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Observations on pill-millipedes of the Western Ghats (India)

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Abstract This paper deals with general information on the distribution, ecology, bioconversion, systematics, conservation and highlights the gaps in our knowledge on the rare and endemic pill-millipedes belonging to the genus *Arthrosphaera* of the Western Ghats of India. So far about 50 morphospecies of *Arthrosphaera* have been reported from India and Sri Lanka. *Arthrosphaera* showed restricted distribution and endemic to specific geographic locations of the Western Ghats due to limited dispersal ability and they are rare in west coast locations. They invade organically managed plantations in the Western Ghats and their biomass was positively correlated with soil moisture, soil organic carbon and soil calcium. However, their richness was higher in the forests than plantations due to accessibility to heterogeneous organic matter. Four *Arthrosphaera* spp. maintained on the mixed leaf litter diet under laboratory conditions showed 75% survival at the end of 12 months. *Arthrospahera*possess good ability of conversion of decomposed leaf litter in to organic manure in the form faecal pellets. Systematics of *Arthrosphaera* currently based mainly on morphology and a few studies dealt with chromosome and molecular biology. As these pill-millipedes are sensitive to narrow spatial scales, their occurrence or invasion of a specific location denotes improved soil qualities. Based on the *ex situ* maintenance, pill-millipedes serve as good candidates for compost production using biodegradable solid wastes. Strategies necessary for *ex situ* and *in situ* conservation of pill-millipedes have been suggested.

Key words: Western Ghats, Pill-millipedes, *Arthrosphaera*, Ecology, Bioconversion, Systematics, Conservation

Introduction

Millipedes are important in organic matter recycling in a wide variety of habitats by mechanical fragmentation and deposition of faecal pellets, which increases the surface area for bacterial and fungal colonization (Hopkin and

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Read, 1992). Conservative estimates of richness of the class Diplopodaexceeds 80,000 species representing the third diverse class after hexapods and arachnids, but only up to 12,000 species are described showing the major gap in our knowledge (Golovatch*et al*., 1995; Hoffman *et al*., 1996, 2002; Pitz and Sierwald, 2010). Currently, the order Sphaerotheriida consists of 325 species (Wesener*et al*.,2010), which has discontinuous geographical distribution (South Africa, Madagascar, Oriental region, New Zealand and Australia) (Jeekel, 1974; Hoffman, 1982; Shelley, 1999; Wesener and vandenSpiegel, 2009). The order Sphaerotheriida encompasses four families: i) Sphaerotheriidae (South Africa): ii) Procyliosomatidae (Australia and New Zealand); iii) Arthrosphaeridae (southern India and Madagascar); iv)Zephroniidae (or Sphaeropoeidae) (Southeast Asia, Sunda Islands and Seychelles) (Wesener and vandenSpiegel, 2009). Currently, Zephroniidae is the richest family consisting of 140 species belonging to 14 genera (Wesener*et al*.,2010).Among the pill-millipedes, *Glomeris* are common in temperate regions, *Arthrosphaera* has disjunct distribution mainly in tropics, *Sphaeromimus* and *Zoosphaerium* are known from Madagascar and *Cynotelopus* restricted to Western Australia (Main *et al*., 2002; Wesener and Sierwald, 2005a, 2005b; Sierwald and Bond, 2007; Wesener*et al*., 2010). Based on the molecular evaluation of *Arthrosphaerabrandtii*, Wesener*et al*. (2010) considered the giant pill-millipedes of Madagascar as a paraphyletic group and the genus *Sphaeromimus* is the sister-taxon of the genus *Arthrosphaera*of India.

Pill-millipedes belong to the genus *Arthrosphaera* are large-bodied devoid of poison glands and roll-up into a complete ball varies from a marble up to a baseball showing island gigantism (e.g. Madagascar) (Wesener*et al*., 2010). Although they are endemic to the tropics and distributed in widely separated geographic regions of South Africa, Madagascar, India, Australia and New Zealand, later they were wiped off in the intermediate regions due to unsuitable climatic conditions (Pocock, 1892, 1899; Wesener*et al*., 2010). Recently some studies have been carried out on the occurrence, distribution, diurnal periodicity, morphology, cytology, influence of soil edaphic factors, leaf litter preference, organic matter processing and gut bacteria of *Arthrosphaera*of the Western Ghats (e.g. Ashwini and Sridhar, 2005, 2006a, 2006b, 2006c; Kadamannaya and Sridhar, 2009a, 2009b;Kadamannaya*et al*., 2010a, 2010b; Kämpfer*et al*., 2011). Studies on pill-millipedes of the Western Ghats are challenging as they are conservative and largely habitat-dependent (e.g. soil/forest floor and climatic features) and needs precise edaphic conditions.The present paper focuses on documenting the current knowledge on the distribution, ecology, bioconversion, systematics and conservation of *Arthrosphaera*in the Western Ghats of India.

Distribution

In 1892, Pocockrevealed that peninsular India encompass 27 species of *Arthrosphaera*.Subsequent studies showed the occurrence up to 50 species in the Western Ghats, Eastern Ghats and Sri Lanka (Pocock, 1899; Attems, 1936; Chowdaiah, 1962, 1966, 1969; Chowdaiah and Kanaka, 1974; Achar 1980, 1986; Janardanan and Ramachandran, 1983; Ashwini, 2003; Kadamannaya, 2008). Nearly 40 species of *Arthrosphaera* are confined to Southern India, while eight species are confined to Sri Lanka (Pocock, 1899; Attems, 1936). Occurrence of *Arthrosphaera*usually restricted to the forests receivinghigh rainfall but marshy areas, regions with sparse canopy and forests with dry flour were not preferred (Ashwini and Sridhar, 2008). Some *Arthrosphaera*are common in high altitudinal ranges of the Western Ghats (e.g.*A. carinata*, *A. dalyi*, *A. davisoni*, *A. fumosa*, *A. hendersoni*, *A. nitida*and *A. scholastica*) (Sridhar and Ashwini, 2011).Abundance and biomass of *Arthrosphaera*was highest in Western Ghats, while earthworms dominated in the foothills of the Western Ghats (Ashwini and Sridhar, 2008).*Arthrosphaera magna* is widely dispersed in the foothills of Maharashtra, Karnataka and Tamil Nadu (Attems, 1936; Sakwa, 1974; Achar, 1980;Ashwini and Sridhar, 2008). Up to five species of *Arthrosphaera w*ere recovered from the Western Ghat forests on one time survey in nine different locations (forests and plantations) (Kadamannaya*et al*., 2010a). Compared to earthworms, the biomass of pill-millipedes was higher in forests but lower in their abundance. In plantations,biomass as well as richness of pill-millipedes was higherthan earthworms denoting prevalence of congenial conditions for pill-millipedes. Monthly surveys in forests and nearby plantations in the foothill regions of the Western Ghats revealed extended activities, higher richness and higher biomass of pill-millipedes in mixed plantations than in forests (Ashwini and Sridhar, 2006a; Kadamannaya*et al*., 2010a). Occasional observations up to 20 years in forests and plantations in the Western Ghats and west coast of Karnataka yielded 24 morphospecies of *Arthrosphaera* with 16 unknown species (Table 1). The coastal regions showed sparse distribution possibly due to low forest cover, insufficient litter strata and intermittent soil erosion (Ashwini, 2003). In coastal *Acacia*plantation near Uppala (Kerala, about 10 km interior to the west coast), a few young individuals of *Arthrosphaera magna* were recovered in the litter strata. Similarly, an unknown species of *Arthrosharea*was abundant in a mixed plantation in Uppala (Kadamannaya*et al*., 2010a). *Arthrosphaera magna* and an unknown species of *Arthrosphaera* were also recovered in the mixed plantation of coastal region near Mangalore (Table 1). Interestingly, these coastal plantations receive organic manure instead of chemical fertilizers.

Table 1. Distribution of pill millipedes (*Arthorpshaera*) in the Western Ghats of Karnataka, India

Arthrosphaera	**Location (altitude m asl approx.)**	**Forest/ Plantation**	**Reference**
*Arthrosphaeracarinata*Attems	Bababudan Hills (1895) Kalhattigiri (1876) and Kemmangundi (1434)	Forest Forest Forest	Attems, 1936
*A. dalyi*Pocock	Kadaba (124)	Mixed plantation	Kadamannaya*et al*., (2010a)
	Uppnangadi (86)	Mixed plantation	Present study
*A. davisoni*Pocock	Basrikallu (1387)	Mixed plantation	Kadamannaya*et al*., (2010a)
*A. disticta*Pocock	Shankaraghatta (651)	Forest	Present study (Fig. 1)
*A. fumosa*Pocock	Madikeri (1147)	Forest	Kadamannaya*et al*., (2010a)
	Madikeri (980)	Coffee plantation	Achar, 1986
	Karike (133)	Mixed plantation	Present study (Fig. 1)
*A. lutescens*Attems	Thirthalli (610)	Forest	Achar, 1986
*A. magna*Attems	Karkala (123)	*Areca* plantation	Achar, 1986
	Mundaje (123)	Forest	Ashwini and Sridhar (2008)
	Sampaje (235)		
	Hosangadi (109)		
	Gundya (138)		
	Adyanadka (91)	Mixed plantation	
	Adoor (113)		
	Peraje (147)		
	Assaigoli (55)	Mixed plantation	Kadamannaya (2008)
*A. zebraica*Butler	Soraba (610)	Forest	Chowdaiah, 1966
	Varadalli (607) and Ulvi (647)	Forest	Kadamannaya*et al*., (2010a)
*Arthrosphaera*sp. (yellowish brown with black patches on either side)	Sakaleshpur (930)	Coffee plantation	Chowdaiah (1966)
*Arthrosphaera*sp.	Karnataka (?)	Forest	Chowdaiah, 1969
*Arthrosphaera*sp. (ivory white without stripes and patches)	Hosabale (585)	Forest	Hosabale, 2000
*Arthrosphaera*sp. 1 (black and shiny with hairs in dipressions)	Augumbe (657)	Forest	Ashwini and Sridhar (2008)
*Arthrosphaera*sp. 2 (steel blue colour without stripes)	Balur (931) Kemphole (953) Made (811) and Someshwara (658)	Forest	Ashwini and Sridhar (2008)
	Pollibetta (945)	Coffee plantation	
*Arthrosphaera*sp. 3 (dark brown-red with yellow stripe) (giant millipede)*	Nittur (351) Hulikal (696) and Kollur (106)	Forest	Ashwini and Sridhar (2008)

*Arthrosphaera*sp. 4 (Shiny black with thin dark brown stripe) **	Tumbri (610)	Mixed plantation	Ashwini (2003)
	Adyanadka (91)	Mixed plantation	Present study
*Arthrosphaera*sp. 1 (yellow to greenish yellow with black patch on either side)	Mulleria (121)	Mixed plantation	Kadamannaya*et al*., (2010a)
	Assaigoli (55)	Mixed plantation	
*Arthrosphaera*sp. 2 (Olivaceous with thin orange bands)	Nalur (626) and Agumbe (657)	Mixed plantation and semi-evergreen forest	Kadamannaya*et al*., (2010a)
*Arthrosphaera*sp. 4 (dark-brown with thin yellowish red stripes)	Geejagaru (604)	*Areca* plantation	Kadamannaya*et al*., (2010a)
	Horanadu (804)	Mixed plantation	
	Basarikallu (1387) and Kalasa (803)	Forest	
*Arthrosphaera*sp. 5 (black with broad greyish-yellow broad bands)	Ulvi (647)	Forest	Kadamannaya*et al*., (2010a)
	Varadalli (607)	Shrub forest	
*Arthrosphaera*sp. 6 (black with thin ivory colour bands)	Agumbe (657) and Ulvi (647)	Forest	Kadamannaya*et al*., (2010a)
*Arthrosphaera*sp. 1 (black with brown thin bands)	Karike (133)	Mixed plantation	Present study (Fig. 1)
	Thalakavery (924)	Wildlife sanctuary	
*Arthrosphaera*sp. 2 (deep yellow with black spots)	Bishettigeri (823)	Coffee plantation	Present study (Fig. 1)
*Arthrosphaera*sp. 3 (light brown with irregular black spots)	Dharwad (700)	Mixed forest	Unpublished
*Arthrosphaera*sp. 4 (*A. disticta*-like in size and light brown with irregular black spots)	Shaknaraghatta (651)	Mixed forest	Unpublished

(?), Not defined

*, Giant among the *Arthrosphaera* spp. so far known

**, Survived and proliferated in Adyanadka mixed plantations along with *A. magna*

Fig. 1. Typical pill-millipedes found in the Western Ghats (moving and conglobated individuals along with faceal pellets): *Arthrosphaeradisticta* (*A.d.*), *A. fumosa* (*A.f.*), *A. magna* (*A.m.*) and *Arthrosphaera*spp. (*A.* sp. 1 and *A.* sp. 2).

Wesener and Sierwald (2005a, 2005b) described endemismof giant pill-millipedes (*Sphaeromimus*and*Zoosphaerium*) in Madagascar due to limited dispersal abilities. Similarly, Hamer and Slotow (2002) classified South African millipedes in to site endemics, local endemics and regional endemics. Studies on pill-millipede distribution and diversity in forests or plantations in India and Sri Lanka are scanty. *Arthrosphaera* are endemic to narrow distributional ranges in Southern India and Sri Lanka possibly due to highly suitable soil edaphic features for their survival and activity. Occurrence of more than one species of millipede in a specific transect is rare. Even though 70 samples from 14 locations of the Western Ghats and plantations were assessed, none of them consists of more than one species of *Arthrosphaera* (Ashwini and Sridhar, 2008). However, 2-3 species were recorded in different sampling locations in a 200 m line transect (Kadamannaya*et al*., 2010a). Recently, three species were recovered in Karike and Bishettigeri, Kodagu (*A. fumosa* and *Arthrosphaera* spp.), two species in Shankaraghatta, Shimoga (*A. disticta* and *Arthrosphaera* sp.) and in Adyanadka, Dakshina Kannada (*A. magna* and *Arthrosphaera* sp.) (Fig. 1; Table 1).Dominance of a specific species of pill-millipede in a location was evident from survey for the last 20 years with a few exceptions. It is possible to classify the Western Ghat region in to different zones based on distribution of specific pill-millipedes. High altitude Kodagu region is endowed with *A. fumosa* (e.g. Madikeri), high altitude Kudremukh region by *A. davisoni*(e.g. Basrikallu), foothill regions of Western Ghats showed dominance of either *A. magna*(e.g. Karkala and Adyanadka) or *A. dalyi* (e.g. Kadaba and Uppinangadi), forests of Shimoga region dominated by *A. disticta* (e.g. Shankaraghatta) and forest and plantations in Sagar region dominated by *A. zebraica* (e.g. Ulvi) (Table 1). One of the *Arthrosphaera*species (*Arthrosphaera*sp. 3: dark brownish-red with yellow stripes) is the gigantic pill-millipedeso far known (male, 25-28 g and 72-80×34-40 mm; female, 19.5-21 g and 62-65×26-28 mm) (Ashwini, 2003). The size of this millipede is higher than its sister-group *Zoosphaerium* (which is larger than 60 mm) (Wesener*et al*., 2010). This millipede is dominant and confined to Nittur, Hulikal (Western Ghat locations) and Kollur (Western Ghat foothill location) (Table 1) may be useful in production of millipede compost for agriculture.

Ecology

According to Meentenmeyer (1978) and Aerts (1997), the climaticconditions and litter chemistry regulates litter decomposition. In humid tropics, the climatic conditions have narrow fluctuations, thus litterchemistry plays a significant role and in turn determines the detritus transformation by soil invertebrates and microbes (Henegan*et al*., 1999; González *et al*., 2001). Millipedes are known to be influenced by the litter chemistry at narrow spatial scales in their habitats (meters to decametres) and become reliable indicators of soil qualities(Warren and Zou,2002).Disjunct distribution of *Arthrosphaera*in the Western Ghats indicates their precise preference of edaphic conditions. In the Western Ghats, the biomass of *Arthrosphaera* was positively correlated with soil organic carbon (Ashwini and Sridhar, 2008), while in plantations it was positively correlated with soil moisture, organic carbon and calcium (Kadamannaya *et al*., 2010a). In spite of higher biomass of *Arthrosphaera*in the Western Ghat plantations, the speciesrichness was highest in the forests indicating availability of heterogeneous plant litter in forests. In monthly sampling, abundance and biomass of *A. magna* were positively correlated with rainfall, soil moisture and soil temperature (Ashwini and Sridhar, 2006a). The biomass of *A. dalyi* in a monthly sampling was positively correlated with soil moisture and negatively correlated with soil temperature during monsoon, while it was positively correlated with calcium and magnesium during post-monsoon (Kadamannaya *et al*., 2010a). Possibly requirement of calcium and magnesium for millipedes was high during post-monsoon than monsoon season. In Madikeri forest, the pill-millipede biomass of was negatively correlated withtemperature and positively correlated withconductivity during post-monsoon. This clearly shows cooler conditions necessary for pill-millipedes in the Western Ghat foothill and west coast for their survival and activities. Pill-millipedes emerge only after sufficient rainfall in the Western Ghats, the adults of *A. magna* in forests were active for five months (July-November),while activity of young ones restricted to four months (August-November) due to decline in soil moisture (Ashwini and Sridhar, 2006a). But in mixed plantations, adults were active for seven months (June-January), while the juveniles emerge during late July or early August, active up to four months and hibernate prior to hibernation of adults in November.

Soils in the high altitude and foothill locations of Western Ghats encompass loamy sand, low temperature, high moisture, water-holding capacity, organic carbon, potassium and magnesium compared to the west coast locations. Plantations in Western Ghats retained native tree species for shade, green manure and organic matter unlike the west coast. Abundance or biomass of pill-millipedes in plantations was significantly higher in the Western Ghats and foothill due to higher water-holding capacity and lower bulk density of soil than forests. Pill-millipedes prefer sufficient litter depth in forests and plantations. Besides, they also prefer to hide in rotting wood stubs. Under cultivated conditions they prefer to hide in the coconut basin with high organic matter. On either side of the roads, those channels possess high organic matter without water logging attracts pill-millipedes. In *Areca* plantation floors, holes made by pill-millipedes are common in North Kanara region (e.g. Ulvi, Soraba and Geejagaru). Similarly, the lawn cultivated in Shankaraghatta consists of *A. disticta* almost throughout the year due to prevalence sufficient moisture.

Studies on mating behaviour in *Arthrosphaera* are meagre. Stridulation is an important event in male pill-millipedes by active movement of ribs (on theposterior surface of the posterior telopod) over a field of sclerotized nubs on the inner margin of the anal shield (Wesener*et al*., 2011). Pill-millipedes are unable to perceive acoustic signals andstridulation initiates mating with female by uncoiling if rolled into a pill. The temporal pattern of stridulation varies between species and serves as species-specific signals in pill-millipedes belong to the genus *Sphaerotherium*. Stridulationwas seen in males of *A.disticta, A. fumosa*and *A. magna* in our study. The mating sequences occur up to seven minutes in *A. disticta* (Fig. 2A-D). The male starts stridulation for less than a minute and approaches the female and roll-up, within two minutes the male stretches above female and ejaculates sperm on the female sexual opening, stay in same position for about two minutes and turn 180°, roll down and stay face to face for another two minutes and separates. Figure 2E shows feeding of decomposed leaf litter by *A. fumosa* and one pair showing mating behaviour (arrowed). Moulting is a very common phenomenon in *Arthrosphaera,* but occasionally seen in the fields (Ashwini, 2003). During *ex situ* maintenance of 6-8 species of pill-millipedes, two species (*A. disticta* and *A. fumosa*) moulted during summer (Fig. 3). During moulting, the colour of tergites attains light blue with ivory white stripes and requires at least two weeks attaining normal coloration in *A. fumosa*.

Bioconversion

Decomposition is one of the major ecological services in soil ecosystem as 60-90% of terrestrial primary production will be transformed mainly in soils (Giller, 1996). Pill-millipedes are known to ingest plantdetritus and convert into mineral-rich faecal pellets(Ashwini and Sridhar, 2005; Kadamannaya and Sridhar, 2009c). *Arthrosphaera magna* preferred conditioned litter over fresh litter and mixed litter than monolitter (Ashwini andSridhar, 2005). The rate of leaf litter ingestion of mixed litter was higher than temperate and tropical millipedes (561–598 vs. 1-157 mg/animal/day), so also the production of faecalpellets (550-570 vs.1-126 mg/animal/day)(Ashwini and Sridhar, 2005). The higher detritus conversion efficiency of mixed litter indicates abundance of *Arthrosphaera*inmixed forests of the Western Ghats. Organic matter in faecal pellets of pill-millipedesfed with *Acacia*, banana, cashew and coconut leaf litteramended with soil was higher compared to those consumed only soil (70.1-75.8 vs. 9.3%) (Ashwini and Sridhar, 2006c). Elevation ofnitrogen, phosphate andpotassium,decrease in C/N ratio and shift of pH to neutral in

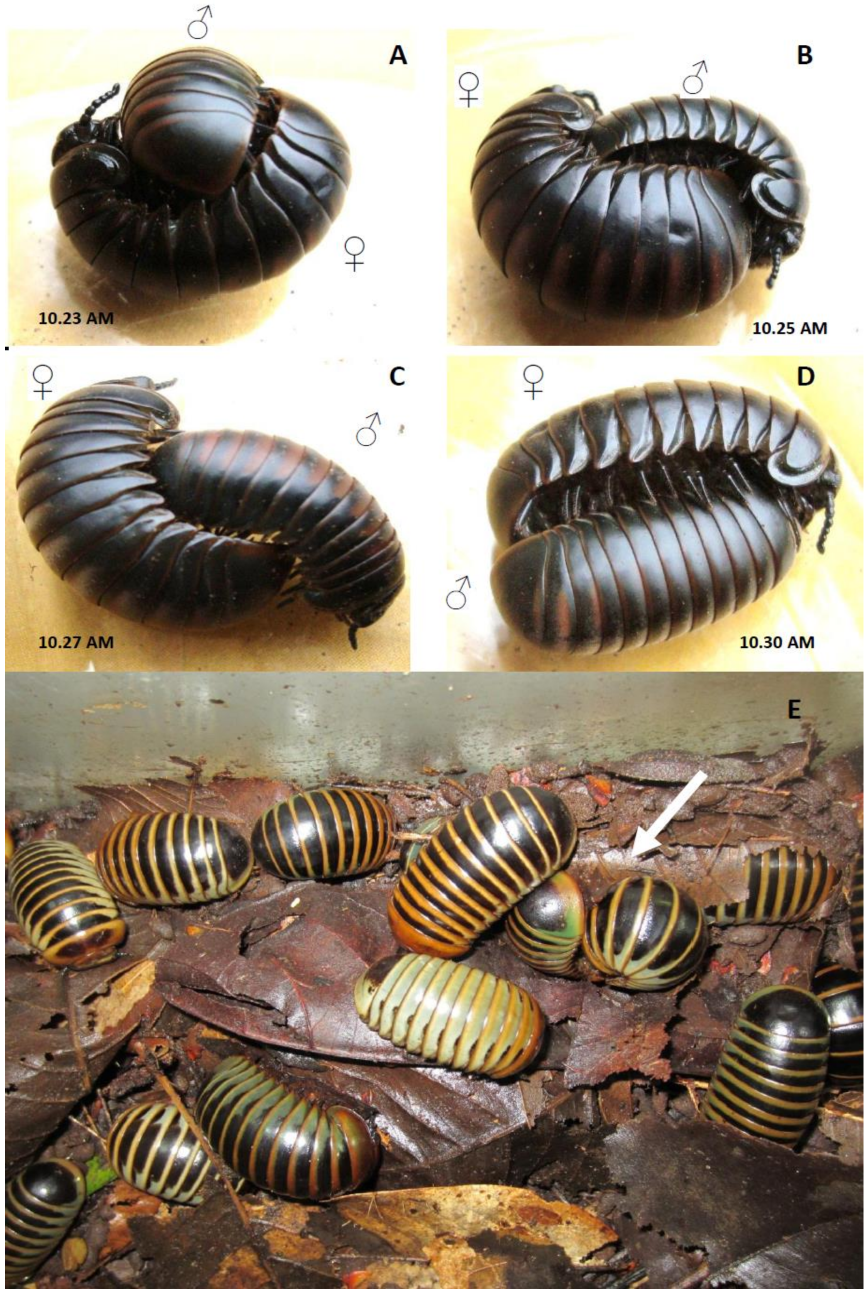

Fig. 2. Mating sequence of *Arthrosphaeradisticta* in the laboratory (A-D) and note the selective mating in *A. fumosa* (E) (arrow).

Fig. 3. Moulting phases of *Arthrosphaerafumosa* in the laboratory.

faecal pellets of *A. magna* grown on mixed litter depicts the possibility of employing *A. magna* to generate compost similar to earthworms (Ashwini and Sridhar, 2006b). It is known that faecal pellets of temperate pill-millipedes (*Glomerismarginata*)are attractive to earthworms(*Lumbricuscastaneus*and *Octolasionlacteum*), they incorporatepellets into soil and increase the carbonmineralization (Scheu and Wolters, 1991;Bonkowski*et al*., 1998). In Western Ghats, pill-millipede faecal pellets and earthworm casts are seen more often in the litter strata and use of combination of pill-millipede and earthworm in compost production may be more rewarding.

The farmyard manure although serves as an ideal source of plant nutrients, it meets the requirements of N, P and K of plantation crops partially (Chowdappa*et al.*, 1999). Experiments on the dry matter yield by black gram (*Phaseolusmungo*) and finger millet (*Eleusinecoracana*) revealed that pill-millipede compost produced on the plantation crop residues compensates the deficiency of nutrients in farmyard manure and serve as an ideal alternative against inorganicfertilizers(Ashwiniand Sridhar, 2006c).If suitable agroclimatic conditions are created in the plantations of the Western Ghats and west coast (e.g. organic farming and zero application ofchemical fertilizers/pesticides), pill-millipedes are ideal candidates for organic matter turnover, improvement of soil fertility and plant production. The global renewable lignocellulosic wasteproduction is estimated up to 20-50$\times 10^9$ tonnes per annum, but onlyabout 4$\times 10^9$ tonnes is utilized by bioconversion (Kelley and Paterson, 1997). There is ample scope to employ pill-millipedes for conversion of biodegradable organic wastes. It is also worth attempting production of compost by solid wastes of urban origin using pill-millipedes.

As a first step, e*x situ* maintenance of pill-millipedes has been attempted in our laboratory. We maintained four species of pill-millipedes in two types of containers. Plastic boxes (30×15×15 cm) kept in horizontal position (to have more space for movement) with decomposing mixed leaf litter is ideal condition to maintain 5-10 pill-millipedes (Fig. 4A). Plastic containers need holes on the top and sides for aeration and to supply a small quantity of water. This set up are also help to study leaf ingestion and faecal pellets production using various detritus with pill-millipede combinations (Fig. 4C, 4D). It is also possible to use the abandoned glass aquarium tanks (60×30×30 cm) to maintain 25-50 pill-millipedes with a thin mesh or cloth cover on the top (Fig. 4B). Four pill-millipedes (*Arthrosphaeradisticta, A. fumosa, A. magna* and *Arthrosphaera* sp.) were maintained on mixed leaf litter diet in glass tanks in laboratory conditions (temperature, 26-28°C) up to one year. The rate of survival was assessed on monthly intervals and survival was above 98% for the

Fig. 4. Containers used in the laboratory to maintain pill-millipedes: animals feeding leaf litter in plastic bottles kept horizontally (A) and in a glass tank (B), close view of millipedes feeding on leaf litter (C) and heap of faecal pellets (D).

first six months (June-November) and at the end of 12 months, survival of *Arthrosphaera* sp. was maximum (86%) compared to other three species (74-77%) (Fig 5). This shows that at least 75% of pill-millipedes can be successfully maintained on the mixed litter diet for production of compost in pilot scale throughout the year. No eggs and juveniles of pill-millipedes were seen on maintaining in the laboratory in the Department of Biosciences, Mangalore University. But, *Arthrosphaerafumosa*maintained similarly in Karike (near Madikeri) in glass tanks (25-27°C) laid the eggs and the juveniles were active especially during post-monsoon season.

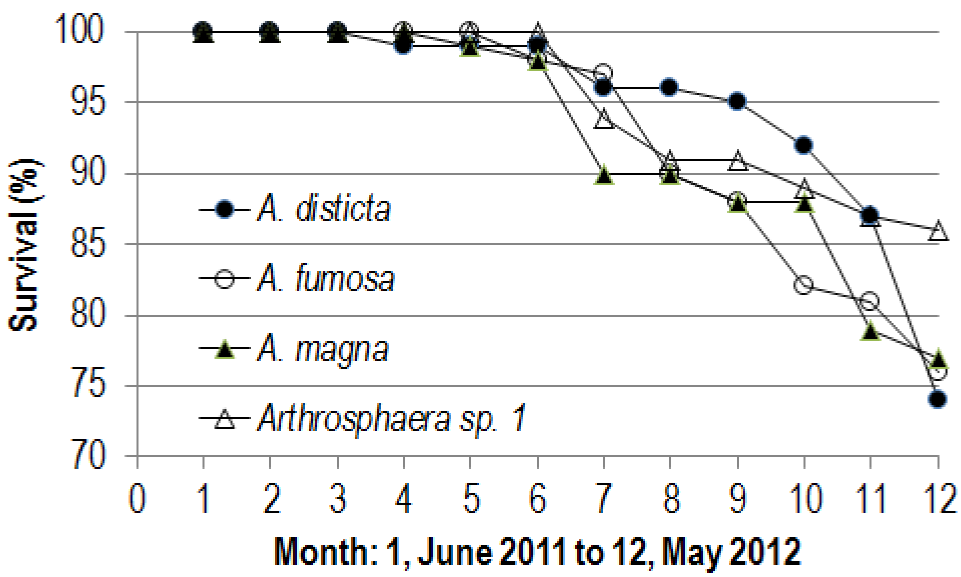

Fig. 5. Rate of survival of pill-millipedes in the laboratory conditions (n=3, mean) (1-12 months: 1, June 2011 to 12, May 2012) (*A. disticta* from Shankaraghatta; *A. fumosa* from Karike; *A. magna* from Adyanadka and *Arthrosphaera* sp. 1 from Thalakavery; see Table 1).

Systematics

Examination of animals those have limited dispersal abilities are valuable to understand their biogeographic history and evolution (Wesener*et al*., 2010). The taxonomy as well as morphology of Diplopoda belonged to the order Sphaerotheriida (pill-millipedes) drew less attention (Sierewald and Bond, 2007). Although Arthrosphaeridae has been supported by unique and complex morphological characteristics, the relationships at family-level is not still very clear (Wesener and vandenSpiegel, 2009; Wesener*et al*., 2010). We have to depend on monographs on pill-millipedes of India and Sri Lanka published by

Pocock (1899) and Attems (1936), which are largely based on preserved specimens. So far, systematics of Sphaerotheriida has been focused mainly based on morphology (light microscopic studies). Future studies needs precise observations based on scanning electron microscopy is warranted.

Classification of Sphaerotheriida using chromosome biology and cytotaxonomy will be valuable. So far, only 11 species of *Arthrosphaera* were investigated cytologically and the 2n chromosome numbers range from 26 (*A. davisoni*, *A. lutescens* and *A. zebraica*), 28 (*A. disticta*and *A. gracilis*) and 30 (*A. bicolor, A. craspedota*, *A. dalyi*, *A. hendersoni*, *A. magna* and *A. nitida*) (see Kadamannaya*et al*., 2010b). Achar (1987) reported that Robertsonian changes and pericentric inversions are the main chromosomal rearrangements occurred during the evolution of diplopods. Further studies on the chromosome architecture of *Arthrosphaera*based on differential banding techniques facilitate to follow the chromosome evolution in Sphaerotheriida more precisely.

There is only one molecular study on the evaluation of *Arthrosphaera Arthrosphaera brandtii*, which has distribution in Southern India and Sri Lanka) with other pill-millipedes (*Sphaeromimus* and *Zoosphaerium*) in Madagascar (Wesener*et al*., 2010). Two mitochondrial genes (partial 16S rRNA and COI) and nuclear genes (18S rDNA) were sequenced. According to them (tree based on combined dataset), Arthrosphaeridae evolved between 160 mya (during split of Madagascar-India) and 88 mya (separation of India from Madagascar) (Krause, 2003). Thus, possibility of drifting between India-Madagascar or Madagascar-India is remote (distance, ~5000 km), depicting separation between *Sphaeromimus* and *Arthrosphaera* occurred at latest 88 mya.

Conservation and outlook

Narrow variations in structure of vegetation in woodlands (e.g. leaf litter fall and soil fertility) cause significant heterogeneity in abundance and diversity of soil fauna (Amlan and Devi, 2001). Unlike earthworms, millipedes are sensitive to litter chemistry at narrow spatial scales(meters to decameters)(Warrenand Zou, 2002) and thus pill-millipedes needs special attention for *ex situ* conservation.The climate desiccation by human interference is a major threat for pill-millipedes. Forest fragmentation by roads, electrical lines, pipelines, plantations and mining activities exert major pressure on the survival and activity of pill-millipedes in the Western Ghats. Besides, conversion of forests into monocrop plantations will be detrimental to pill-millipedes as they prefer heterogeneous leaf litter. However, invasion of pill-millipedes into several organically managed plantations in the Western Ghats (e.g. *Areca*, cardamom and coffee) shows their survival and prevention of local extinctions as they have least ability of dispersal. Preservation of natural habitats plays an important role in *in situ* conservation of pill-millipedes as they require intra-site heterogeneity in soil organic matter. For instance, maintenance of natural terrain with boulders, rocks and woody litter serve as suitable refuge for colonization of pill-millipedes in the Western Ghats. Such obstructions serve to accumulate sufficient plant detritus and organic matter suitable for pill-millipedes. Sensitivity of pill-millipedes to narrow ecological fluctuations qualifies them to serve as authentic indicators ofsoil quality or habitat restoration in the forests and plantations.

In plantations of the Western Ghats and west coast of India, two important plantation practices are followed such as creating basins for each plant to accommodate organic manure or trenches and bunds in rows to facilitate water and manure application (e.g. *Areca*, coconut and coffee). Some forest or plantation practices like windrowing (shelter by accumulation of rotting logs), mound ploughing (long moist furrows with leaf and twig litter), pruning (accumulation of large amount of green matter) and thinning (adds rotting logs with persistent bark and leaves) facilitate rejuvenation of soil invertebrates from native forests and lowers the risk of their extinction(Bonham *et al*., 2002). Maintenance of native tree species in around the plantations generates leaf litter useful as manure and suitable diet for pill-millipedes. Physicalchanges in litter decomposition are mainly controlled by the litter chemical composition, range of decomposersand environmental conditions prevailing on the site of decomposition (Ambasht and Srivastava, 1995). Humus (mull, moder and mor) formation is the result of multipleinteractions of soil fauna and microflora (Ponge, 1999). Although the ecological gains occur in slow pace by pill-millipedes, it is significant in soil conservationwith increased nutrients, nutrient recycling, and diversity and stability of decomposer community. Millipedes ingest leaf litter along with soil and elevate soil respiration and leaching of ions (e.g. calcium, magnesium and nitrate) by increased microbial activity in forestsoils (Kaneko, 1999). For instance, mean carbon mineralizationof faecal pellets of pill-millipedes (*Glomerismarginata*) and casts of earthworms (*Octolasionlacteum*) fedwith mechanically fragmented litter exhibited more or less equal rates of CO^2-C production (Scheu andWolters, 1991). Although *ex situ* annual active period of pill-millipedes is shorter than other soil fauna, it seems they generate processed organic matter suitable or beneficial to other soil fauna (e.g. ants and earthworms) and plants.

Unlike other millipedes, pill-millipedes are not pests and devoid of offensive secretions or odour helps in easy handling. It is likely, duel culture of pill-millipedes and earthworms *ex situ* doubly benefit in manure production. Persistence of *A. disticta* and allied pill-millipedes in the lawns of

Shankaraghatta (Shimoga) also provides a clue for maintenance throughout the year in continuous moisture regime. Our studies also showed how to maintain up to 75% of pill-millipedes *ex situ*throughout the year for compost production. It is interesting to find out whether pill-millipedes process the solid biodegradable urban wastes exclusively or along with natural decomposing leaf litter. If pill-millipedes establish in a plantation means, the conditions prevailing is congenial for their activities as they are influenced by the litter chemistry atnarrow spatial scales and serve as indicators of soil quality. For instance, *Arthrosphera* sp. collected from the mixed plantations of Thumbri (Sagar, Karnataka) on transfer to mixed plantation in foothill location (Adyanadka, Dakshina Kannada) survived and established the progeny along with *A. magna* (Ashwini, 2003; Table 1). This indicates that there are possibilities to raise different pill-millipedes in organically managed plantations with adequate moisture. Such strategies also help in deliberate invasion of coastal plantations with pill-millipedes.

There are several gaps in our knowledge on pill-millipedes. Studies on their distribution in the Western Ghats, Sri Lanka and Madagascar attracted less attention. Meagre studies are available on the use of pill-millipedes to generate compost based on their food and feeding strategies. Pill-millipede research needs a strong taxonomic foundation by morphology, cytology and molecular systematics. Lastly, repository of preserved pill-millipedes is essential for further research progress.

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