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The influences of anthropogenic modification after the Great East Japan Earthquake on ground insects and their relationship with vegetation

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The influences of anthropogenic modification after the Great East Japan Earthquake on ground insects and their relationship with vegetation

On the Pacific coast of Northeastern Japan, tidal embankments and coastal forests were constructed following the Great East Japan Earthquake. Although coastal forests are regarded as green infrastructure, the impact of their reconstructions on ecosystems is concerning. To mitigate these impacts on the Sendai coast of Miyagi prefecture, non-modified areas were established, and coastal sand was covered over the mounds constructed as coastal forest beds. This study surveyed the distribution of ground insects and vegetation in this area to evaluate differences associated with these anthropogenic modifications and mitigations. The results showed that coastal insect abundance and vegetation coverage were lower on the mounds compared to the areas without afforestation or mounding. However, inland insect abundance and vegetation coverage was higher on the landward side of the tidal embankment compared to the seaward side, regardless of the mounds. On the landward side of the tidal embankment, coastal insect abundance was lower when inland vegetation coverage was dense. Additionally, no quantitative differences in coastal insects and plants were observed between the sand-covered mounds and not covered mounds. We suggest that the influence of green infrastructures such as coastal forests on the native ecosystem should be considered.

Keywords: Tidal embankment; coastal forest; coastal defense; coastal dune ecosystem; interaction of insects and plants

1. Introduction

Sandy beaches and subsequent coastal dunes form the boundaries between terrestrial and marine areas. Their terrestrial ecosystems are strongly affected by disturbances and stresses such as waves, salt spray, sand burial, dryness, wind exposure, and nutrient deficiency, and they contain characteristic species because the flora and fauna need to adapt to such environmental conditions (Hesp 1991; McLachlan 1991; McLachlan and Brown 2006). Coastal ecosystems are among the most threatened ecosystems in the world due to human impacts (Barbier et al., 2011; Defeo et al. 2009). In recent years, the demand has been increasing to protect coastal lands, residents, and communities from sea threats, such as sea level rise, extreme weather events, and natural disasters. Conventionally, hard infrastructure such as seawalls and levees have been applied for coastal defense, but their ecological and economic limitations have been pointed out (Morris et al. 2018). This situation has led to the advanced nature-based concept of "green infrastructure," which utilizes the resistance and resilience of natural coastal ecosystems such as coastal dunes, salt marshes, mangroves, and coral reefs, and "hybrid infrastructure," which combines hard and green infrastructure. However, there is no universal solution because artificial structures, natural ecosystems, and hybrids have their own strengths and weaknesses (Jordan and Fröhle 2022; Morris et al. 2018;

Sutton-Grier, Wowk, and Bamford 2015). To design coastal defense engineering that can be compatible with ecosystems, knowledge of the relationship between anthropogenic modification and natural ecosystems in various situations is necessary.

Large-scale coastal defense structures have been constructed along the Pacific coast of eastern Japan since the Great East Japan Earthquake (GEJE) on March 11, 2011. This region, especially Iwate, Miyagi, and Fukushima prefectures, was severely damaged by the tsunami caused by the GEJE. The 2011 earthquake was only the fourth-largest earthquake in recorded history (Earthquake Hazards Program 2019) and the area inundated by the tsunami was 561 km^2, especially in Miyagi Prefecture, which accounted for 327 km^2 or 58.3% of the total inundated area (Geospatial Information Authority of Japan 2011). The tsunami was also a natural event that caused low-frequency and large-scale disturbances to the coastal ecosystem. Even after the tsunami, vegetation on the sandy beaches of Southern Sendai Bay, one of the areas severely affected by the tsunami, survived or self-recovered (Kanno et al. 2014; Kurosawa 2016; Oka and Hirabuki 2014). Despite these recovering ecosystems, coastal defense structures, such as tidal embankments and coastal forests, were reconstructed over these recovered areas (Furuta and Seino 2016; Kurosawa 2021).

As part of the post-disaster reconstruction project, tidal embankments with T.P. (Tokyo Peil; mean sea level of Tokyo Bay) 7.2 m height were constructed along the sandy beaches of the Southern Sendai Bay coast mainly by the Ministry of Land, Infrastructure, Transport, and Tourism, Japan (MLIT), or the Public Works Department of Miyagi Prefecture (Kurosawa 2021). The impacts of these tidal embankments have been a concern, for example, the division of seaward and landward environments, the prevention of animal movement, and the dispersal of plants (Kurosawa 2021; Nishihiro, Hara, and Hirabuki 2014; Oka and Hirabuki 2014). In addition, coastal forests of the Japanese black pine (*Pinus thunbergii),* were established as another coastal defense structures in the inland areas of these tidal embankments by the Forestry Agency of Japan (Kurosawa 2021; Yamanouchi et al. 2021). Guidelines from the Forestry Agency of Japan states that the reconstruction of coastal forests should be performed with the construction of mounds in height 2−3 m above groundwater level as planting beds to increase tsunami resistance by ensuring adequate pine roots development.

In most of the coastal forests in Japan, including those on Southern Sendai Bay before the GEJE, black pine or red pine have been planted since the Edo period (1603–1868) to protect human habitation areas from coastal sand blows, salt spray, strong winds, and other disturbances from the sea. Historically, these coastal forests have been

managed by local residents, who have used pine leaves and wood for fuel and building materials (Kikuchi 2017; Kikuchi et al. 2024; Yoshizaki 2011). After World War II, because the demand for fuel from pine trees decreased with the spread of fossil fuels, management of coastal forests by local residents has been discontinued, leading to the occurrence of pine wilt disease by pine wood nematode (*Bursaphelenchus xylophilus)* (Nakamura 2017; Yoshizaki 2011). On the other hand, coastal forests have been regarded as green infrastructure in recent years, especially after the GEJE (Kurosawa 2021; Natuhara 2018).

For the coastal forests that established after the GEJE, the impact of the mounds constructed as forest beds on ecosystems is concerning. These mounds were constructed using mineral soil obtained by cutting through inland hills, not sand of the surface in the coastal area, and have buried not only surviving and self-recovering living organisms but also the newly emerged environments after the tsunami (Kurosawa 2021; Nishihiro, Hara, and Hirabuki 2014). New habitats established in these mounds impede the colonization and growth of coastal plants (Mabuchi, Yamanouchi and Kurosawa 2020; Yamanouchi et al. 2021). On the other hand, the Forestry Agency of Japan has made several attempts to conserve biodiversity in coastal forests based on the opinions of ecological experts (Kurosawa 2021; Kurosawa et al. 2023). One example is designating

conservation areas without afforestation or mounds, which were established patchy to preserve coastal ecosystems consisting of sandy areas, wetlands, and surviving coastal forests after the tsunami (Kurosawa 2021; Kurosawa et al. 2023; Oka and Hirabuki 2017). Another example is covering mounds for coastal forest beds with coastal sand that were stored prior to the reconstruction to restore coastal vegetation from the seed bank (Kurosawa 2021; Kurosawa et al. 2023). These have been reported to have a conservation effect on coastal plants for at least several years after implementation (Oka and Hirabuki 2017; Yamanouchi et al. 2021). However, because these attempts were experimental, the necessity for continuous monitoring and multiple evaluations of biodiversity and ecological aspects has been highlighted (Kurosawa 2021).

In this study, quantitative data on ground insects and vegetation in these areas were surveyed. Insects, particularly Coleoptera, Hymenoptera, and Diptera, are among the dominant taxonomic groups on sandy beaches and coastal dunes, and vegetation cover is one of the most important factors influencing animal habitats in these environments (McLachlan 1991; McLachlan and Brown 2006). This study focused on ground insects, including Coleoptera, because they are considered to be more sensitive to land modifications, such as tidal embankments and mounding, owing to their low mobility. Because of their relative ease of trapping and quantification, ground insects,

126 especially Coleoptera, are often used as indicator taxa in terrestrial ecosystems,
127 including coastal dunes (Bird et al., 2017; Pearce and Venier, 2006; Rainio and
128 Niemelä, 2003; Schirmel and Buchholz, 2011). Some studies have recorded ground
129 insects on the beach in Southern Sendai Bay after the reconstruction (Igarashi 2019;
130 Kamuro, Hirabuki, and Igarashi 2020), but no comprehensive and quantitative
131 comparison studies of these areas have been conducted.

132 The aims of this study were 1) to evaluate the differences in ground insect
133 abundance and vegetation coverage between mounds constructed as coastal forest beds
134 using soil from inland hills and areas without mounds, 2) to identify the relationship
135 between vegetation coverage and ground insect abundance on the landward side of the
136 tidal embankment, and 3) to compare the differences in ground insect abundance and
137 vegetation coverage between mounds for coastal forest beds that covered with coastal
138 sand and that not covered.

139 2. Materials and methods

140 *2.1. Study site*

141 The survey was conducted on sandy beaches in the Arahama and Shinhama areas
142 (adjacent areas), located on the Southern Sendai Bay coast in the Tohoku (northeastern)

region of Japan (Figure 1). The Southern Sendai Bay coast faces the Pacific Ocean and has sandy beach extending approximately 65 km from the Miyagi Prefecture to the Fukushima Prefecture. Geomorphologically, this area is characterized by a landscape of sandy beaches, salt marshes, and coastal forests planted during the Edo period (1603−1868). The tsunami caused by the GEJE is estimated to have reached up to 4 km from the coastline in this area (Sugawara et al. 2013). The Arahama and Shinhama areas are located approximately 6 km northeast of the mouth of the Natori River and 3 km southwest of the mouth of the Nanakita River, which are the second- and third-largest rivers flowing into Sendai Bay. In this area, the reconstruction of tidal embankments with T.P. 7.2 m was completed in 2013 (Sendai Office of River and National Highway n.d.), and the construction of mounds for coastal forest beds with T.P. 3.2 m on the landward side of the tidal embankment was completed in 2015 (Yamanouchi et al. 2021) (Figure 2). Before the GEJE, the height of the tidal embankment was T.P. 6.2 m, and black pines were planted directly on the coastal dunes without artificial coastal forest beds (Figure 3(a)). After the tsunami, these structures were destroyed and vegetation recovery and new emergence was observed (Oka and Hirabuki 2014; Onza et al. 2014) (Figure 3(b)). Subsequently, new tidal embankment and coastal forest were reconstructed (Figure 3(c)) [**Figure 1, 2, and 3 near here**].

Three survey sites were selected for the study. Modification conditions at these sites were categorized into four categories focusing on the tidal embankment, mounding, and afforestation: 1) Seaward, areas on the seaward side of the tidal embankment, and were considered to be the least affected by the modifications; 2) mounded, areas where mounds were constructed using soil from inland hills as the coastal forest beds, and were considered to be affected by the tidal embankment, mounding, and afforestation; 3) non-mound, areas on the landward side of the tidal embankment without mounding or afforestation, and were considered to be affected only by the tidal embankment; and 4) sand-covered, areas where mounds for the coastal forest beds were covered with coastal sand 10 cm thick that were stored prior to the reconstruction, and were considered to be affected by the tidal embankment, mounding, and afforestation, but the influence of mounding was expected to be mitigated by sand-covering.

Survey lines were established perpendicular to the shoreline at all survey sites (Figure 4). Note that two of these lines were not perpendicular, one at Site 1 was established along the biodiversity conservation area, and one at Site 3 was established across the others. Considering the environmental changes from sea to land, these lines

were set such that the mounded, non-mound, and sand-covered areas were mixed at the same distance from the sea [**Figure 4 near here**].

Site 1 was located around an area designated as a biodiversity conservation area. This site was selected to compare the seaward, mounded, and non-mound areas and to identify the relationship between vegetation coverage on ground insect abundance in the mounded and non-mound areas. Five survey lines were established from the shoreline to 200 m inland of the tidal embankment at this site (Figure 4(a)). The distance from the shoreline to the tidal embankment was 60−100 m as of September 2022 (varying between survey lines). On the landward side, from the lower edge of the tidal embankment to approximately 70 m was non-mound area, and a gravel road ran through this area. Further inland, the area was a mixture of mounded and non-mound areas.

Site 2 was located approximately 1 km northeast of Site 1. This site was selected to compare the seaward, mounded, and non-mound areas and to identify the relationship between vegetation coverage on ground insect abundance in the mounded and non-mound areas, similar to Site 1. A survey line was established from the shoreline to 200 m inland of the tidal embankment at this site (Figure 4(b)). The distance from the shoreline to the tidal embankment was 110 m as of September 2022. On the landward side, from the lower edge of the tidal embankment to approximately 30 m was non-

mound area, and a gravel roadway ran through this area. Further inland, there was a 30 m wide mounded area, followed by a 90 m wide non-mound area, and again by a 100 m wide coastal forest that are mounded area.

Site 3 was located approximately 400 m northeast of Site 1 and 600 m southwest of Site 2. This site was selected to compare the mounded, non-mound, and sand-covered areas. Three survey lines and one survey line crossing them were established at this site (Figure 4(c)). The former three survey lines were established from 30 to 160 m inland from the tidal embankment, perpendicular to the tidal embankment, and 30 m apart from each other. One line was established to include a 30 m wide sand-covered area, the other was established to include an 80 m wide sand-covered area, and one was established to include an 80 m wide mounded area. Beyond these sand-covered and mounded areas, there is a non-mound area approximately 160 m from the lower edge of the tidal embankment. The last one survey line was established at 55 m from the tidal embankment, perpendicular to the other three lines.

2.2. Data collection

Survey at Site 1 and 2 was conducted to compare the seaward, mounded, and non-mound areas and to identify the relationship between vegetation coverage on ground

insect abundance in the mounded and non-mound areas. Survey points were established every 20 m perpendicular to the shoreline on the survey lines. The total number of survey points was 29 in the seaward area, 21 in the mounded area, and 38 in the non-mound area.

Survey at Site 3 was conducted to compare the mounded, non-mound, and sand-covered areas. Survey points were established every 20 m on the survey lines perpendicular to the tidal embankment and every 10 m on the survey line crossing them. The total number of survey points was six in the mounded area, 12 in the non-mound area, and eight in the sand-covered area.

Ground insects were collected using pitfall traps (Figure 5). Plastic cups with a diameter of 75 mm and depth of 125 mm were used as traps, and 50 mL of 20% propylene glycol solution was poured into the cups to prevent escape. Two traps were placed at each survey point, 2 m apart across the survey line. The samples were collected approximately 48 h after setting and sorted in a laboratory. Insect sampling was carried out in September 2022 at Site 1 and 2 and September 2023 at Site 3 [**Figure 5 near here**].

A vegetation survey was conducted using a 2 m × 2 m quadrat set between the pitfall trap placement points. All vascular plants that appeared within the quadrat were

recorded and the coverage of each species was visually estimated. Vegetation surveys were conducted in October 2022 at Site 1 and 2 and September 2023 at Site 3.

2.3. Data analysis

2.3.1. Species categorization

Only ground insects were used for the analysis of samples collected using the pitfall traps. Arthropods other than insects, flying insects, and larvae of unidentified species were excluded from the analysis. The collected ground insects were categorized into the following two categories based on their habitats with reference to previous records: 1) Coastal, species that are unique to sandy beaches or coastal dunes and rarely found in inland areas, or species that mainly inhabit sandy beaches or coastal dunes but are also found in inland areas, such as riversides or other sandy areas; and 2) inland, other species that do not usually inhabit sandy beaches or coastal dunes. Therefore, "coastal insects" in this study are not limited to species that specialized in coastal environments, but all of them are typical species on natural sandy beaches and coastal dunes. To assess deviations from the natural coastal environment on the landward side of the tidal embankment, species that inhabit wrack near the shoreline (*Aleochara fucicola* (Staphylinidae), *Adota* sp. (Staphylinidae), *Hypocaccus varians* (Histeridae), *Cercyon*

aptus (Hydrophylidae)) were excluded from coastal insects in the analysis of abundance described below. Analysis of species richness was not performed because the mean and maximum species richness at each survey point were very small.

Herbaceous plants observed in the vegetation survey were classified as coastal species based on Nakanishi (2020) and species that were not listed were classified as inland species. The coastal and inland vegetation coverage in each quadrat was calculated as the sum of the coverage of the species classified in each category.

2.3.2. GLM analysis of the differences in insect abundance and vegetation coverage between the seaward, mounded, and non-mounded areas

A generalized linear model (GLM) analysis was performed to compare insect abundance and vegetation coverage between the seaward, mounded and non-mound areas at Site 1 and 2. Four models were applied with the abundance of coastal and inland insects (total number of individuals per survey point in each category), and the coverage of coastal and inland vegetation (%) at each survey point as response variables. Due to overdispersion, a negative binomial distribution was used. The explanatory variables were the modification conditions (seaward, mounded, and non-mound) as factor variables and distance from the sea (m) as numeric variables. The effects of the modification conditions (mounded and non-mound) are described with

reference to seaward areas. After modelling, pairwise comparisons of the estimated marginal means, which are the means extracted from the statistical model, among the seaward-side, non-mound and mound areas were performed. The analysis was performed using R ver. 4.2.0 (R Core Team 2022) with the “emmeans” package (Lenth, 2023).

2.3.3. Hurdle model analysis of the relationship between vegetation coverage and coastal insect abundance in the mounded and non-mound areas

The differences associated with environmental factors (vegetation coverage, mounding, and distance from the tidal embankment) in the mounded and non-mound areas at Site 1 and 2 was analyzed using a hurdle model because of the large number of zeros in coastal insect abundance, mainly in the mounded area. The hurdle model comprises two steps: a zero component and a count component (Zeileis, Kleiber, and Jackman 2008). In the first step, a binomial distribution model or a censored count distribution determines whether the response variable is zero or a positive count value. The zero component indicates the occurrence of a positive count value, meaning that an explanatory variable with a positive coefficient increases the probability of being non-zero. In the second step, the positive counts are estimated, as in the GLMs only when the hurdle in the first step is exceeded.

A binomial model with a logit link was used for the zero component and a truncated Poisson model with a log link was used for the count component. The explanatory variables were the modification conditions (mounded and non-mound) as factor variables, and inland vegetation coverage (%) and distance from the tidal embankment (m) as numeric variables. The effects of the mounded area were described with reference to the non-mound area. Coastal vegetation coverage was excluded as an explanatory variable because of its correlation with mounding. R ver. 4.2.0 (R Core Team 2022) with the function hurdle from the "pscl" package (Zeileis, Kleiber, and Jackman 2008; Jackman 2020) was used for the analysis.

2.3.4. Hurdle model and GLM analyses of the differences in insect abundance and vegetation coverage between the mounded, non-mound, and sand-covered areas

Comparison of coastal insect abundance between the mounded, non-mound, and sand-covered areas were attempted, as in the comparison between the seaward, mounded, and non-mound areas. However, it was unable to use the same statistical methods because no coastal insects were collected in the mounded area at Site 3. Instead, data at Site 1 and 2 in 2022 and that at Site 3 in 2023 were combined to compare the mounded, non-mound, and sand-covered areas.

A hurdle model was applied with coastal insect abundance as the response variable, owing to the large number of zeros. The explanatory variables were survey year (2022 and 2023) and the modification conditions (mounded, non-mound, and sand-covered) as factor variables, and distance from the tidal embankment (m) as numeric variables. The effects of the modification conditions (mounded and sand-covered) were described with reference to the non-mound area. Pairwise comparisons of the estimated marginal means of the mounded, non-mound, and sand-covered areas were performed using R ver. 4.2.0 (R Core Team 2022) with the “emmeans” package (Lenth, 2023).

Comparison of inland insect abundance and coastal and inland vegetation coverage (%) between the mounded, non-mound, and sand-covered areas were analyzed using GLMs with data only at Site 3. A negative binomial distribution was used because of overdispersion. The explanatory variables were the modification conditions (mounded, non-mound, and sand-covered) as factor variables, and distance from the tidal embankment (m) as numeric variables. The effects of the modification conditions (mounded and sand-covered) were described with reference to the non-mound area. Pairwise comparisons of the estimated marginal means of the mounded, non-mound, and sand-covered areas were also performed.

3. Results

3.1. Overall insect abundance and richness

A total of 3466 individuals from 53 insect taxa were found at Site 1 and 2 in 2022, and 1416 individuals from 29 insect taxa were found at Site 3 in 2023 (Figure 6, Figure 7, Appendix 1). Coastal insects comprised 812 individuals of 20 taxa at Site 1 and 2 in 2022 (586 individuals of 17 taxa on the seaward side of the tidal embankment and 226 individuals of 12 taxa on the landward side) and 39 individuals of nine taxa at Site 3 in 2023, most of which were dominated by were Coleopterans (724 and 39 individuals at Site 1 and 2 in 2022 and Site 3 in 2023, respectively). Dermapterans were the second most abundant coastal insect group Site 1 and 2 in 2022 (82 individuals). Inland insects comprised 2654 individuals of 33 taxa Site 1 and 2 in 2022 (187 individuals of eight taxa on the seaward side and 2467 individuals of 31 taxa on the landward side) and 1377 individuals of 20 taxa Site 3 in 2023, most of which were dominated by Hymenopterans (i.e. ants, 2262 and 1274 individuals at Site 1 and 2 in 2022 and Site 3 in 2023, respectively). Orthopterans were the second most abundant inland insect group (308 and 88 individuals at Site 1 and 2 in 2022 and Site 3 in 2023, respectively) [**Figure 6 and 7 near here**].

3.2. Differences in insect abundance and vegetation coverage between the seaward, mounded, and non-mounded areas

GLM result showed that different modification conditions (seaward, mounded, and non-mound) were associated with insect abundance and inland vegetation coverage at Site 1 and 2. For coastal insect abundance, a negative coefficient without 0 in the 95% CI was observed for the variable "mounded," meaning that the number of coastal insect individuals would be low in the mounded area (coefficient = -3.311 ± 0.731 SE) (Table 1). A weak negative coefficient was also observed for distance from the sea (-0.005 ± 0.003) (Table 1). Pairwise comparison using this model showed that coastal insect abundance in the non-mound area was equivalent to that on the seaward area, whereas abundance in the mounded area was significantly lower (Figure 8(a)) [**Figure 8 and Table 1 near here**].

For inland insect abundance, positive coefficients without 0 in the 95% CI were observed for all explanatory variables (distance from the sea: 0.005 ± 0.002, mounded: 1.153 ± 0.581, non-mound: 1.243 ± 0.464) (Table 1). A pairwise comparison showed significantly higher inland insect abundance in the non-mound area compared to the seaward area; however, abundance in the mounded area was not significantly different from either of the other two (Figure 8(b)).

No significant coefficient on coastal vegetation coverage was observed for any of the explanatory variables (distance from the sea, mounded, or non-mound) (Table 1). The mean coastal vegetation coverage was the highest in the non-mound area, and pairwise comparison showed a significant difference only between the non-mound and mounded areas (Figure 8(c)).

For inland vegetation coverage, positive coefficients without 0 in the 95% CI was observed for the variables “mounded” and “non-mound” (mounded: 5.804 ± 0.639, non-mound: 5.634 ± 0.591) (Table1). Pairwise comparisons showed significantly lower inland vegetation coverage in the seaward area and no significant difference between the mounded and non-mound areas (Figure 8(d)).

3.3. Relationship between vegetation coverage and coastal insect abundance in the mounded and non-mound areas

The results of the zero component in the hurdle model showed a negative coefficient without 0 in the 95% CI for the variable “mounded” (-2.316 ± 0.696) (Table 2), which means that the probability of the presence of coastal insects was lower in the mounded area. Small negative coefficients were also observed for distance from the tidal embankment and inland vegetation coverage (distance from the tidal embankment: -0.010 ± 0.006, inland vegetation coverage: -0.009 ± 0.015) (Table 2) [**Table 2 near**

here].

The results of the count component in the hurdle model also showed a negative coefficient without 0 in the 95% CI for the variable "mounded" (-1.913 ± 0.672) (Table 2), indicating that the abundance of coastal insects in the mounded area would be lower than on the non-mound area, if present. A negative coefficient without 0 in the 95% CI was also observed for inland vegetation coverage (-0.012 ± 0.004), which means that coastal insect abundance would decrease as inland vegetation coverage increased (Table 2, Figure 9). A small negative coefficient was observed for distance from the tidal embankment (-0.002 ± 0.001) (Table 2) [**Figure 9 near here**].

3.4. Differences in insect abundance and vegetation coverage between the mounded, non-mound, and sand-covered areas

At Site 3 in 2023, no coastal insects were observed in the mounded area; they were observed only in the sand-covered and non-mound areas (Figure 10). However, the overall abundance was lower than that at Site 1 and 2 in 2022. Combining the data at Site 1 and 2 in 2022 and that at Site 3 in 2023, the results of the zero component in the hurdle model showed a negative coefficient without 0 in the 95% CI for the variable "mounded" (-2.712 ± 0.647), which means that the probability of the presence of coastal insects would be low in the mounded area. The results of the count component showed

negative coefficients without 0 in the 95% CI for the variables “mounded” and “sand-covered” (mounded: -2.151 ± 0.670, sand-covered: -1.214 ± 0.564) (Table 3), and small negative coefficients were observed for distance from the tidal embankment and the variable “Survey in 2023” (distance from the tidal embankment: -0.002 ± 0.001, year: -0.343 ± 0.207) (Table 3). A pairwise comparison using this model showed that coastal insect abundance was significantly higher in the non-mound area, and there was no significant difference between the mounded and sand-covered areas (Figure 11(a)) [**Figure 10 and 11 and Table 3 near here**].

For inland insect abundance at Site 3 in 2023, GLM results showed a negative coefficient without 0 in the 95% CI for the variable “sand-covered” (-1.939 ± 0.641) (Table 4). A pairwise comparison showed that inland insect abundance was significantly lower in the sand-covered area, and no significant difference was observed between the mounded and non-mound areas (Figure 11(b)) [**Table 4 near here**].

For coastal vegetation coverage, negative coefficients without 0 in the 95% CI were observed for the variables “mounded” and “sand-covered” (mounded: -2.756 ± 0.565, sand-covered: -1.693 ± 0.504) (Table 4). A pairwise comparison showed that coastal vegetation coverage was significantly higher in the non-mound area, and there

was no significant difference between the mounded and sand-covered areas (Figure 11(c)).

For inland vegetation coverage, positive coefficients without 0 in the 95% CI were observed for all explanatory variables (distance from the tidal embankment: 0.019 ± 0.008, mounded: 1.575 ± 0.628, sand-covered: 1.837 ± 0.630) (Table 4). A pairwise comparison showed that inland vegetation coverage was significantly lower in the non-mound area, and there was no significant difference between the mounded and sand-covered areas (Figure 11(d)).

4. Discussion

This study compared the seaward, mounded, and non-mound areas, focusing on the distribution of ground insects and vegetation. In the mounded area, coastal insect abundance and coastal vegetation coverage was lower compared to those in the non-mound areas (Figure 8(a) and (c)). The mounds buried surviving, self-recovering, and newly emerging environments, and the flora and fauna that inhabited them after the GEJE (Nishihiro, Hara, and Hirabuki 2014; Kurosawa 2021). In addition, the mounds were created using soil obtained from inland hills and not from coastal areas (Kurosawa 2021). Because of the few buried seeds and organic matter in the soil, herbaceous plants

that are typical of early secondary succession were dominant, and coastal plants were scarce on the mounds within three years of the construction of mounds (Mabuchi, Yamanouchi, and Kurosawa 2020; Yamanouchi et al. 2021; Kurosawa 2021). In this study, few coastal insects and plants were observed in the mounded areas, in contrast to their inhabitation in non-mound areas. Therefore, we concluded that the construction of mounds caused a loss of habitat for coastal insects and plants due to direct land alteration, resulting in an unsuitable environment for their habitat.

In contrast, the coastal insect abundance and coastal vegetation coverage in the non-mound area did not significantly differ from those in the seaward area, considering the distance from the sea (Figure 8(a) and (c)). In addition, the estimated marginal mean of coastal vegetation coverage was the highest in the non-mound area. This result suggests the effectiveness of avoiding mounding on the landward side of the tidal embankment in conserving coastal insects and vegetation. Survey by Oka and Hirabuki (2014) in 2013 (before the construction of tidal embankments, coastal forests, and mounds) showed that the recovery of coastal plants after the tsunami was more advanced in the current coastal forest area and concluded that this was due to the presence of buried seeds in the sand deposited in the coastal forest by the tsunami. After low-frequency and large-scale disturbances such as volcanic eruptions, fires, and floods,

biological legacies such as seeds buried in the soil and the resulting microtopography influence subsequent successions (Foster, Knight, and Franklin 1998; Turner et al. 1998). Tsunamis are also considered a type of low-frequency and large-scale disturbance, and at the Sendai coast after the tsunami, some studies have indicated that biological legacies may have increased plant diversity (Kanno et al. 2014; Nishihiro, Hara, and Hirabuki 2014; Onza et al. 2014). We concluded that the coastal vegetation and insect communities that established after the tsunami persisted for nine years after the construction of the tidal embankment as a result of avoiding mounding. In some locations where tidal embankments were reconstructed after the GEJE, they were set back inland to preserve beaches and tide flats (Kurosawa 2021). In situations where such solutions or not constructing tidal embankments are unfeasible, the results of this study suggest the potential for conserving coastal vegetation and insect habitats inland from the tidal embankments. However, this option is only supplementary, because some coastal species, including an endangered species such as *Cicindela laetescripta* (Carabidae: Cicindelinae), were observed only in the seaward area (Appendix 1).

Inland insect abundance and vegetation coverage was high on the landward side of the tidal embankment regardless of the mounded and non-mound areas (Figure 8(b) and (d)). At other sites along the Southern Sendai Bay coast, inland plants were more

460 abundant in inland areas of the tidal embankment and coastal forest (Oka and Hirabuki,
461 2017). Sandy beaches and coastal dunes are environments with severe disturbances such
462 as strong winds, sand blasts, and sand burial, and coastal species adapt to these
463 disturbances (Hesp 1991; Maun 1998; McLachlan 1991; McLachlan and Brown 2006).
464 However, human activities and artificial modifications are related to the invasion of
465 non-coastal and exotic plants, even in environments exposed to such disturbances
466 (Tordoni et al. 2021; Vecchio, Pizzo, and Buffa 2015). In this study, the blocking of
467 disturbances such as wind and sand blows by tidal embankments and artificial
468 modifications in inland areas seem to have resulted in the abundance of inland plants
469 and insects.

470 The results of the hurdle model, considering the relationship between inland
471 vegetation coverage and coastal insect abundance in the mounded and non-mound areas,
472 showed that coastal insects would decrease as inland vegetation coverage increased
473 (Table 2, Figure 9). Invasive plants can directly affect the food source and propagation
474 of herbivorous insects and can also affect other insects through the food web or changes
475 in the characteristics of microhabitats (Bezemer, Harvey, and Cronin 2014). In coastal
476 ecosystems, ground arthropods, including insects, are frequently found in vegetated
477 zones, and vegetation provides not only food resources but also refuge from high

temperatures, dryness, and predators (Colombini et al. 2003; Comor et al. 2008; Fattorini 2023). Some coastal insect species in this study were also reported to be found mainly in vegetation zones (Asano, Kawashima, and Ono 2012; Hayashi 2015). The results of this study indicate that native coastal plants may be necessary for vegetation zones to provide habitats for insects, and that the invasion of inland plants resulting from anthropogenic modifications can reduce coastal insect abundance. Although the underlying mechanism has not yet been clarified, the control of inland plants may be necessary for the conservation of coastal biodiversity.

The non-mound areas in this study site were established to preserve the environments that survived or appeared after the GEJE (Kurosawa 2021). Although this study revealed that the non-mound areas on the landward side of the tidal embankment could provide habitat for coastal insects and plants nine years after the tidal embankment construction, it should be noted that there may be limitations to their persistence. Coastal dunes are strongly influenced by the sea; thus, the connectivity between the sea and inland areas is considered important for ecosystem conservation (Acosta, Blasi, and Stanisci 2000; Ciccarelli and Bacaro 2016; Malavasi et al. 2018). Because of the time lag in species responses to habitat degradation and loss (Kuussaari et al. 2009), the presence of tidal embankments between the sea and inland areas may

496 cause future declines in coastal species. Additionally, if the succession to inland
497 vegetation proceeded, coastal insects may decline as inland vegetation increases, as
498 indicated in this study. Previous studies have shown that the stabilization of dynamic
499 coastal dunes negatively affects some species and the diversity of ground insects (Bird
500 et al., 2017; Schirmel and Buchholz, 2011). A similar situation may occur on the
501 landward side of a tidal embankment as a result of environmental stabilization. In any
502 case, because the study site was experimental, subsequent studies on temporal changes
503 would provide further information.

504 At Site 3, no coastal insects were observed in the mounded area; however, they
505 were observed in the sand-covered area (Figure 10). However, their abundances were
506 equivalent to those of the mounded area when combined with the data at Site 1 and 2
507 (Figure 11(a)). Coastal vegetation coverage was also lower in the sand-covered area
508 compared with the non-mound area and was not significantly different from that of the
509 mounded area (Figure 11(c)). In addition, inland vegetation coverage was higher in the
510 sand-covered area compared to the non-mound area and was not significantly different
511 from the mounded area (Figure 11(d)). Accordingly, we concluded that sand-covering
512 may have been insufficient to provide habitat for coastal insects and plants on the
513 mounds. In a previous study at this site, the species richness of coastal plants in the

514 sand-covered area was higher compared to the mounded area in 2018, an estimated
515 three years after the construction of mounds (Yamanouchi et al. 2021). For insects, the
516 same species in the non-mound area and species that were absent in the mounds were
517 observed in the sand-covered area (Igarashi 2019; Kamuro, Hirabuki, and Igarashi
518 2020). However, no quantitative differences between the mounded and sand-covered
519 areas were observed in this study, suggesting that these effects observed in previous
520 studies may have been limited to a short period or to a few species. It should be noted
521 that differences in survey years might have affected coastal insect abundance. The count
522 component in the hurdle model estimating coastal insect abundance showed a small
523 negative coefficient for the 2023 survey (Table 3). The absence of coastal insects on the
524 mounds in the 2023 survey may have been due to a decrease in the abundance of coastal
525 insects over time. In addition, although the surveys were conducted during
526 approximately the same season in 2022 and 2023 (the difference in dates was only one
527 week), the climatic differences between the years might have also affected the
528 appearance of the insects.
529 In summary, this study showed that mounds constructed as coastal forest beds
530 using soil from inland hills are unsuitable for coastal insect and plant habitats, and that
531 coastal sand-covering over the mounds is not quantitatively different from the mounds

where it is not. In contrast, avoiding mounding or afforestation on the landward side of the tidal embankment was effective in conserving coastal insect and plant habitats for at least nine years after the construction of the tidal embankment. However, inland vegetation coverage was higher on the landward side of the tidal embankment and showed a negative relationship with coastal insect abundance. Since there is a possibility of vegetation succession and environmental stabilization, it will be necessary to monitor temporal changes to verify the persistence of the habitat for coastal insects and plants. In the post-disaster reconstruction project after the GEJE, coastal forests of black pine were established as green infrastructure for mitigating disasters (Kurosawa 2021). Although biodiversity conservation is one of the functions of green infrastructure, our results showed that these coastal forests established with mounds are different habitats from native environments. We suggest that the influence of green infrastructures such as coastal forests on the native ecosystem should be considered. Therefore, from an ecological aspect, we propose to conserve areas without afforestation or mounds by reducing the areas of the coastal forest or by setting them back on the landward side, considering their coastal defense function.

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Declaration of interest statement

No potential conflict of interest was reported by the authors.

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Appendices

Appendix 1. Insect species list and their abundance in each area.

Table 1. Summary of generalized linear models comparing the seaward, non-mound and mounded areas at Site 1 and 2. SE: standard error.

Table 2. Summary of hurdle model predicting abundance of coastal insects on the mounded and non-mound areas at Site 1 and 2. SE: standard error.

Table 3. Summary of hurdle model comparing coastal insect abundance on the non-mound, sand-covered and mounded areas at Site 1, 2, and 3. SE: standard error.

Table 4. Summary of generalized linear models comparing the non-mound, sand-covered and mounded areas at Site 3. SE: standard error.

Figure 1. Study area, located on the Southern Sendai Bay coast in the Tohoku (northeastern) region of Japan. Created by editing district data of the National Land Numerical Information by MLIT of Japan (https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-N03-2024.html: accessed March 4, 2024) and coastline data by Natural Earth (https://www.naturalearthdata.com: accessed March 4, 2024). The aerial photo was taken using an unmanned aerial vehicle (UAV) in May 2019.

Figure 2. (a) Schematic image of the tidal embankment and coastal forest in the study area. (b) Photograph of the tidal embankment at Site1, taken on August 20, 2022. This photograph was taken from non-mound area, on the landward side of the embankment. (c) Photograph of the coastal forest at Site2, taken on August 21, 2022. This photograph was taken from mounded area. (d) Cross-shore profile of Site1, based on topographic data measured by a UAV in May 2019.

Figure 3. Aerial photos of Site 1 (a) before the tsunami (May 2008), (b) immediately after the tsunami (March to April 2011), and (c) after the construction of the coastal defense structures (April 2019). Crosshairs indicate the same locations. Created by

editing aerial photos of the GSI Maps by the Geospatial Information Authority of Japan (https://maps.gsi.go.jp/: accessed August 2, 2024).

Figure 4. (a) Aerial photos of the survey sites and survey lines at Site1, (b) at Site2, (c) at Site3. SW = seaward area; MO = mounded area; NM = non-mound area; SC = sand-covered area; white dashed lines = boundary between the mounded, non-mound, and sand-covered areas; red solid lines = survey lines. These photos were taken using a UAV in May 2019.

Figure 5. Photograph and schematic image of a pitfall trap.

Figure 6. Photographs of representative insect samples. (a) *Craspedonotus tibialis*, collected mainly on non-mound areas. (b) *Labidura riparia japonica*, collected mainly on seaward and non-mound areas. (c) *Idisia ornata*, collected mainly on seaward areas.

Figure 7. Cross-shore distributions of insect abundance and vegetation coverage in representative survey lines. Points and line graphs represent insect abundance, and bar graphs represent vegetation coverage. Solid line and dark gray points = coastal insect; dashed line and light gray points = inland insect; dark gray bars = coastal vegetation; light gray bars = inland vegetation; SW = seaward area; MO = mounded area; NM = non-mound area; SC = sand-covered area. (a) The southernmost line at Site 1, (b) the line at Site 2, (c) the middle line at Site 3.

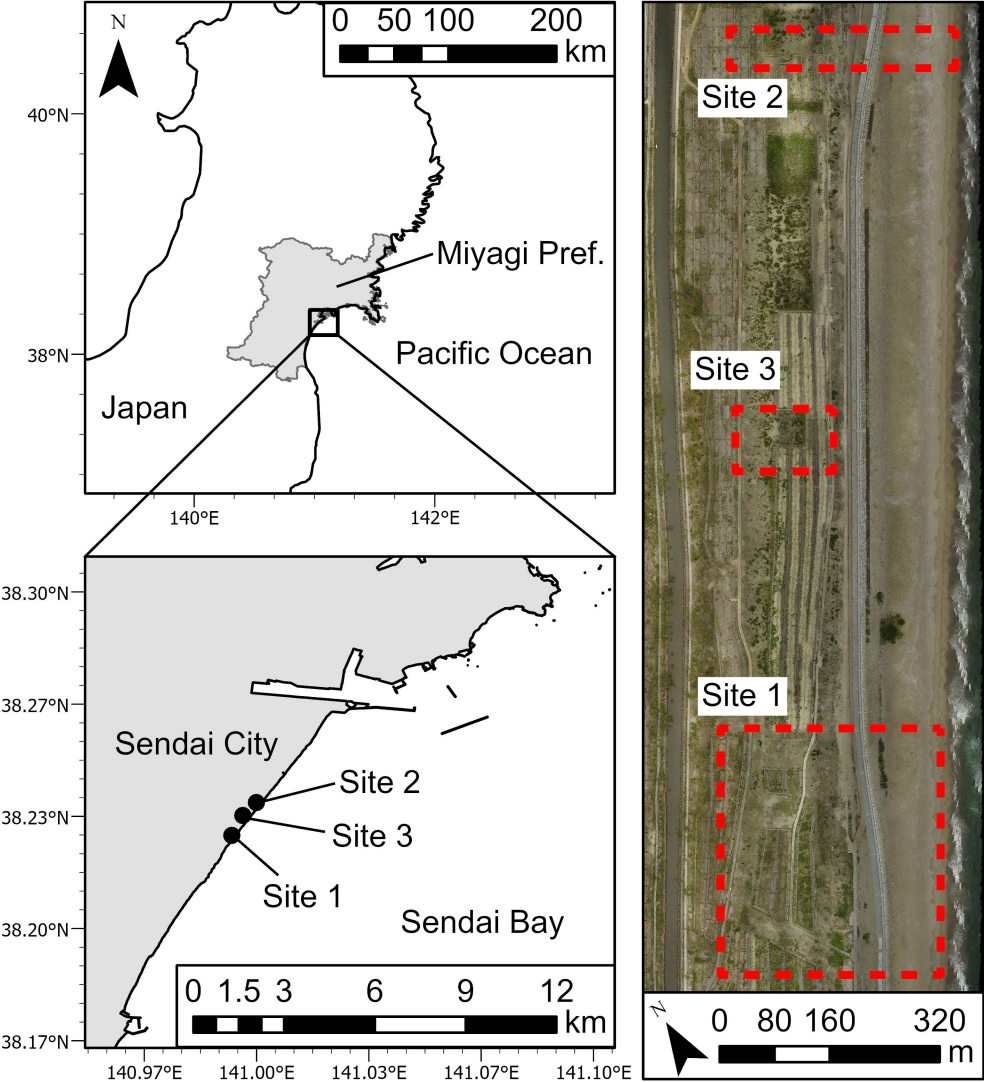
Figure 8. The estimated marginal means ± 95% confidence interval (black) and boxplot (gray) comparing the seaward, non-mound, and mounded areas at Site 1 and 2. (a) Coastal insect abundance, (b) inland insect abundance, (c) coastal vegetation coverage,

(d) inland vegetation coverage. Different letters indicate significant differences of the estimated marginal means in the pairwise comparison.

Figure 9. Hurdle model regression between inland vegetation coverage and coastal insect abundance on the mounded and non-mound areas at Site 1 and 2. Solid line and black points = the non-mound area; dotted line and white points = the mounded area.

Figure 10. Boxplot comparing abundance of coastal insects on the non-mound, sand-covered, and mounded areas at Site 3.

Figure 11. The estimated marginal means ± 95% confidence interval (black) and boxplot (gray) comparing the non-mound, sand-covered and mounded areas at Site 3 (combined the survey at Site 1, 2, and 3 for coastal insect abundance). (a) Coastal insect abundance, (b) inland insect abundance, (c) coastal vegetation coverage, (d) inland vegetation coverage. Different letters indicate significant differences of the estimated marginal means in the pairwise comparison.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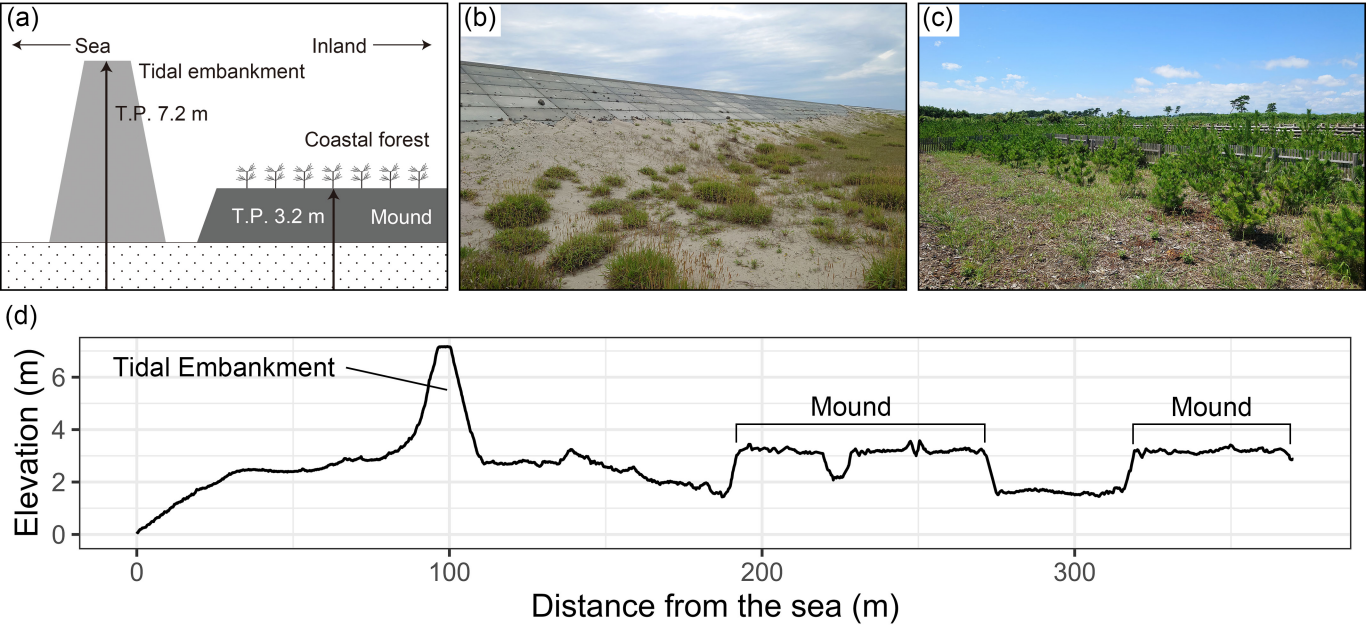
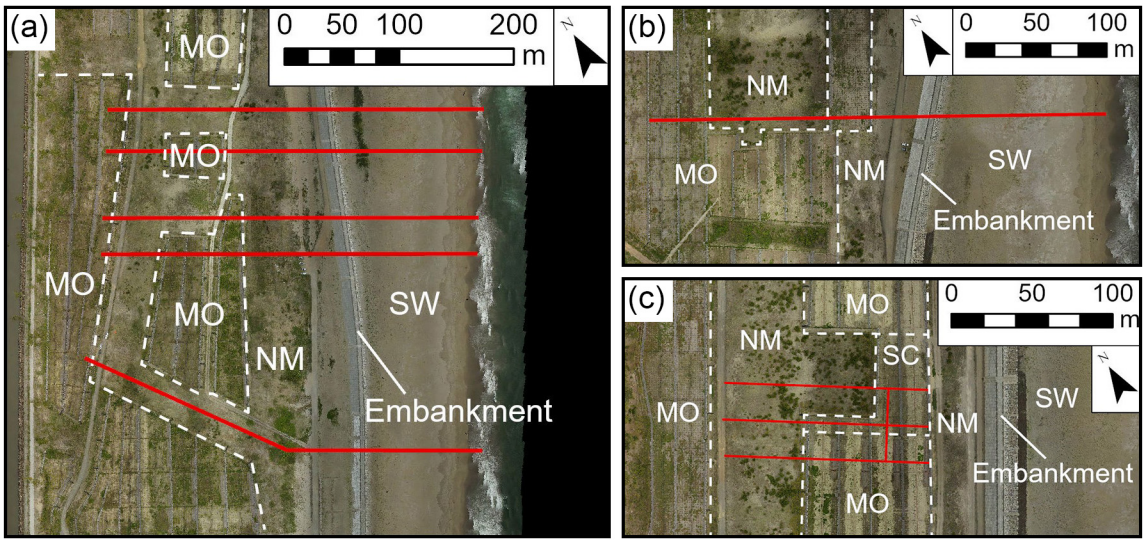
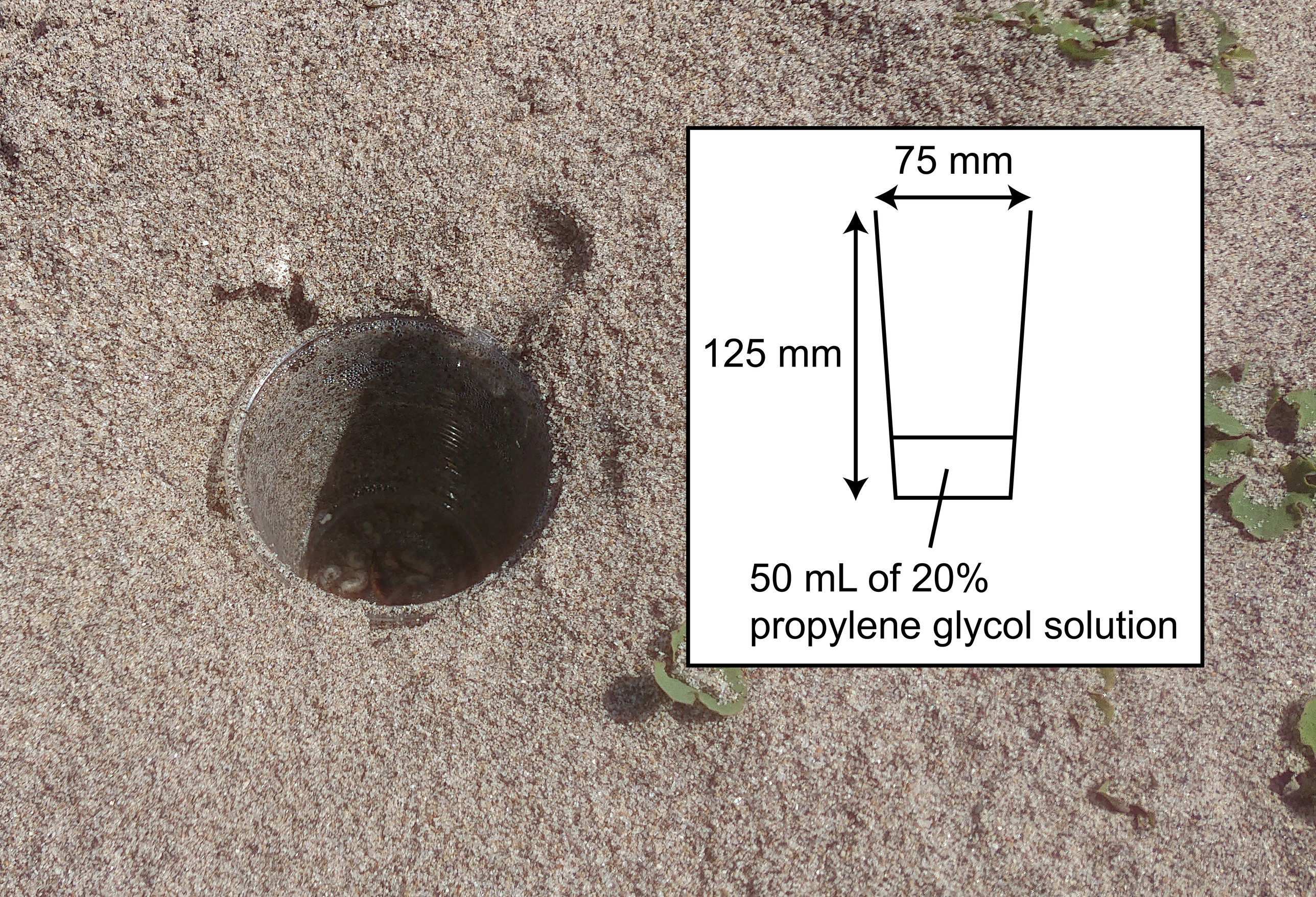
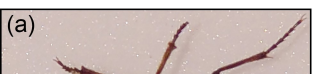
Site 2
Site 3
Site 1
Sendai Bay
0 1.5 3 6 9 12
km
140.97°E
141.00°E
141.03°E
141.07°E
141.10°E
Site 2
Site 3
Site 1
N
0 80 160 320
m


(a)
Sea
Inland
Tidal embankment
T.P. 7.2 m
Coastal forest
T.P. 3.2 m
Mound
(b)
(c)
(d)
Tidal Embankment
Mound
Mound
Elevation (m)
0
2
4
6
0
100
200
300
Distance from the sea (m)

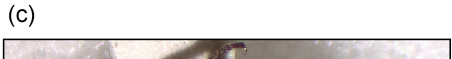
(a)
(b)
(c)
N
200 m

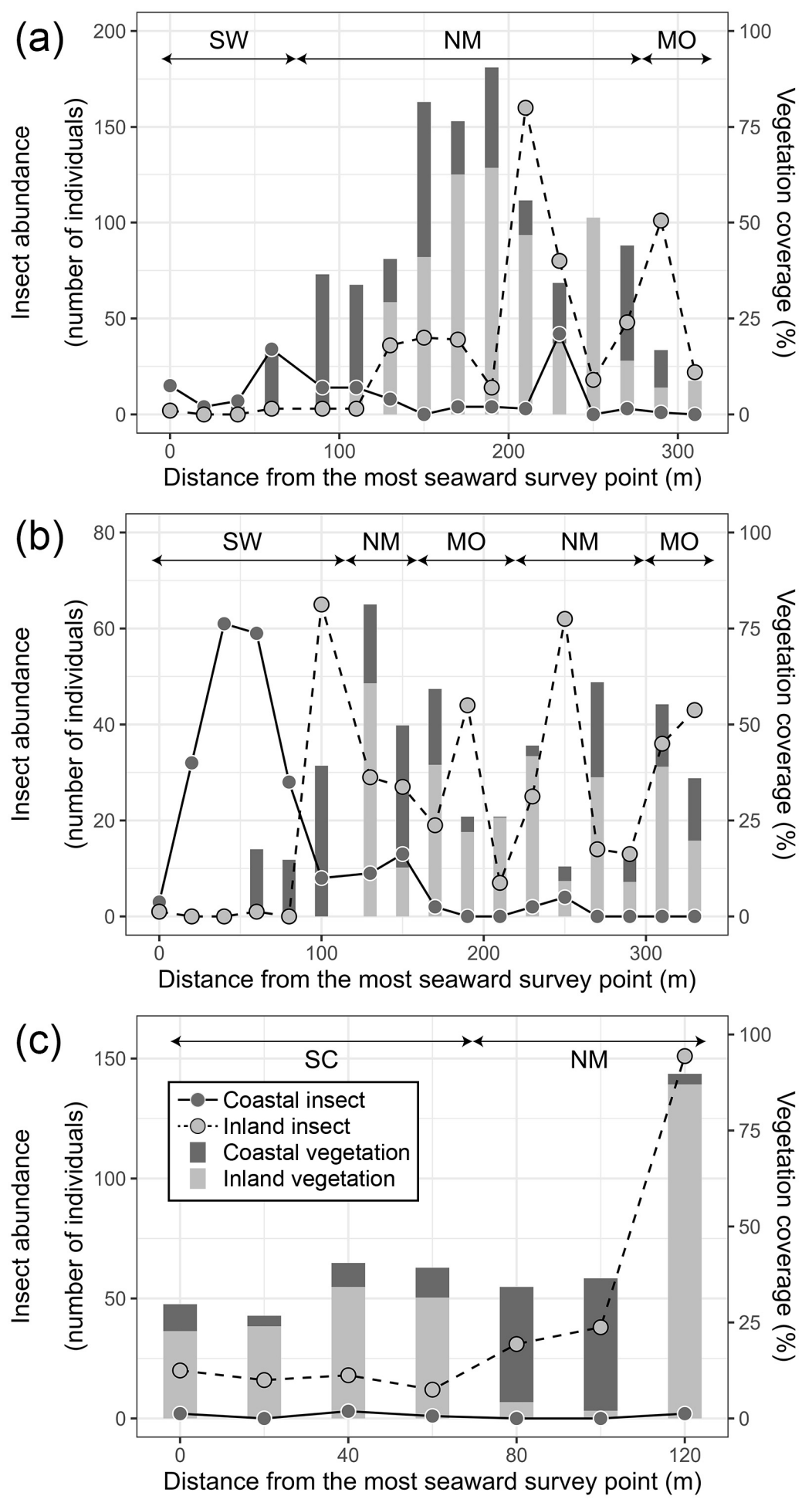

(a)
0 50 100 200
m
N
MO
MO
MO
MO
NM
SW
Embankment
(b)
0 50 100
m
N
NM
MO
NM
SW
Embankment
(c)
0 50 100
m
N
MO
NM
SC
MO
NM
SW
Embankment
MO

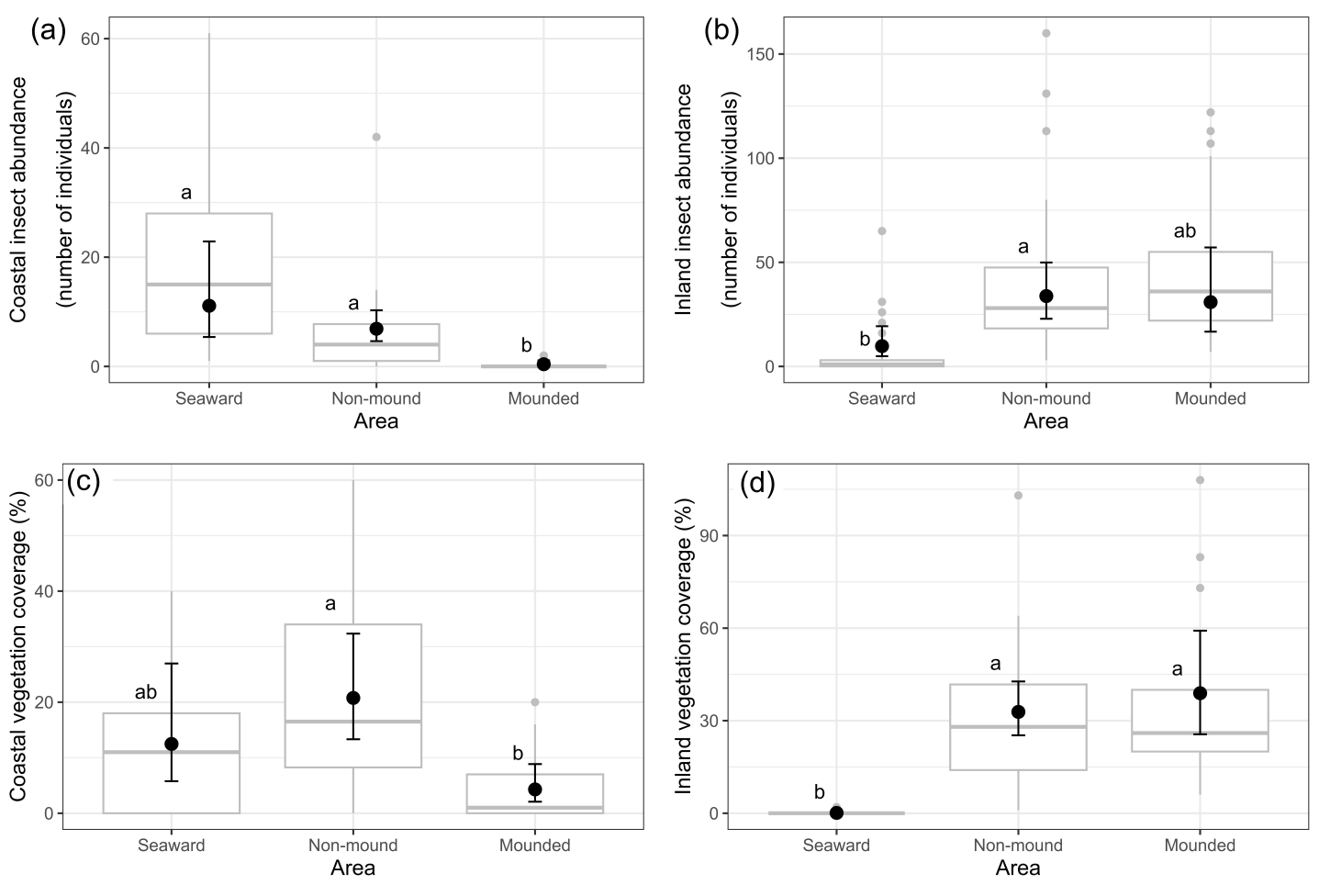

75 mm
125 mm
50 mL of 20%
propylene glycol solution

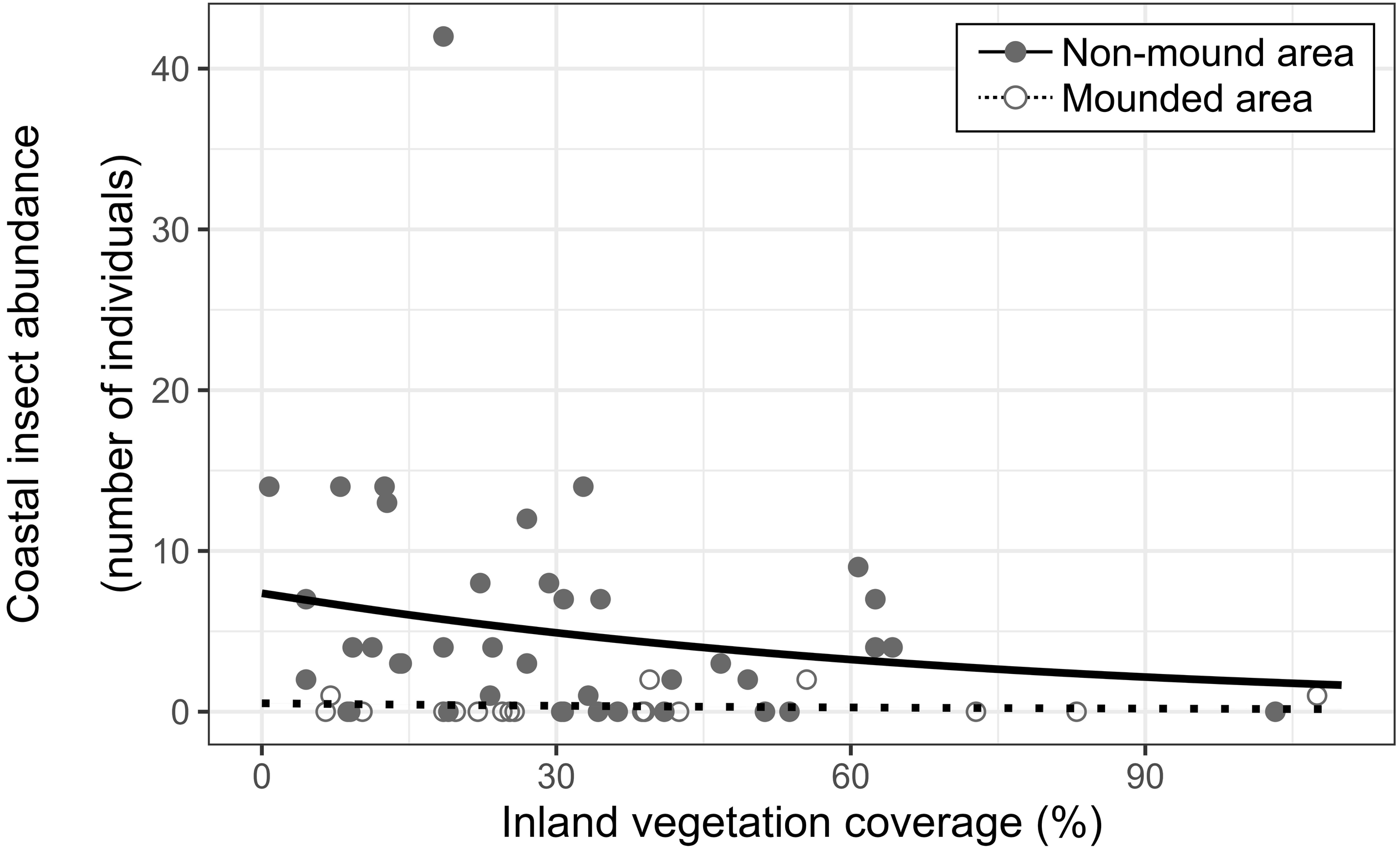

(a)
1 cm

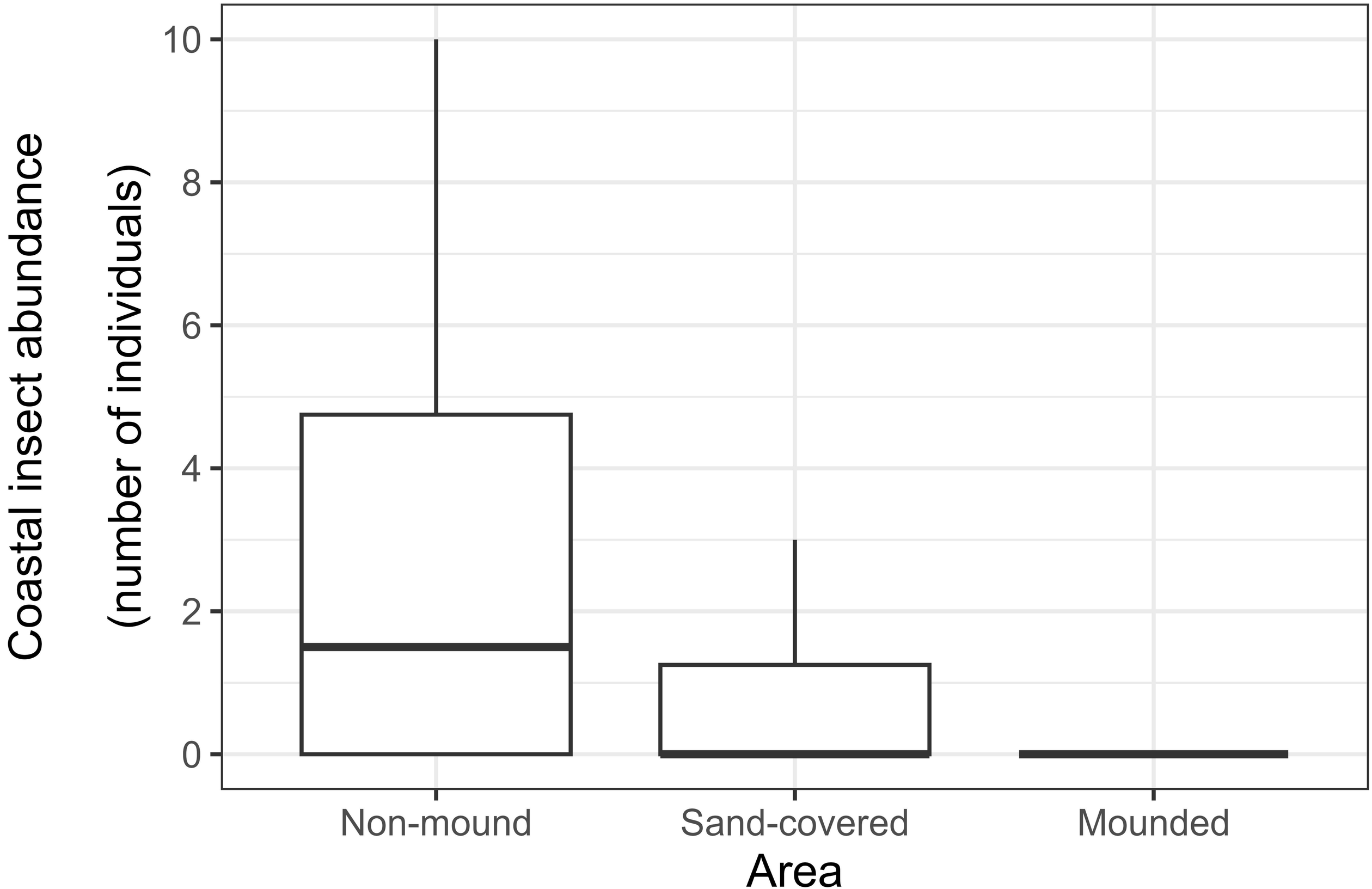
(b)
1 cm


(c)
1mm


(a)
SW
NM
MO
Insect abundance
(number of individuals)
Vegetation coverage (%)
Distance from the most seaward survey point (m)
(b)
SW
NM
MO
NM
MO
Insect abundance
(number of individuals)
Vegetation coverage (%)
Distance from the most seaward survey point (m)
(c)
SC
NM
Coastal insect
Inland insect
Coastal vegetation
Inland vegetation
Insect abundance
(number of individuals)
Vegetation coverage (%)
Distance from the most seaward survey point (m)


(a)
Coastal insect abundance
(number of individuals)
60
40
20
0
a
a
b
Seaward
Non-mound
Mounded
Area
(b)
Inland insect abundance
(number of individuals)
150
100
50
0
b
a
ab
Seaward
Non-mound
Mounded
Area
(c)
Coastal vegetation coverage (%)
60
40
20
0
ab
a
b
Seaward
Non-mound
Mounded
Area
(d)
Inland vegetation coverage (%)
90
60
30
0
b
a
a
Seaward
Non-mound
Mounded
Area


Non-mound area
Mounded area
Coastal insect abundance
(number of individuals)
40
30
20
10
0
0
30
60
90
Inland vegetation coverage (%)


Coastal insect abundance
(number of individuals)
10
8
6
4
2
0
Non-mound
Sand-covered
Mounded
Area

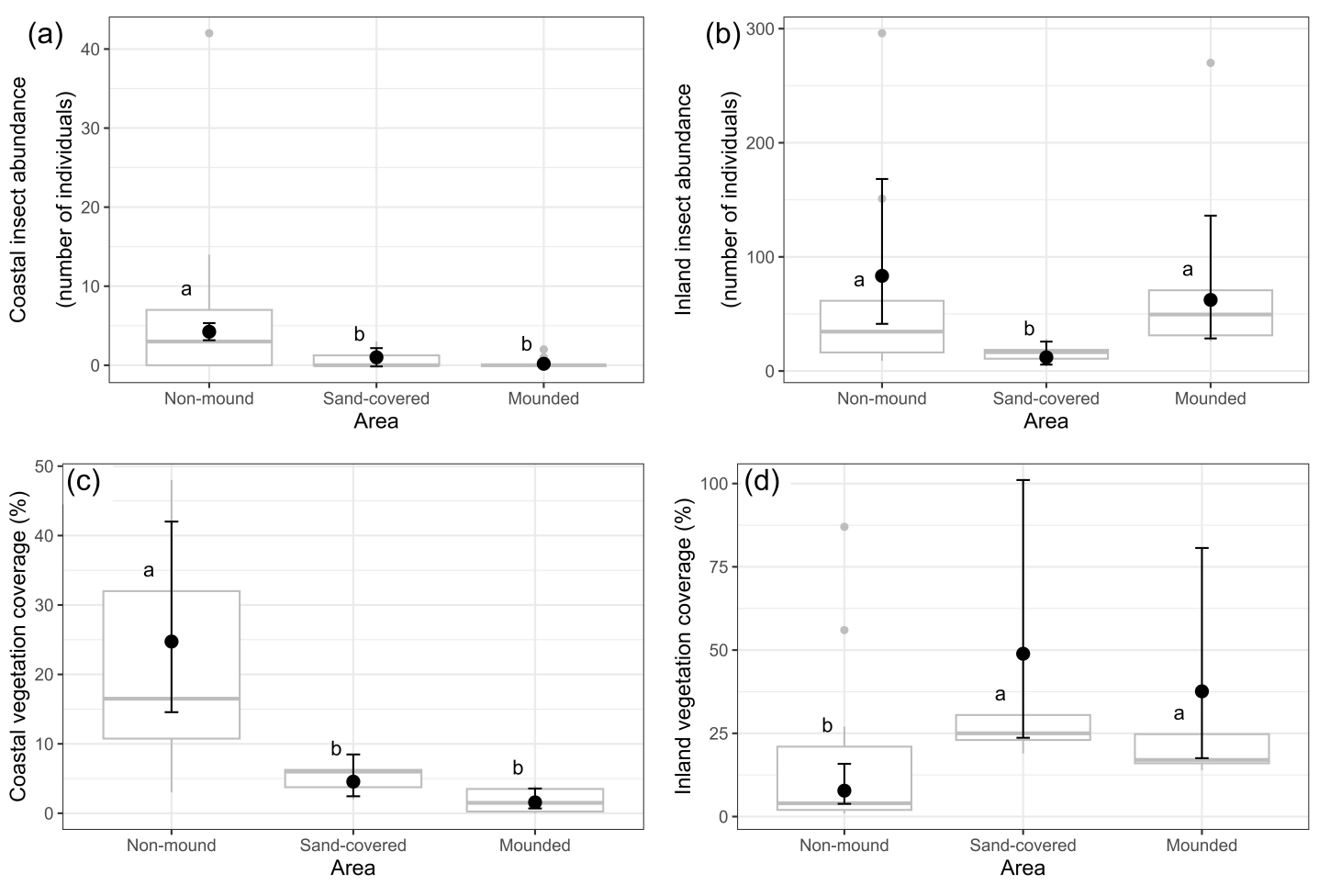

(a)
Coastal insect abundance
(number of individuals)
40
30
20
10
0
a
b
b
Non-mound
Sand-covered
Mounded
Area
(b)
Inland insect abundance
(number of individuals)
300
200
100
0
a
b
a
Non-mound
Sand-covered
Mounded
Area
(c)
Coastal vegetation coverage (%)
50
40
30
20
10
0
a
b
b
Non-mound
Sand-covered
Mounded
Area
(d)
Inland vegetation coverage (%)
100
75
50
25
0
b
a
a
Non-mound
Sand-covered
Mounded
Area

Table 1. Summary of generalized linear models comparing the seaward, non-mound and mounded areas at Site 1 and 2. SE: standard error.

Response variables	Explanatory variables	Coefficient	SE	z value	p value
Coastal insects	(Intercept)	3.160	0.217	14.533	0.000
	Distance	-0.005	0.003	-1.777	0.076
	Mounded	-3.311	0.731	-4.529	0.000
	Non-mound	-0.476	0.493	-0.966	0.334
Inland insects	(Intercept)	1.500	0.233	6.446	0.000
	Distance	0.005	0.002	2.079	0.038
	Mounded	1.153	0.581	1.986	0.047
	Non-mound	1.243	0.464	2.678	0.007
Coastal vegetation	(Intercept)	2.387	0.253	9.426	0.000
	Distance	0.001	0.003	0.318	0.750
	Mounded	-1.067	0.668	-1.598	0.110
	Non-mound	0.509	0.526	0.968	0.333
Inland vegetation	(Intercept)	-1.923	0.519	-3.702	0.000
	Distance	-0.001	0.002	-0.835	0.404
	Mounded	5.804	0.639	9.077	0.000
	Non-mound	5.634	0.591	9.531	0.000

Table 2. Summary of hurdle model predicting abundance of coastal insects on the mounded and non-mound areas at Site 1 and 2. SE: standard error.

Component	Explanatory variables	Coefficient	SE	z value	p value
Zero	(Intercept)	2.423	0.974	2.487	0.013
	Distance	-0.010	0.006	-1.527	0.127
	Mounded	-2.316	0.696	-3.327	0.001
	Inland vegetaion coverage	-0.009	0.015	-0.615	0.539
Count	(Intercept)	2.476	0.148	16.712	0.000
	Distance	-0.002	0.001	-1.432	0.152
	Mounded	-1.913	0.672	-2.848	0.004
	Inland vegetaion coverage	-0.012	0.004	-2.934	0.003

Table 3. Summary of hurdle model comparing coastal insect abundance on the non-mound, sand-covered and mounded areas at Site 1, 2, and 3. SE: standard error.

Component	Explanatory variables	Coefficient	SE	z value	p value
Zero	(Intercept)	1.532	0.545	2.811	0.005
	Survey in 2023	-0.889	0.655	-1.357	0.175
	Distance	-0.005	0.006	-0.817	0.414
	Mounded	-2.712	0.647	-4.189	0.000
	Sand-covered	-0.962	0.963	-0.999	0.318
Count	(Intercept)	2.139	0.089	24.076	0.000
	Survey in 2023	-0.343	0.207	-1.658	0.097
	Distance	-0.002	0.001	-1.835	0.067
	Mounded	-2.151	0.670	-3.208	0.001
	Sand-covered	-1.214	0.564	-2.152	0.031

Table 4. Summary of generalized linear models comparing the non-mound, sand-covered and mounded areas at Site 3. SE: standard error.

Response variables	Explanatory variables	Coefficient	SE	z value	p value
Inland insects	(Intercept)	4.951	0.868	5.705	0.000
	Distance	-0.007	0.008	-0.929	0.353
	Mounded	-0.291	0.632	-0.460	0.645
	Sand-covered	-1.939	0.641	-3.025	0.002
Coastal vegetation	(Intercept)	3.557	0.677	5.255	0.000
	Distance	-0.005	0.006	-0.780	0.435
	Mounded	-2.756	0.565	-4.879	0.000
	Sand-covered	-1.693	0.504	-3.356	0.001
Inland vegetation	(Intercept)	0.619	0.866	0.715	0.475
	Distance	0.019	0.008	2.562	0.010
	Mounded	1.575	0.628	2.509	0.012
	Sand-covered	1.837	0.630	2.915	0.004