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Review on Possible Factors for Outbreak of Wood Boring Isopod, *Sphaeroma* spp. Which Causes Destructive Impact on Mangrove Forest in China

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Abstract

The tropical and subtropical mangrove biomes form the foundation of a highly productive and biologically rich ecosystem providing essential goods and services to human beings. Despite its values, the stability and survival of mangroves are consistently threatened by anthropogenic activities and their associated degradation, resulting in their disappearance. After realizing their ecological importance, in recent years, rehabilitation and restoration programs for mangrove forests have been launched globally. Unfortunately, most mangrove restoration efforts yielded negative results and failed to re-establish mangrove forests because of technical and social failures. Besides, the continued outbreak of wood borer, *Sphaeroma* spp., in mangrove forests has become one of the destructive causes of natural and restored mangrove forests in some nations including China. However, few studies on the biology of *Sphaeroma* spp. found in Chinese mangrove ecosystem have been done, and little is known concerning the factors affecting their outbreak in China. In this review, we discussed the possible factors that affect the rapid growth and recruitment of *Sphaeroma* spp. in the mangrove ecosystem by examining the information of the wood borer *Sphaeroma* spp. from the scattered pieces of literature with great regard. We discussed the relationship between the recruitment of *Sphaeroma* spp. and the tide and flow of water, food availability from the surrounding water and water quality including salinity, temperature, and the pollution of water. In addition to these factors, the reduced biodiversity of restored mangrove forest could be one of the main reasons for the outbreak of isopod. We also discussed the destructive impact of the isopod's outbreak and the possible ways to control their outbreak in mangrove forest.

Keywords

Isopod's Outbreak, *Sphaeroma* Species, Destructive Impact, Mangrove Forest, Restoration

1. Background

Although the terms such as mangal [1], mangrove ecosystem, mangrove forest and mangrove swamp are interchangeably used to describe the entire community, the term "mangrove" can refer to both the ecosystem as a whole and the plant species that it comprises. Mangroves are renowned for their highly developed morphological and physiological adaptations to be capable of thriving in extreme conditions. Mangrove provides a unique ecological environment that provides a home and feeding ground for a wide range of different species, many of which are endangered and protected species [2]-[7]. Mangrove forests are integral and highly productive habitats across tropical and sub-tropical coastlines [5] [6] [7]. Even though mangroves constitute less than 1% of all tropical forests around the world, mangroves and their associated biodiversity contribute essential goods and services that play a critical role in supporting human well-being through security of coastal communities, food security, poverty reduction and climate regulation [7].

In the past, mangroves were often perceived as nothing more than muddy wastelands promoting the spread of diseases [8] and their ecological values were unrecognized. Therefore, destruction of mangrove forests had been occurring globally at alarming rates [9] [10]. People can be highly dependent on mangrove ecosystem services. When mangroves are degraded, people especially those who live near the coastline will undergo a lot of hardships [7]. Although the statistics for the covered areas of mangroves in different countries are controversial issue, the broad consensus is that over one-quarter of the world's original total mangrove cover has now already disappeared [7] [11] [12]. In the past several decades, nearly all mangroves have experienced significant losses as a result of destructive activities by human beings [13]. Global climate change and its associated issues such as sea-level rise increased temperature and CO_2 level, altered precipitation patterns and increased intensity and frequency of storms, are the secondary threat to the loss of mangrove [7] [10] [14] [15]. Projections imply that an estimated 10% - 15% of mangroves could be lost due to climate change by the year 2100 [7].

In addition to these two factors, mangrove trees are damaged by a variety of herbivore and wood-boring organisms including insects, bivalves and in particular marine or estuarine isopods [16] [17]. These wood borers burrow into the newly forming roots' tips, anchored roots, branches and trunks of different mangrove species in search of food and shelter [17] [18] [19] [20]. Their potential threat and destructive impact on different mangrove species had been highlighted by several researchers. Among the crustacean wood-borers, the isopod *Sphaeroma terebrans* is very common among mangroves [21] [22]. They attack the live pneumatophores of *Avicennia* spp., the stilt roots of *Rhizophora* spp., the knee roots of *Bruguiera* spp., the roots and trunks of *Aegiceras* spp. and other mangrove species in India, Pakistan, Kenya, Florida and China. All the other marine borers were found infesting floating logs or dying and decaying mangroves wood [22]-[27]. The Sphaeromids isopods colonize the prop roots and trunks of mangroves, thereby making hollows and undermining the structural integrity and stability of mangroves. When a severe storm, e.g. typhoon in China, has blown on the shoreline, those hollow mangroves cannot withstand the strong wind and then die off. This may lead to serious destruction in mangrove forest and shoreline erosion [24] [27]. Some studies discussed that the burrowing activity of Sphaeroma isopods also has a controversial biological influence on mangroves ranging from the damages being described as ecocatastrophe to the benefits such as the replacement of damaged root tissues rather than the stimulation of new tissue formation. However, the attack of isopod impacts directly on the mangrove tree by changing root architecture, increasing root atrophy, reducing root production and root growth rate which is leading to alter the nutrient provision and the structural support [17] [18] [19] [20] [28] [29].

Nowadays, most ecologists acknowledge the importance of mangrove community to people. As mangroves become smaller and more fragmented, the important ecosystem goods and services will be diminished or lost. It is critical to conserve the remaining mangrove and to restore the damaged and lost mangrove forests. Since, the wood borer, *Sphaeroma* spp. isopod can create a lot of damage in conservation and restoration of mangrove ecosystem, these isopods become a facet for the conservation and restoration of natural and restored mangrove forests. The huge gap for knowledge of relationship between the ecology of *Sphaeroma* spp. and mangrove ecosystem is needed to reduce. More effective research should be done in order to find out the way which can control the ecological balance between mangroves and the outbreak of isopods.

2. Status of China's Mangrove Forests

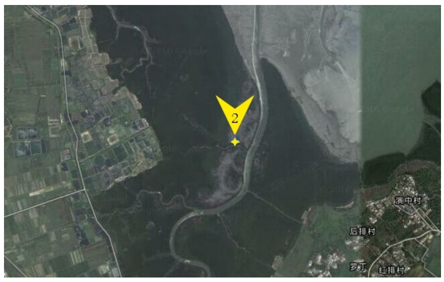
In China, mangrove forests naturally occur along the southeast Chinese coast and traverse the provinces of Hainan, Guangdong, Guangxi, Fujian, Hong Kong, Macao and Taiwan. In 2013, the total mangrove forest area of China was 32,077 ha [22]. About 94% of the total area of China mangrove forests mainly occurs in three provinces: Guangdong, Guangxi and Hainan. Totally 37 mangrove species representing 20 families and 25 genera have been recorded in Chinese mangrove forest. Of 37 species, 26 species are true mangroves and the others are mangrove associates. These 37 species can be classified into three main ecological types, namely, 1) comparatively cold-resistant eurytopic species, e.g., *Kandelia candel*, *Avicennia marina* and *Aegiceras corniculatum*; 2) cold-intolerant (thermophilic) stenotopic species, e.g., *Rhizophora* spp., *Lumnitzora littorea, Nypa fruticans;*

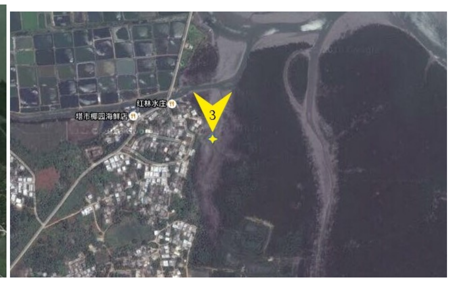
and 3) thermophilic eurytopic species, e.g., *Rhizophora stylosa, Bruguiera sexangula, B. gyminorrhiza, Excoecaria agallocha* and *Acrostichum aureum* [30]. The dominant components of China's mangroves are thermophilic eurytopic species, representing about two-thirds of the total mangrove forest [30] [31] [32]. Even though China's mangrove area can be accounted only a little more than 0.1% of the world's total mangrove area (17,075,600 ha in 2000), 26 true mangrove species are found in China which is about one-third of the total true mangrove species worldwide [22] [30] [31] [32]. In China, along with the increasing latitude, the mangrove trees become smaller and the species diversity decreased, remarkably from 35 species in Hainan (18˚N - 20˚N) to 9 species in Fujian (23.5˚N - 27˚N). Among the major mangrove areas, Hainan Island, the province with the highest average temperature and lowest latitude, possesses the highest mangrove species richness and the best-developed mangrove forests with a maximum tree height of 15 m. Chinese mangrove communities can be classified into seven groups depending on their species composition and the characteristic appearance of mangrove community, which are *Bruguiera* formation, *Rhizophora* formation, *Kandelia* formation, *Aegiceras* formation, *Avicennia* formation, *Sonneratia* formation, and *Nypa* formation. *Kandelia candel* (L.) Druce, one species in the family of Rhizophoraceae, has long been recognized as a monotypic mangrove genus and occurs in all seven mangrove distribution zones of China [30] [31] [32].

2.1. Conservation and Restoration of China's Mangrove Forests

During the past several decades, nearly two-thirds of China's mangrove forest area have been lost due to land conversion into rice-farming, embankment for aquaculture ponds and, recently, rapid urban development [31]. In China, mangrove afforestation was initiated in the late 1950s and interrupted from 1966 to 1979 and then resumed in 1980. Since 1980s, the government of China has launched a series of programs for conservation, afforestation and restoration to protect mangroves [30] [32]. In 1973, the total mangrove forest area of China was 48,750 ha. Since 1970, the mangrove forest area continuously decreased to 18,587 ha area in 2000 (**Figure 1** and **Figure 2**). After implementation of mangrove forest restoration program, the area has increased gradually and it was 32,077 ha in 2013 [22]. In 1950s, only one mangrove species, *Kandelia candel* which is the comparatively cold-resistance eurytopic species, was successfully transplanted to Yueqing County in Zhejiang Province (27 - 31˚N) where mangroves were not naturally found. In 1995, this successfully transplanted mangrove area remained only 8 ha and most of it had been destroyed by human disturbance [31]. Among all 37 species of Chinese mangrove, only *Sonneratia hainanensis* is category 1 protected national plant because only five trees of this species exist in China [32]. According to Chen *et al.* (2009), a total of 34 mangrove natural reserves have been established in different locations of China, and the total protected area was more than 18,000 ha, accounting for more than 80% of China's mangrove area in 2007. During the last two decades, apparent success in mangrove conservation and reforestation was achieved. However, there are still many serious threats to Chinese mangrove ecosystem such as urban and aquaculture wastewater discharge, oil pollution, biological invasion, insect outbreak and the influence of water transportation [30].

(a)





(b) (c)

Figure 1. Satellite view of seriously damaged mangrove forests after typhoon in Hainan Island. (a) Dongzhai Gang National Nature Mangrove Reserve, (b) Houpai Village and (c) Tashi Village.

(a)

(b) (c)

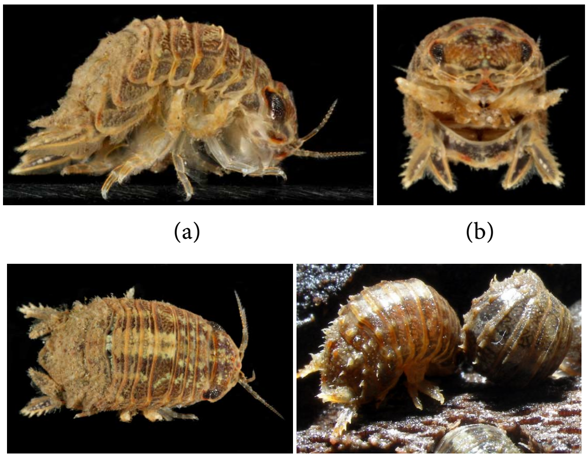
Figure 2. Damaged mangrove forests after typhoon in Hainan because of hollowed mangrove roots burrowed by wood borers. (a) Dongzhai Gang National Nature Mangrove Reserve, (b) Houpai Village and (c) Tashi Village.

2.2. China's Mangrove Forests Destroyed by Insects and Wood Borers

Insects and isopods constitute a significant portion of the fauna in many mangrove ecosystems and they may be permanent residents or only temporary visitors in mangrove communities. In either case, they often play important roles in the food chain of mangrove ecosystem and also contribute to the unique character of these habitats [5] [33]. China's mangrove ecosystem is rich in flora and fauna with a total of 2854 species, of which 434 species were recorded as insects [5]. However, while their existence and outbreak increase beyond the ecological balance, they become pests which can harm the health of mangrove plants and eventually lead to the death. Thus, their outbreak can stress the resilience of mangrove ecosystems. In the past few years, there have been a lot of reports discussing the diseases of mangroves; several reports focusing on the impact of insect damaging to mangrove species and also reports of associations between fungi and insects on mangroves in the worldwide [34].

During the past 15 years, the different species of insects and wood boring isopods infecting on different mangrove species at different seasons become noticeable in seven mangrove regions of China. The frequent outbreak of pests, diseases and the extent of infected mangrove forest area were increasing year by year in most of China's mangrove habitats which can be attributed to the degradation of coastal environment in China. Huang and Zhou (1997) reported six species of mangrove trees in Guangxi were infected by plant pathogen fungus *Colletotrichum* sp.; in 2001, Jia *et al.* reported that there were several insect pests damaging Shenzheng's mangroves in Guangdong Province [22]. Fu *et al.* (2012) reviewed the different types of insect pests harming the different parts of mangrove trees in six mangrove habitats of China. They listed 30 species of insect pests infecting 6 mangrove species in total [33]. Li *et al.* (2012) also reported totally 18 main species of insect pests with their observed first outbreak time infecting seven mangrove species in mangrove habitats of Hainan, Guangdong, Guangxi, Fujian, and Taiwan [35].

Xu *et al.* (2014) studied on the degradation and death of mangrove in Dongzhai Gang of Hainan Island. It was found that the main cause of mangrove degradation in Hainan Island was the outbreak of wood boring isopod, *Sphaeroma* species. They found that *Sphaeroma* spp. mainly distributed in the prop roots of red mangrove at 0 to 30 cm above the sediment, especially in 10 to 20 cm. The population density of *Sphaeroma* was 2.94 per square centimeter and the drilling area accounted for 23.93% of total area Dongzhai Gang mangrove [27]. Fan *et al.* (2014) also reported the damages of mangroves caused by two species of wood boring isopod, *S. terebrans* [21] and *Sphaeroma reteolaeve*, in Hainan and Guangxi provinces. It was found that the area of mangroves destructed by *Sphaeroma* sp. in Dongzhai Gang, Hainan increased at a mean continuous rate of 66.4% annually from 1.17 ha in 2010 to 5.39 ha in 2013 (**Figure 3**). In 2013, the protected mangrove area of Dongzhai Harbor, Hainan was 2065 ha of which 33.3 ha of *S. terebrans* infected area including 5.39 ha of the died off



(a) (b)

(c) (d)

Figure 3. Sphaeroma terebrans, one of the several destructive isopods that are able to burrow of wood; (a), (b) and (c) Magnified views, (d) Conglobation of their body (Photo from http://www.roboastra.com/Crustacea1/brde430.htm).

mangrove area with 11,400 dead mangrove plants. In Guangxi province, the *S. terebrans* infected area was 1 ha and the dead mangrove area was 0.27 ha with 352 dead mangrove plants in Chaotoucun, Beihai while the *S. reteolaeve* infected area was 1.33 ha and the dead mangrove area was 0.23 ha with 329 dead mangrove plants in Silver Beach, Beihai. They found that wood borers attacked the mangroves species *Bruguiera* spp. mostly, and followed by the other mangrove species; *Ceriops tagal* and *Avicennia marina*, *Kandelia obovata* and *Aegiceras corniculatu* [24].

2.3. Discovery of *Sphaeroma* spp. in China's Marine and Mangrove Environment

Kussakin and Malyutina (1993) reported 35 species of the Sphaeromatidae (Crustacea: Isopoda: Flabellifera) from the South China Sea. Their report was based mainly on the collections of isopods made by Soviet-Chinese, Soviet-Indonesian and Soviet-Vietnamese expeditions of 1958-90 from the intertidal zone of southern China (including Hainan Island and a small collection from Cape d'Aquilar, Hong Kong), Vietnam and Java, and from the sub-littoral zone of the Gulf of Tonkin and Nhatrang province (south-eastern Vietnam).Two males of *Sphaeroma walkeri* in the pier fouling samples were collected from Hainan Island in 1958. In March 1958 and December 1959, totally 99 specimens of *S. terebrans* in the burrows of mangrove stems were collected at Hainan Island, China. *S. walkeri* and *S. terebrans* are circumtropical-subtropical species widespread across the Pacific, Indian and Atlantic Oceans. These species, presumably, were carried through three oceans by trans-oceanic ships [36]. However, in 2003, Yu and Li described 12 isopod species belonging respectively to 8 genera of the family Sphaeromatidae from Chinese coastal water including *S. retrolaeve*; *S. terebrans* [37]; *Sphaeroma triste*; *S. walkeri* . In their report, *S. terebrans* and *S. triste* were recorded as for the first time among the 4 species of the genus *Sphaeroma* [38]. Astudillo *et al.* (2014) reported that *S. walkeri* is non-native marine species in Hong Kong and has been well established since the 1980's and their abundance on piers seemed to increase when the seawater quality decreased. Li *et al.* (2016) collected the *Sphaeroma* spp. from mangrove forests of Hainan, Guangxi, Guangdong, Shenzhen and Macao (**Figure 5**). They identified these *Sphaeroma* spp. based on morphological characteristics in combination with mitochondrial cytochrome *c* oxidase subunit I (COI) gene as an effective DNA barcode for identification. The wood borers found in Chinese mangroves can be identified as *S. terebrans* and *S. retrolaeve*. They focused on the identification of *S. terebrans*, seriously infected in Chinese mangroves, in order to establish a good foundation for mangrove restoration program. Among these areas, mangroves of Hainan and followed by Guangxi were seriously infected by *S. terebrans* and *S. retrolaeve* [24] [39]. According to the Global Invasive Species Database (GISD), *S. retrolaeve* is one of invasive species found in China. Most Chinese researchers assumed that *S. terebrans* also could be the invasive species for China [24] [27]. However, more insight research for *S. terebrans* are still needed to be done in order to confirm whether native or invasive species.

3. Biology of Wood Boring Isopods, *Sphaeroma* sp.

Wood boring isopod, *Sphaeroma* sp., commonly known as pill bugs, is an economically and ecologically important cosmopolitan species. This species has a widespread distribution ranging from Africa to South East Asia and Australia; and from South America to the Mediterranean Sea (**Figure 6**) [26] [40] [41] [42] [43]. These isopods are found burrowing in wood and marine structures of fresh to saline water. The genus *Sphaeroma* sp. belonging to the family Sphaeromatidae and to the order Isopoda, are generally found in a variety of environments such as in the sea, estuaries, brackish water and fresh water, particularly in the tropics [26] [40] [41] [44]. According Li *et al.* (2016), the wood borers, *S. terebrans*, and *S. retrolaeve*, were found in Chinese mangrove forest. *S. terebrans* is often regarded as the most common and destructive wood-boring isopod crustacean in brackish tropical waters, and has been held responsible for causing extensive damage to both living mangrove trees and wooden structures [39]. A multitude of biological studies of the effects of *S. terebrans* on mangroves were generated because of their infestation impact on the growth of mangrove and considerable ecological damage to maritime structures [17] [18] [19] [20] [21] [39] [40] [41] [44] [45] [46].

3.1. Morphological Characteristics of *Sphaeroma* spp.

Mangrove boring isopods, *S. terebrans* and other members of the family Sphaeromatidae can be recognized by their compact, convex bodies, usually capable of rolling into a ball, conglobation [47]. The taxonomic characters for the species of Sphaeromatidae are the number and disposition of large tubercles on the dorsal posterior part of body, posterior part of the telson and the shape of the epistome (**Figure 4**). Among these characters, the arrangement of the large tubercles is remarkably different and shows variation characteristics of each species [48]. *S. terebrans* can be separated by morphologically by examining the number and arrangement of tubercles on the pereonite, number of teeth on the uropodal exopod, shape of the pleotelson, setae distribution, and length of the second and seventh pereopods.

3.2. Life History

The life span of tropical *Sphaeroma* isopod is approximately 10 months attaining the average length of different species varied from 4 mm to 15 mm [25] [44] [45]. For *S. terebrans*, they become sexually distinguishable when they reached about 3.5 mm [26] and the average size of adult females varied between 8 and 10 mm and the average size of males between 6.5 and 8.5 mm. Females grew to larger sizes than the males and the number of embryo per female was strongly correlated with the female body length [45]. Reproduction of *Sphaeroma* is sexual and occurs within their excavated burrows where they complete their life cycle. As the genus *Sphaeroma* are peracarida crustaceans, the fertilized eggs are retained by the female in the brood pouch under her thorax and these eggs develop to the embryos. After fully developing to the early juveniles in the pouch, females release their offspring [44] [45]. *S. terebrans* seems to be a continuous breeder because young and ovigerous females are found throughout the year.The production of first brood in *S. terebrans* starts within one month of their life [25] [26] [45]. The production of a second brood usually only occurs a considerable time (3 to 8 months) after production of the first brood and the females of *S. terebrans* most probably died after releasing this second brood. Males did not participate in extended parental care, since most of them left the females after copulation. Parental females hosted generally on average between 5 and 20 juveniles for

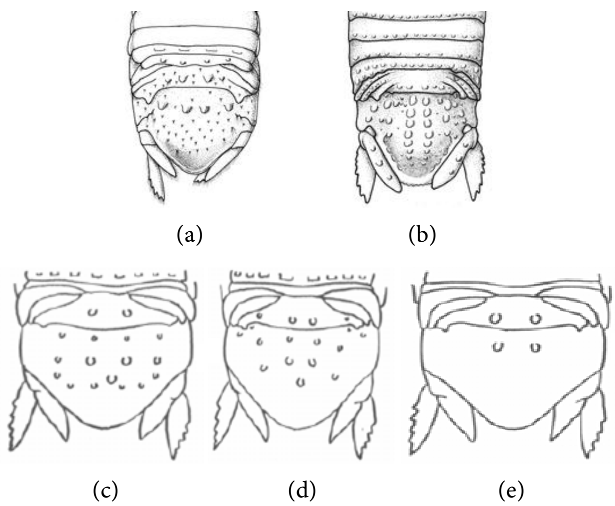


Figure 4. Pleotelson of *Sphaeroma* spp. showing the arrangement of tubercles; (a) *S. terebrans*; (photo from http://peracarida.myspecies.info/taxonomy/term/62885) (b) *S. walkeri*; (Photo from http://peracarida.myspecies.info/taxonomy/term/62893) (c) *S. annandalei*, (d) *S. annandalei travancorensis*; (e) *S. triste* [48] [73].

relatively long time periods in their family burrows and during this period, juveniles did not increase in size. While extended parental care in *S. terebrans* may help to protect small juveniles from predation (as in other peracarid crustaceans), the physical environment of female burrows may also be conducive to juvenile survival [45]. The mother spends most of the time in the hole, blocking the entrance with her telson and creating a flow of water with her pleopods to oxygenate the environment and provide a food supply. Therefore, the protective behavior of the female is crucial for survival of the offspring [21] [45] [46].

3.3. Burrowing Behaviors

Sphaeroma produces cylindrical burrows almost perpendicular to the grain of the wood surface or other material (**Figure 5**) with 8 mm to 10 mm in diameter and 20 mm to 40 mm in depth depending on the sizes of individuals [41] [44]. In active burrows, the isopods can usually be seen at the end of the burrows facing inward (**Figure 6**) [41]. *S. terebrans* create burrows by moving their mandibles up and down, and the cephalon and the first two pereonites back and forth like a rake, then the pleotelson and the pleopods flap up and down to create a current to evacuate the wood fragments and any air bubbles. Activity within the burrow consists mainly of digging, ventilation, cleaning, and filtering particles (**Figure 7**) [4] [26]. Juveniles of *S. terebrans* remained in the maternal burrows for up to 40 days after hatching from the female's brood pouch. Then, the juveniles start burrowing to the outside from within the female's burrows but some left the mother's burrow and start to build their own burrows in the immediate vicinity of the natal burrow on the maternal wood rather than emigrating from it. Juveniles require several days to establish a burrow whereas small adults can create a new burrow within 48 hours [49] and the adult ones bore within 24 hours and produce extensive hollowing within a few days [20]. Once constructed, the burrow is used as refuge area for protection from both abiotic (exposure, desiccation) and biotic factors; for filter feeding activities (suspended sediment, algae, and bacteria); and for reproduction along with extended maternal care [18] [40] [41] [43] [45] [46] [50].

Sphaeroma will readily colonize wooden materials including pilings, fender, bulkheads, ship hulls and planking and even non-wood materials like rope, carpet, soft rock, salt marsh banks and foam [41]. *S. terebrans* can inhabit natural wood such as cork, cypress, cedar, palm, pine, and especially prefer to inhabit aerial roots of red mangroves within the intertidal zone, other mangrove and mango, living or dead stems of black needle rush and leather fern, cattail, smooth cord grass, bulrush, saw grass in estuarine and brackish marshes and other non-wood material such as Styrofoam [26] [41]. *Sphaeroma* can inhibit such a wide variety of material largely due to the fact that these animals do not consume wood as their primary food sources and burrow wood as their shelter [41]. This is in contrast to wood boring isopods of genus *Limnoria* spp. who consume the wood they excavate as their principle food source. Studies observed that *S. quoyanum* and *S. terebrans* are primarily filter feeders by using the filtering brush or setae on the first three pairs of pereiopods that are able to filter out particulate materials such as suspended sediment, microscopic algae, and bacteria from the water column, by means of the filtering setae on the first three pairs of pereiopods. *S. walkeri* also occupys brushes on the legs and maxillipeds which

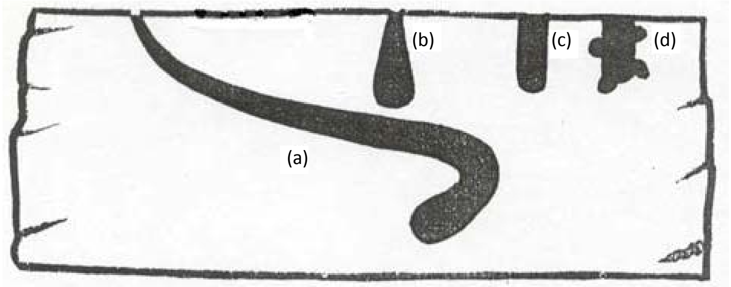


Figure 5. Different shape of burrows produced by marine different wood borers. (a) Shipworms; (b) Pholad; (c) Pill bugs; (d) Pill bugs with juveniles [73]

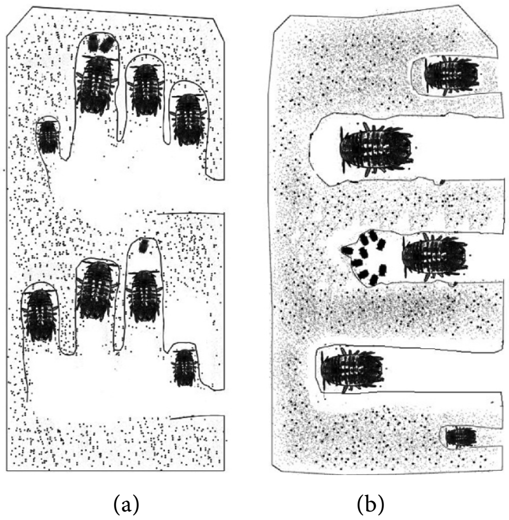


Figure 6. Different burrowing behavior of the two *Sphaeroma* species in the wood. (a) *S. terebrans* and (b) *S. retrolaeve* [24].

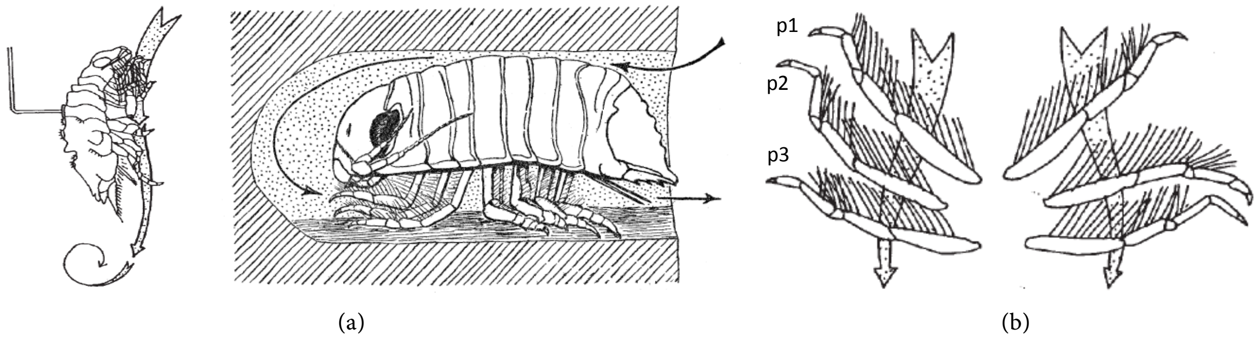


Figure 7. Filter feeding activity of *S. terebrans.* (a) Diagram showing the direction of the water current generated by the beating action of the pleopods [42] [50]; (b) Diagram showing the brush like setae on the first three pereiopods and the orientation of these pereiopods in relation to the water current. Abbreviations: p1-3, pereiopods 1-3 [42].

suggest that this species too may be filter-feeder. Thus some species of *Sphaeroma* filter feed, while others do not [41] [43] [50].

4. Possible Factors Effecting on the Outbreak of Wood Boring Isopod *Sphaeroma* sp.

The distribution rate of mangrove wood borer *Sphaeroma* and their destruction rate on mangrove forests of China have been noticeably increased during the recent 10 years [27]. So, an understanding of the possible factors that can cause the outbreak of *Sphaeroma* in mangroves is important as the activity of this wood-borer can have wide negative impacts on the conservation and restoration of mangrove ecosystem. Their attack and burrowing activity can impact the mangrove tree directly by changing root architectural system, reducing root production, and increasing root atrophy [18] [19] [28] [29] [51] [52] [53] [54]. These effects on root system can not only change support and nutrient provisioning for the tree but also may indirectly affect other fauna that utilize the mangrove roots as either substratum or protective habitat [19] [52] [53] [55]. The following factors could be the main factors that support the outbreak of *Sphaeroma* in mangrove ecosystem.

4.1. Salinity

Sphaeroma isopods are extremely euryhaline species and they can tolerate and thrive in a wide range of salinity [25] [56] [57]. Charmantier and Charmantier-Daures (1994) studied on the ontogeny of osmoregulation and salinity tolerance in *S.serratum* that is closely related to *S. terebrans*. Sphaeromid isopods have specialized brood pouches in which organic concentrations are differ from the external environment that can act osmotic shelters for the young. Even juveniles are able to hyperregulate at birth and all stages after birth are euryhaline. Adult *S. serratum* can perform hyper regulation at low salinity, hyperosmoconform in seawater and hypoosmoconform in high salinity media [58]. Poirrier *et al.* (1998) form India indicated that the lethal salinities for *S. terebrans* occurred below 0.5 ppt and above 50 ppt while John (1969) concluded the optimum for the growth and reproduction was a narrow range between 4 ppt and 28 ppt [57] [59]. The sudden increase in salinity of water can decrease the burrowing activity of *Sphaeroma* [25]. Global climate change has resulted in a gradual sea level rise which can cause saline water to migrate upstream in estuaries and rivers; thereby the optimum habitats to reproduce and create shelter for *Sphaeroma* become increase to a wide range. Salinity of the surrounding water could be one of the main factors that affect the outbreak of *Sphaeroma*.

4.2. Temperature Increase by Climate Change

The world is getting warmer and the average global temperature on Earth has increased by about 0.8˚C (1.4˚F) since 1880 [60]. Warming has caused melting of polar ice and the increase of ocean water levels. It has produced shorter and warmer winters, with earlier arrival of spring temperatures and later onset of winter conditions. New study shows that the organisms living in warmer areas are more likely to undergo rapid population growth because they have higher metabolic rates and reproduce more frequently [61].

Since *S. terebrans* and some of the other *Sphaeroma* species are found in subtropical and tropical climates around the world [26], they can endure reasonably wide daily and seasonal variations in temperature and individuals may occasionally experience lethal winter low temperatures [57]. Rehm and Humm (1973) studied *S. terebrans* from Florida and found that when the temperature was set at 24˚C, reproduction occurred within 2 to 4 weeks in captivity [20]. Thiel (1999) examined on the reproductive biology of *S. terebrans* in the Indian River Lagoon, along the Atlantic coast of Florida, USA. Reproductive isopods were found throughout the year but reproductive activity of *S. terebrans* was highest in the fall and during late spring or early summer. During the latter periods, large numbers of subadults establish their own burrows in aerial roots [45]. According to the report of Sankaranarayana *et al.* in 1987, the highest breeding levels for *S. terebrans* in India occurred during the northeast monsoon season (average daily maximum temperatures range between 28˚C and 34˚C) [26]. *S. terebrans*, the most destructive of all the species, has a truly circumtropical distribution and their distributional pattern appears to indicate that uniformly high temperature is essential for their maximum development [56]. Therefore, the temperature created by global warming could give favorable condition to rise in reproduction for more fast-growing juvenile populations. Additionally, while juveniles are under maternal care, the abiotic conditions of the burrow may be regulated by the parent and thus, the extended parental care behavior of *Sphaeroma* can help their juveniles, who are important for recruitment, to protect from lethal conditions [45] [46] [49].

4.3. Food Availability

Sphaeroma shows a preference to attack in the aerial roots of mangrove but it can be found in any kind of live and rotting wood and other materials. *Sphaeroma* apparently does not eat wood and they burrow only for their refuge areas where mating and the reproductive cycle take place. *Sphaeroma* are probably either detritivore (obtaining nutrients from decaying plants and animal parts) or planktivore (consuming on phytoplankton) or filter feeder or a grazer of the epiphytic material that grows on their burrow walls. They are considered filter-feeders that utilize nutrients and phytoplankton in the water column [17] [41] [43] [50]. They also may consume algae from their burrows and substrate According to the study of Rotramel (1975), *S. quoyanum* possesses filter feeding ability by using the brushes on the first 3 pairs of legs and the maxillipeds, which gather particles strained from a current setup in their burrow by beating with their pleopod [50]. Si *et al.* (2002) studied on the morphology of mouth parts and gut support of *S. terebrans* in order to confirm their filter feeding pattern

[43]. Some species of the genus *Sphaeroma* possessing those brushes may also be filter feeders [50]. The filter setae on the pereiopods are well suited to trap particulate food material of a size smaller than 5 μm. Several types of phytoplankton fall within this size range and several types of algal species could form an important part of the diet of *S. terebrans* [17] [50]. In addition to these larger (20 to 200 μm) phytoplankton, smaller species of nano-plankton (2 to 20 μm) may also figure prominently in the diet of *S. terebrans*. Svavarsson *et al.* (2002) found that *S. terebrans* prefer to attack the mangrove at the low water muddy site where the trees were directly exposed to the sea. The water above the muddy sites is likely to contain much more organic matter than at sandy sites. This is likely to result in higher food availability for this filter feeder at muddy sites [17]. Although predation [53] and competition [52] [54] can influence the species distribution and can reduce the burrowing activity, *S. terebrans* should have reduced exposure to predation because they don't need to do risky excursion outside of the burrow for their food since they are filter feeders [43]. As *S. terebrans* are unlike from other fouling organisms found on mangrove roots (e.g., barnacles and gastropods), they excavate and resides within their burrow. They would be susceptible to predation only during times of burrow construction.

Fan *et al.* (2014) also reported that the attack and colonization of *Sphaeroma* spp. on mangrove were found abundantly in the mangrove forest growing across the creeks delivering pollutants and at the habitats depositing pollutants. Those aggregated pollutants also increase excessive eutrophication leading to the blooms of macroalgae and phytoplankton in estuaries and mangrove swamps though eutrophication is a common phenomenon in shallow coastal waters [24]. Moreover, the physical structure of mangroves slows the water flow allowing sands, clays, heavy metals, and other sediments to drop out of suspension in the water column, thereby, mangroves alter the turbidity of ambient waters [7]. This property of mangroves, itself, is inviting the invasion of *Sphaeroma* and supplying enough food sources for their establishment.

4.4. Tide and Flow of Water

Sphaeroma needs the water to initiate burrowing the wood and for their filter feeding. The *Sphaeroma*, especially *S. terebrans* preferentially bore in the intertidal zones where the floods are on a regular tidal cycle, oxygen levels are high at low tide, suspended material is abundant when submerged at high tide [17] [18] [19]. These borers can withstand several hours of exposure out of the water during low tide since they typically retreat into their burrows and remain inactive [41]. When the roots are submerged at high tide, as *S. terebrans* are active swimmer, they can move quickly from one root to another root. Obviously, with increasing intertidal height, the isopods may have enough time to be submerged in water which will not only provide their feeding time but also their time to attack new roots. It has recently been shown with experimental manipulations that submergence is an important physical factor for the colonization of *S. terebrans* onto the red mangrove, *R. mangle* [19]. However, further study is still needed to perform concerning the ecology of the isopod including their survival rate at different submergence time and the interactions between submergence times and feeding or food availability [17].

4.5. Water Quality

In China, polluted water originated from industrial and domestic wastewater was discharged directly and indirectly into the reserved mangrove. In addition to this, duck farms, pig farms and shrimp farms along the coast area are additional pollution sources for water body of mangrove [62]. Mangrove wetlands are famous for maintaining surrounding water quality by filtering riverine and tidal waters of sediments, minerals, contaminants, and nutrients [7]. Mangrove wetlands and estuaries receive pollutants that affect water quality including salts, heavy metals and nutrients such as nitrogen, phosphate, and sulfur compounds originated from urban, agricultural or industrial activities. These pollutants are delivered via land run-off, river inputs, discharges and dumping and atmospheric inputs to mangroves and estuaries [7]. Although eutrophication is a common phenomenon in estuaries and shallow coastal waters, these aggregated pollutants lead to excessive eutrophication which can cause the increase in biomass of algae and phytoplankton and depletion of dissolved oxygen leading to decreased biodiversity [62]. Increased biomass of algae and phytoplankton can support *Sphaeroma* with abundant food source for their establishment. In addition to this, dissolve oxygen depletion in water causes the death of natural enemies such as fishes, crabs and other marine animals who also inhabit in mangrove ecosystems. Thus, *S. terebrans* can take advantages on water pollution for their abundant food sources and the reduction in chances of predation by natural enemies. Thereby, water quality, especially water pollution could play a critical role for the outbreak of wood borers in mangrove ecosystem.

4.6. Reduced Biodiversity of Restored Mangrove Forest

During last two decades, China's government has established and started a series of conservation, afforestation, and restoration programs for mangroves forests. A few species of native mangroves and some fast-growing exotic mangrove species were intensively used to plant in monoculture for most of restoration projects. As an example, *Sonneratia apetala* from Bangladesh were planted in many locations along the coastline of Southern China, such as the Dongzhaigang Mangrove Nature Reserve of Hainan, the Zhanjiang, Qi'ao and Futian Mangrove Nature Reserves of Guangdong, Beilunhe Mangrove Nature Reserve of Guangxi, and several locations in Fujian. As most of these reforestation projects are aimed mainly for the appearance of the planted trees and for the high survival rates, these projects followed monocultures [30]. It has been known that monocultures in reforestation can reduce the biodiversity of replanted forests and lead to change in food web interaction. Those forests with reduced biodiversity are vulnerable to pest outbreak because of their low ecological value. However, empirical studies investigating this relationship between the pest outbreak risk and the monoculture reforestations are rare. Dalin *et al.* (2009) studied the temporal variability in the density of the leaf beetle, *Phratora vulgatissima*, between 20 willow plantations and 20 natural willow stands over a seven-year period (1999-2005) in order to confirm that insect pest outbreak risk is higher in monocultures. They found that the leaf beetle had a greater temporal population variability and outbreak risk in willow plantations than in natural willow habitats. In natural stands, the relatively high density of generalist predators and the competition for depleted resources (plant foliage) can cause the stable low population equilibrium of beetle. Planting trees in dense monocultures can facilitate the pests for finding their host plants without interruption by other plant species and for their dispersal from tree to tree without competition, thereby; promoting their population growth [63]. In addition to this, the wood borer *Sphaeroma* might be one of invasive species in China's mangroves since *Sphaeroma* is native to Indian Ocean and Indo Pacific region. Invasive species have high adaptability to harsh environmental conditions for their survival. Non-native species represent a biodiversity, social, and economic threat [64]. Therefore, reduced biodiversity of forests restored by monoculture stands could be one of the main factors causing the outbreak of *Sphaeroma*.

5. Destructive Impacts of *Sphaeroma* spp. Outbreak on Mangrove Forest

The colonization of wood borers created the hollows inside the roots and trunks of mangroves but the appearance of mangrove tree looks healthy and some mangrove showed gradually dieback. When the typhoon blew on the shoreline, these hollowed mangroves cannot stand and be cut down by the strong wind and eventually die off (**Figure 4**, **Figure 5**) which may lead to serious destruction in mangrove forest and shoreline erosion. Perhaps, the bio-deterioration of vegetation by various insects and marine wood borers can also be taken into account as one of the threats to the conservation and restoration of mangrove in China.

The mechanical composition of sediment of mangrove flats can influence the insertion and germination of viviparous propagules; soft muddy flats allow easy penetration of propagules, but hard sandy flats handicap the insertion of propagules. In addition, the mechanical composition of mangrove soil is related to soil nature and textures. It was suggested that the quantity of tiny glutinous grains (<0.01 mm) of mangrove soil are positively correlated to the amount of organic matter, total N, total P, and total K in the soil. The cementation and agglomeration of tiny soil grain with organic matter forms nutritious soil for mangrove forests.

Plant becomes weak.

6. Possible Control and Prevention Method for Isopod Outbreak

The distribution of Sphaeromids in a variety of environments namely, in sea, estuaries, brackish water and fresh water, subjects them to a variety of stresses, and therefore, population in different habitats exhibit physiological adaptations and variation of different magnitude. Standards wood preservatives CCA (chromated copper arsenate), ACA (ammonical copper arsenite) and creosote were used to test the effectiveness on the control of isopod population. As some of Sphaeromids isopods including *S.terebrans* are filter feeders, there is little evidence that chemical treatments and preservatives impact on isopod colonization [41] [65]. Although little evidence of arsenic or chrome accumulation was found in these animals, the levels of copper found in the digestive glands of these isopods were remarkably high. *S. terebrans* and *S. triste* differed in their response to the elevated levels of copper in their immediate environment, with one species storing excess copper in granules and the other apparently being able to regulate its body copper levels. As copper is required for their respiratory pigments, the presence of elevated copper levels may even be beneficial [65]. In addition to this, these preservatives are not possible for applying in living vegetated plants. Using insecticides with additives will be in vain to protect the establishment of Sphaeromids isopods and may also lead to polluting the marine environment which can negatively affect to the other inhabitants.

Fan *et al.* (2014) conducted on the survival rate of *Sphaeroma* isopods by using Calcium oxide and the fish *Bostrich thyssinensi*, the natural enemy of isopods, in laboratory. It was found that the 50% of tested isopod individuals can be killed by 1:1 of Calcium oxide to water (w/w) during 90 minutes treatment time and the average 42 isopod individuals can be consumed by a fish in 24 hours, the feeding rate of fish on the isopods was relatively stable. Such inorganic compounds could be useful to apply to the seriously isopods infected mangrove areas for emergencies but detailed consideration should be taken accounted on the impacts on and the consequences of the ecological health of surrounding environment. On the other hand, reduction of water pollution sources could be effective for the control of *Sphaeroma* outbreak by restoring the water quality to create the favorable conditions for their natural enemies [24].

However, more detail researches are still need to conduct the biology of *Sphaeroma* found in China's mangrove forests including migration pattern, reproduction and recruitments season, the optimum temperature and salinity for their reproduction and so on. For instance, the sudden increase and decrease in salinity could impact on the survival of juveniles and the burrowing activity of adults. As successful establishment within an area would require reproductive activity or juvenile recruitment, we could control their outbreak by using ecological engineering methods after understanding their reproduction and recruitment season.

In addition to this, the tests on the substratum preference of *Sphaeroma* should be conducted in field trial by using the other substrates such as polystyrene foam and decaying woods rather than mangrove living. Understanding the substratum preference of borers and aspects of colonization may also help to determine methods for managing and controlling this species. For example, their preferred substratum could be placed in infected mangrove forests, and the isopods could be allowed to bore and colonize in these substrates. After their colonization and reproduction period, the newest cohort may be able to remove from the tested area. If this process was continued for several seasons even though the high consumption of time and cost, populations of borers could be lowered enough to reduce their impacts. Moreover, intensive care should be performed on the damaged mangrove forests such as removal of decaying woods and twigs preferred by wood borers and removal of infested stumps and other trash wood lying in the habitat from mangrove forest as they provide a perennial source for the supply of borer larvae for fresh attack.

Besides these, the other important and indirect impact of their outbreak could be the reduced biodiversity of restored mangrove forest. Hence, the strength of biodiversity is one of the most important factors for ecosystem and should take into consideration carefully for the successful restoration of damaged forests and conservation of the existing mangrove forests.

7. Restoration of Mangrove Ecosystem and Its Associated Issues

After realizing the ecological importance of invaluable mangrove ecosystems for human beings, almost all nations possessing these valuable mangals around the world had been trying to restore these forests where they have previously existed. In the past few decades, the rehabilitation of mangrove forests in different countries was done with different purposes such as conservation and landscaping; multiple-use systems for sustainable yield of natural resources and protection of coastal area [7] [66] [67] [68]. According to the information analyzed by Field (1996) and Spalding (1997), only some 20 nations with mangal around the world attempted the rehabilitation of their mangrove forests by replanting relatively only a few mangroves' species, for example, the largest mangrove afforestation program in the world, with plantings of primarily one species (*Sonneratia apetala*) over 1600 km^2 on newly accreting mudflats in Bangladesh [69] [70]. However, this approach usually fails over the long term because the underlying soil and hydrological requirements of the mangroves are not being met. While the concepts of ecological restoration are considered, the reforestation projects planting only one or two species did not mean the ecological restoration even if it succeeded [67] [68] [69] [71]. Besides, the diversity of restored mangrove forests with mono- or few species of mangrove become reduced which is leading to weaken the biodiversity strength of the forest and invite the diseases and pests.

In addition, many mangrove restoration projects moved immediately into the planting of mangroves without taking consideration into the ecological requirements of mangroves. There have been unfortunately many failed restoration projects to achieve the stated goals over the years, invariably wasting both time and money [68]. Farnsworth and Ellison (1997) discussed various conservation issues concerning mangrove ecosystems and they concluded that more information and education needs to be disseminated at the local level [54]. Based on the failure experiences of restoration projects, Lewis, and Marshall (1997) suggested five critical steps and then developed Ecological Mangrove Restoration (EMR) as a proven six critical steps for successful mangrove restoration project modified by Lewis and his colleagues [72] [73]. These six steps are:

1) To understand both the autecology (individual species ecology) and the community ecology of the mangrove species;

2) To understand the normal hydrology;

3) To assess modifications to hydrology or added stress;

4) To select the restoration site based on technical, political, social, and economic considerations;

5) To restore or create normal hydrology, or remove or reduce stress, and as a final step;

6) To utilize actual planting propagules, collected seedlings, or cultivated seedlings after determining through steps 1-5 that natural recruitment will not provide the quantity of mangroves desired.

Another important thing for restoration projects is cooperation and working together of communities and organizations with local government. In addition to restoration, protection and sustainable management of the remaining mangrove ecosystems is also critical for the benefit of future generation before too much precious habitat of the remaining mangroves is irretrievably lost, and our restoration efforts are in vain. Once a mangrove rehabilitation project has been completed, it is also essential to monitor long-term progress and to maintain for ensuring the sustainability of the restored mangrove site [7] [66].

8. Conclusions

Mangrove forests are found along ocean coastlines throughout the tropics and subtropics. These remarkable forests are of great importance to coastal communities by providing not only a source of food and resources but also protecting coastlines, preventing erosion, and helping to mitigate climate change. However, the extent of global mangrove forest areas had threatened and declined by 30% to 50% over the past half-century as a result of coastal development, aquaculture expansion and over-harvesting. After recognition of their ecological values, all nations possessing mangrove communities have been trying to rehabilitate and restore their mangrove forests. However, most of the restoration projects experienced failures to reestablish the forest because of technical and social failures.

In addition to this, the pests of mangroves including herbivory insects and wood borers are additional destructive causes for mangroves forests. The cosmopolitan wood-boring *Sphaeromids* isopods, especially *S. terebrans* bores into the aerial roots of mangrove trees that can cause death and subsequent breakage of the inhabited root and, debatably, may reduce the support system of the tree. Therefore, it seems that the presence of isopods in mangroves can impact the ecology of mangrove forest. Even though the potential threat of the isopod to mangrove forests has been highlighted by several researchers, there is a huge gap in our ecological knowledge of this borer. Little research concerning the *Sphaeroma* wood borer in Chinese mangroves was done. It is also important to study the nature of physiological adaptations and variations in the different animal populations. So, more attempts should be done in order to get insight into the factors affecting the outbreak of *Sphaeroma* in mangroves forests and to find out the potential way to control their outbreak.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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