8	17.7	16.3
32	6/8/2009	3.08	20.95	18.00	n.a.
32	20/8/2009	3.10	21.35	18.40	17.50

Appendix B



Length increment after molting of *Z.* cf. *viridescens* population.

BIOGRAPHY

Miss Nattarin Wongthamwanich was born on March 2, 1980 in Ratchaburi Province. She enrolled in the Department of Biology, Faculty of Science, Chulalongkorn University, majoring in Zoology and received her Bachelor's degree in May 2002. After that, she became a Master student in Department of Forestry, Kasetsart University, majoring in Forest Management and graduated in May 2005. Then, she took a career as a researcher at King Mongkut's University of Technology Thonburi from November 2005 to March 2007. She continued her study for the degree of Doctor of Phylosophy in Biological Sciences Program with a major in Ecology, Faculty of Science, Chulalongkorn University in 2007. During her study, she had an experience working with millipede experts at Field Museum, USA for one month. She attended and presented part of her works in three international conferences at Malaysia, Australia and Singapore.

Publications

Wongthamwanich, N., Panha, S., Sierwald, P., Wesener, T. and Thirakhupt, K. 2012. A new species of the giant pill-millipede genus *Sphaerobelum* Verhoeff, 1924 from northern Thailand, with an extensive description and molecular characters (Diplopoda: Sphaerotheriida: Zephroniidae). *Zootaxa* **3220**: **29–43**.

Wongthamwanich, N., Panha, S., Sitthicharoenchai, D., Pradatsundarasar, A., Seelanan, T., Enghoff, H. and Thirakhupt, K. 2012. Daily activities of *Zephronia* cf. *viridescens* Attems, 1936 (Diplopoda: Sphaerotheriida: Zephroniidae) in a deciduous forest in northern Thailand. *Zoological Studies* (accepted with some revisions, May 2, 2012).