A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

NeoBiota 95: 77–95 (2024)
DOI: 10.3897/neobiota.95.129483

Research Article

# Testing a trapping protocol for generic surveillance of wood-boring beetles in heterogeneous landscapes

Giacomo Santoiemma[1], Andrea Battisti[1], Claudine Courtin[2], Gianfranco Curletti[3], Massimo Faccoli[1], Nina Feddern[4], Joseph A. Francese[5], Emily K. L. Franzen[6,7], Filippo Giannone[8], Martin M. Gossner[4,9], Chantelle Kostanowicz[10], Matteo Marchioro[1], Davide Nardi[1], Ann M. Ray[7], Alain Roques[2], Jon Sweeney[10], Kate Van Rooyen[10], Vincent Webster[10], Davide Rassati[1]

1 *Department of Agronomy, Food, Natural Resources, Animals and Environment (DAFNAE), University of Padova, Viale dell'Università 16, 35020, Legnaro (PD), Italy*
2 *Institut National de Recherche pour l'Agriculture, l'Alimentation et l'Environnement (INRAE), UR 0633, Zoologie Forestière, 45075, Orléans, France*
3 *Museo Civico di Storia Naturale, Parco Cascina Vigna, 10022 Carmagnola, Italy*
4 *Forest Entomology, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zürcherstrasse 111, Birmensdorf, Switzerland*
5 *USDA-APHIS-PPQ-S&T Forest Pest Methods Laboratory, 1398 W. Truck Road, Buzzards Bay, MA 02542, USA*
6 *USDA APHIS PPQ S&T Bethel Field Station, Bethel, OH 45106, USA*
7 *Department of Biology, Xavier University, 104 Albers Hall, 3800 Victory Pkwy., Cincinnati, OH 45207, USA*
8 *Padova, Italy*
9 *Department of Environmental Systems Science, Institute of Terrestrial Ecosystems, ETH Zürich, Zürich, Switzerland*
10 *Natural Resources Canada, Canadian Forest Service, Atlantic Forestry Centre, 1350 Regent St., Fredericton, NB, E3C 2G6, Canada*

*Corresponding authors: Giacomo Santoiemma (giacomo.santoiemma@unipd.it); Davide Rassati (davide.rassati@unipd.it)*


## Abstract

Baited traps are a basic component of both specific and generic surveillance programs targeting wood-boring beetles at risk of introduction to new habitats because of global trade. Among the numerous protocols developed over the years for generic surveillance of longhorn beetles, jewel beetles, and bark and ambrosia beetles is the simultaneous use of black multi-funnel traps set up in the understory and green multi-funnel traps set up in the canopy of forested areas surrounding ports and other entry points. These traps are commonly baited with multi-lure blends of pheromones and host volatiles. In this study, we tested this trapping protocol in areas surrounding eight entry points located in Europe and North America to determine: i) the relative performance of black-understory traps and green-canopy traps among the targeted taxa; and ii) whether the dissimilarity among communities of beetles collected by the understory *vs.* canopy traps was affected by taxon and amount of forest cover in the traps' surroundings. A total of 96,963 individuals belonging to 358 species of wood-boring beetles were collected, including 21 non-native species. Black-understory multi-funnel traps were generally more efficient than green-canopy multi-funnel traps for detecting longhorn beetles and bark and ambrosia beetles, whereas the opposite trend was observed for jewel beetles. Differences between beetle communities caught in black-understory and green-canopy traps were mainly attributed to differences in species richness in jewel beetles, while both differences in species richness and species turnover contributed to the dissimilarity between communities of longhorn beetles and bark and ambrosia beetle. The difference in the number of jewel beetle species caught by the two trapping methodologies decreased with increasing forest cover, whereas species turnover increased when moving from an urban-dominated to a forest-dominated landscape. Overall, these results suggest that the simultaneous use of both black-understory and green-canopy multi-funnel traps can be considered a very efficient approach for generic surveillance of longhorn beetles, jewel beetles and bark and ambrosia beetles in both urban-dominated and forest-dominated areas surrounding entry points.




**Academic editor:** Jianghua Sun
**Received:** 16 June 2024
**Accepted:** 20 July 2024
**Published:** 30 August 2024

**Citation:** Santoiemma G, Battisti A, Courtin C, Curletti G, Faccoli M, Feddern N, Francese JA, Franzen EKL, Giannone F, Gossner MM, Kostanowicz C, Marchioro M, Nardi D, Ray AM, Roques A, Sweeney J, Van Rooyen K, Webster V, Rassati D (2024) Testing a trapping protocol for generic surveillance of wood-boring beetles in heterogeneous landscapes. NeoBiota 95: 77–95. https://doi.org/10.3897/neobiota.95.129483

**Key words:** Buprestidae, Cerambycidae, early-detection, exotic species, monitoring, Scolytinae

## Introduction

The continuous increase in global trade in recent decades, combined with deliberate plant introductions in the past, has resulted in increasing number of non-native insects moved outside their native ranges (Seebens et al. 2017; Isitt et al. 2024). This trend is evident for wood-boring insects, especially bark and ambrosia beetles (Coleoptera: Scolytinae), longhorn beetles (Cerambycidae) and jewel beetles (Buprestidae) (Rassati et al. 2016; Ruzzier et al. 2023a) which can be accidentally transported within wood packaging materials, logs, processed wood, and live nursery stock (Meurisse et al. 2019; Fenn-Moltu et al. 2023). After introduction, wood-boring beetles may become invasive pests, with high economic, ecological, and social impacts in urban and natural forests (Aukema et al. 2011). The jewel beetle *Agrilus planipennis* and the longhorn beetle *Anoplophora glabripennis*, for example, are listed among the top 10 of all invasive species for post-invasion management costs and are estimated to be among the costliest non-native insects worldwide (Cuthbert et al. 2022). For these reasons, substantial investments globally have focused on mitigating the arrival and establishment rate of non-native wood-boring beetles through more efficient biosecurity measures (Nahrung et al. 2023), including tools and strategies for early-interception of non-native species at and around entry points.

Among the numerous tools developed for surveillance of wood-boring beetles (Poland and Rassati 2019), traps baited with attractive lures are part of the biosecurity systems of several countries around the world (Rassati et al. 2015a, 2015b; Carnegie et al. 2018, 2022; Rabaglia et al. 2019; Hoch et al. 2020; Allison et al. 2021; Holusa et al. 2023; Mas et al. 2023; Wardhaugh and Pawson 2023). The knowledge acquired over the years on the key factors influencing trap efficacy (Allison and Redak 2017; Dodds et al. 2024) and on the chemical ecology of hundreds wood-boring beetle species (e.g., Byers 2007; Millar and Hanks 2017; Ranger et al. 2021) has led to the definition of a set of trapping protocols tailored to the target taxa or objective of the surveillance program. In the case of generic surveillance aimed at intercepting as many non-native species as possible, the simultaneous use of black multi-funnel or intercept panel traps set up in the understory and green multi-funnel traps set up in the canopy, all baited with multi-lure blends, in areas surrounding entry points (e.g., Wong et al. 2012; Hanks et al. 2018; Fan et al. 2019; Rice et al. 2020; Roques et al. 2023), might be considered as a potentially efficient approach. Baited black traps set up in the understory are known to attract longhorn beetles and bark and ambrosia beetles commonly living in the lower forest strata (De Groot and Nott 2001; McIntosh et al. 2001; Dodds et al. 2010; Flaherty et al. 2019; Ulyshen and Sheehan 2019), while baited green multi-funnel traps set up in the canopy are known to catch jewel beetles well (Francese et al. 2011, 2013; Petrice and Haack 2015; Skvarla and Dowling 2017; Santoiemma et al. 2024) but also longhorn beetles and certain bark and ambrosia beetles living in mid and upper forest strata (Rassati et al. 2019; Marchioro et al. 2020). Nonetheless, this trapping protocol remains to be tested in surveillance programs targeting areas surrounding high-risk sites, such as international ports and airports or warehouses, which can be characterized by heterogeneous landscapes ranging from urban-dominated areas to forest-dominated areas.

In addition to testing overall efficacy, there is an urgent need to better understand whether the simultaneous use of baited black multi-funnel traps placed in the understory and baited green multi-funnel traps placed in the canopy is always necessary, irrespective of the characteristics of the landscape. Previous studies showed that the efficacy of a trapping methodology can be context-dependent (e.g., Bouget et al. 2009; Marchioro et al. 2020; Rassati et al. 2021) as it can be affected by a number of environmental variables (Dodds et al. 2024), including the amount of tree cover occurring around the trap (Schroeder 2013; Nunes et al. 2021). In areas surrounding high-risk sites, traps can be set up either on isolated trees that are present along streets or private gardens (i.e., in urban-dominated areas) or on trees that are present in urban parks or forest patches and that are surrounded by many potential hosts (i.e., in forest dominated landscapes or where urban areas are intermixed with forest areas) (Bashford 2008; Rassati et al. 2015a; Mas et al. 2023). Thus, understanding whether the proposed trapping protocol can be simplified depending on the amount of tree cover occurring in the trap surroundings is crucial to optimize efforts and reduce overall costs of the surveillance program (Epanchin-Niell et al. 2014; Nguyen et al. 2024).

In this study, we conducted a trapping experiment in areas surrounding eight entry points located in Europe and North America using black multi-funnel traps set up in the understory and green multi-funnel traps set up in the canopy, all baited with the same multi-component blend of longhorn beetle pheromones complemented with plant volatiles. We first compared the relative efficacy of black-understory traps and green-canopy traps for detecting different target taxa, i.e., longhorn beetles, jewel beetles and bark and ambrosia beetles. Second, we calculated dissimilarity indices to compare the communities of longhorn beetles, jewel beetles and bark and ambrosia beetles collected by black-understory *vs.* green-canopy traps, and then we tested the effect of the amount of forest cover in the trap surroundings on the dissimilarity indices. These analyses allowed us to investigate whether the simultaneous use of black-understory traps and green-canopy traps is required irrespective of the taxon and the landscape in which this protocol is used, or whether a simpler protocol (e.g., using only black-understory traps) may detect as many species of a particular taxon, depending on the surrounding landscape.

## Methods

### Study sites, trap types and experimental scheme

The study was conducted at eight sites in five different countries in the temperate zone of Europe and North America: France, Italy, Switzerland, Canada (Nova Scotia) and USA (Ohio) (Suppl. material 1: fig. S1, table S1). Selected sites were characterized by the presence of mixed forest and urban patches, and were located in the proximity of entry points or high-risk areas such as ports, airports, warehouses and high-use recreation areas (Suppl. material 1: table S1).

At each site we used sixteen black and sixteen green multi-funnel traps (Suppl. material 1: fig. S1), supplied by Synergy Semiochemical Corporation (Delta, BC, Canada) and ChemTica Internacional (Santo Domingo, Costa Rica). Both trap types were pre-treated with a 50% solution of Fluon (active ingredient polytetrafluoroethylene) as a trap coating because of its ability to increase trap catches of wood-boring beetles (Graham and Poland 2012; Allison et al. 2016). Trap-collecting cups were filled with 150–200 ml of a 50% propylene glycol solution mixed with either water or as a pre-mixed marine/RV antifreeze solution. Propylene glycol solutions were replaced at each trap check.

Traps were set up using a 2 km × 2 km grid as reference (Suppl. material 1: fig. S1), with one black and one green multi-funnel trap set up in each of 16 grid cells of 0.5 km × 0.5 km. The only exceptions were the two sites in France, where traps were coupled along a horizontal transect due to limits in space within the selected sites and local restrictions. Black multi-funnel traps were set up with the top of the trap about 1.5–2 m above the ground on lower tree branches, whereas green multi-funnel traps were set up in the upper one-third of the tree canopy at heights ranging from 7 m to 15 m. We selected this approach even though it confounded the effects of trap height and trap color on catch of targeted taxa because the latter was already addressed in several previous studies (reviewed in Dodds et al. 2024). Canopy traps were set up following the methods of Hughes et al. (2014). The two traps within the same grid cell were suspended on different trees, separated by 50–100 m. Trees were selected based on position and suitability to hold the weight of the traps, irrespective of the species. Traps were set up in mid-May 2019 and emptied every 2–3 weeks until the end of August 2019. All trapped longhorn beetles, jewel beetles, and bark and ambrosia beetles were identified to species level using morphological features and taxonomic keys. Voucher specimens were deposited in the insect collection of each institution.

## Lures

All traps were baited with a lure containing a blend of eight cerambycid pheromones attractive to a wide range of longhorn beetle species (Fan et al. 2019; Roques et al. 2023), plus UHR (ultra-high release rate) ethanol and alpha-pinene lures. The pheromone blend included racemic fuscumol (volume amount: 50 mg), racemic fuscumol acetate (50 mg), geranyl acetone (25 mg), racemic 3-hydroxyhexan-2-one (50 mg), prionic acid (1 mg), 2-methylbutan-1-ol (50 mg), anti-2.3-hexanediol (50 mg), and monochamol (50 mg), all dissolved in isopropanol as a carrier to a total volume of 1 ml per lure (see Fan et al. 2019 for release rate). All pheromones were purchased from ChemTica Internacional (Santo Domingo, Costa Rica) except prionic acid (Alpha Scents Inc., West Linn, Oregon, USA); the ethanol and alpha-pinene lures were provided by Econex (Spain). One-milliliter aliquots of the pheromone blend were filled in glass vials with screw caps and stored at 4 °C until used. At the beginning of the trial and during each trap check, the 1-ml aliquots were poured into a clear polyethylene sachet containing a cotton cylinder, which was hung on the trap using a string. The addition of the two host volatile lures increases both the attractiveness of the pheromones to many species of longhorn beetles (e.g., Collignon et al. 2016; Miller et al. 2017) as well as the likelihood of trapping certain species of jewel beetles (Miller et al. 2015) and bark and ambrosia beetles (Miller and Rabaglia 2009; Marchioro et al. 2020).

## Analysis of dissimilarity indices to investigate wood-boring beetle communities

To investigate differences in the communities of wood-boring beetles collected in black-understory multi-funnel traps and green-canopy multi-funnel traps, we used the β-diversity approach outlined in Carvalho et al. (2012) (see also Podani and Schmera 2011; Legendre 2014). The general term "β-diversity" refers to the total compositional change between two communities (in our case study, the community of wood-boring beetles collected using the two trapping methodologies), and can be partitioned into two components: species richness difference and species replacement (Carvalho et al. 2012). "Species richness difference" refers to the relative difference in the number of species between two communities, whereas "species replacement" refers to the substitution of species by others when two communities are compared. The two components are additive, and their sum provides the β-diversity index.

Given "a" = number of species exclusive to the first community, "b" = number of species exclusive to the second community, and "c" = number of species common to both communities, the β-diversity is given by the Jaccard dissimilarity index:

$$\beta_{cc} = (a + b)/(a + b + c)$$

with values ranging from 0 (perfect similarity) to 1 (total dissimilarity). The species richness difference component is given by:

$$\beta_{rich} = |a + b|/(a + b + c)$$

with values ranging from 0 (no richness difference) to 1 (maximum richness difference). The species replacement component is given by:

$$\beta_{-3} = 2 \min(a, b)/(a + b + c)$$

with values ranging from 0 (no replacement) to 1 (maximum replacement). To calculate these indices, data collected across the entire sampling season from black-understory and green-canopy traps (i.e., total catch per trap over the entire trapping season) of each grid cell at each site were paired, creating n × m presence/absence matrices for each taxon, whereby n = 2 (one row for each trapping method) and m = number of species. Then, for each matrix, the three indices were computed using the "vegan" package (Oksanen et al. 2022) in R software (R Core Team 2021).

### Quantification of tree cover in the area surrounding the traps

Forest patches around each trap were manually digitized by visual inspection of high-resolution satellite images in Google Earth Pro (Google Inc.© 2023) within a buffer of 250 m radius. This spatial scale was selected based on the results of previous studies testing the attraction range of baited traps towards wood-boring beetles (e.g., Dodds and Ross 2002; Jactel et al. 2019). For each buffer, the total forest cover (%) was then quantified in GIS (Quantum GIS 3.22, QGIS Development Team 2021) after importing the digitized patches from Google Earth Pro (Google Inc.© 2023). Forest cover within the buffers ranged from 0% (where only urban patches were present) to 100% (where only forest was present), with a mean value (± standard deviation) of 51.4 ± 39.3%.

### Statistical analyses

We used generalized linear mixed models for all the analyses. Data collected from all sites were analyzed together to increase both the statistical power of the models and the gradient of forest cover around the traps.

First, we tested the effect of the taxon and the trapping methodology on species richness and abundance. Species richness (i.e., total number of species) and abundance (i.e., total number of individuals) for each trap and pooled over the sampling rounds were considered as response variables. The taxon (categorical variable: longhorn beetles, jewel beetles, and bark and ambrosia beetles), the trapping methodology (categorical variable: black-understory and green-canopy multi-funnel traps) and their interaction were considered as explanatory variables. The site identity, the identity of each grid cell within each site and the identity of each trap within each grid cell were included in the models as nested random factors.

Second, we tested the effect of the taxon and the forest cover on beta-diversity indices. The three beta-diversity indices $\beta_{cc}$, $\beta_{rich}$ and $\beta_{-3}$ calculated for each pair of traps (within a cell) were considered as response variables. The taxon (categorical variable: longhorn beetles, jewel beetles, and bark and ambrosia beetles), the forest cover (continuous variable: mean % of forest cover in the buffers of 250 m radius around the pair of traps present in the same cell) and their interaction were considered as explanatory variables. The site identity and the identity of each cell of the grid within each site were included in the models as nested random factors.

Models were fitted with a Poisson distribution (log link function) for species richness, negative binomial distribution (log link function) for abundance, and Gaussian distribution for the beta-diversity indices. Pairwise comparisons between each taxon and between the two trapping methodologies within each taxon were run using Tukey correction of *p*-values. All the analyses were carried out in R software (R Core Team 2021). Models were fitted using the 'glmmTMB' (Brooks et al. 2022) and 'nlme' (Pinheiro et al. 2021) packages, and validated using the 'DHARMa' (Hartig 2022) and 'car' (Fox and Weisberg 2019) packages. There was no evidence of spatial autocorrelation of models' residuals, checked with Moran's I test for distance-based autocorrelation using the 'DHARMa' package (Hartig 2022). Pairwise comparisons and slope estimates were calculated using the 'emmeans' package (Lenth 2021).

## Results

### General results

A total of 96,963 individuals belonging to 358 species of wood-boring beetles were collected (Suppl. material 1: table S2). The most species-rich taxon was represented by longhorn beetles (169 species), followed by bark and ambrosia beetles (123) and jewel beetles (66). Longhorn beetles and bark and ambrosia beetles represented the most trapped species at all sites (Fig. 1). For abundance, bark and ambrosia beetles had the highest number of trapped specimens (73,109), followed by longhorn beetles (17,970) and jewel beetles (5,884) (Suppl. material 1: table S2). *Xyleborinus saxesenii* (48,042 individuals) and *Orthotomicus erosus* (4,180) were the most abundant ambrosia and bark beetle species collected, respectively, whereas *Phymatodes amoenus* (2,954) and *Agrilus olivicolor* (2,213) were the most abundant longhorn beetle and jewel beetle species, respectively. Although most of the trapped species were native, 21 species were non-native for 14,772 specimens. These non-native species included four longhorn beetle species (i.e., *Phymatodes testaceus* in North America, *Neoclytus acuminatus*, *Xylotrechus chinensis* and

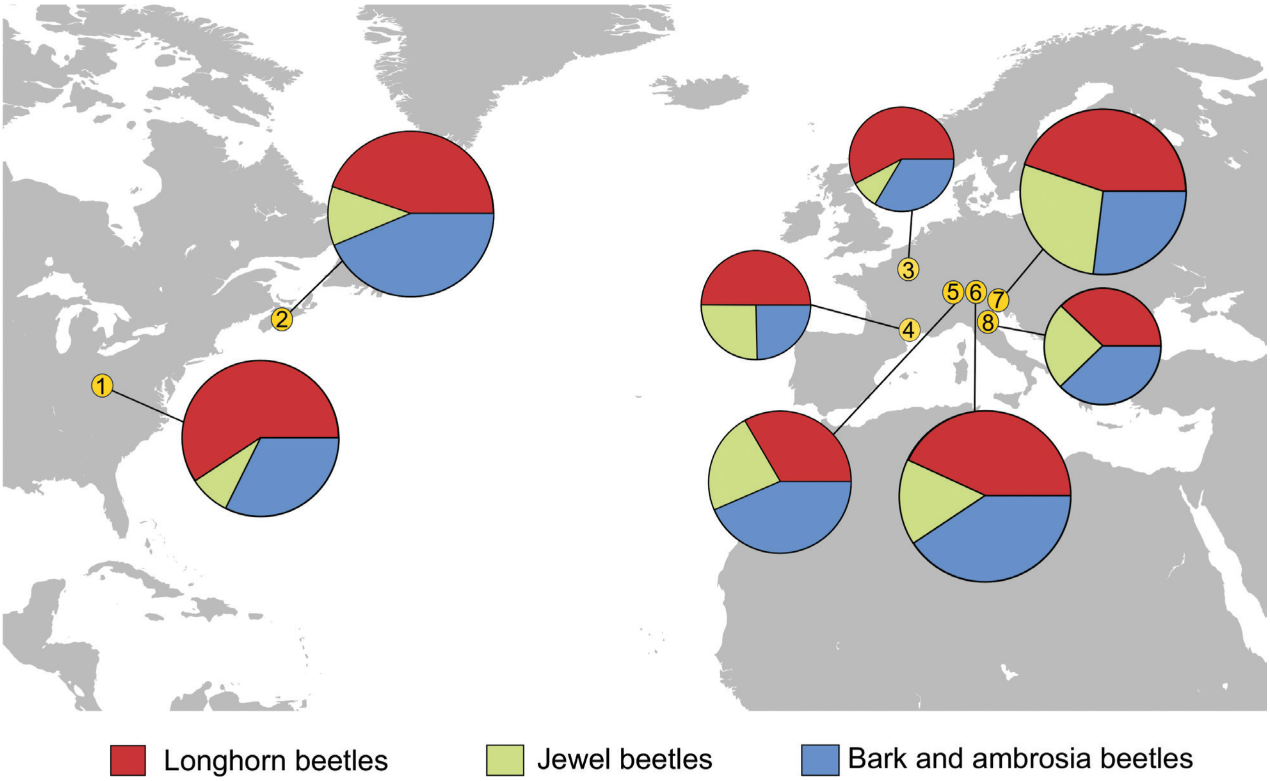


**Figure 1.** World map describing the communities of longhorn beetles, jewel beetles, and bark and ambrosia beetles collected at each experimental site. Circle size indicates the number of trapped species ranging from 55 (smallest circle) to 100 (biggest circle). The different colors within each circle indicate the relative percentage of species attributed to each taxon: red = longhorn beetles; green = jewel beetles; blue = bark and ambrosia beetles. Numbers in yellow circles represent the different study sites according to Suppl. material 1: table S1 column ID number.

*Xylotrechus stebbingi* in Europe), two jewel beetle species (i.e., *Agrilus cyanescens* and *Agrilus planipennis* in North America), and 15 bark and ambrosia beetle species (nine in North America, two in Europe and four in both continents) (Suppl. material 1: table S2).

### Effect of taxon and trapping methodology on trap captures

Species richness was significantly affected by taxon and by the interaction between taxon and trapping methodology (Table 1). The mean number of species (± standard error) was significantly higher for longhorn beetles (8.34 ± 0.26) than bark and ambrosia beetles (7.42 ± 0.26) and jewel beetles (1.79 ± 0.15). In addition, the effect of trapping methodology differed depending on the taxon (Fig. 2A–C). For longhorn beetles, the mean number of species caught in black-understory traps was not significantly different from the number of species caught in green-canopy traps (Fig. 2A). For jewel beetles, green-canopy traps caught significantly more species than black-understory traps (Fig. 2B), whereas the opposite trend was observed for bark and ambrosia beetles (Fig. 2C).

Abundance was significantly affected by all tested variables (Table 1). The mean number of individuals (± standard error) was significantly higher for bark and ambrosia beetles (286.70 ± 25.47) than for both longhorn beetles (70.47 ± 4.03) and jewel beetles (23.08 ± 5.43). In addition, black-understory traps generally caught more individuals than green-canopy traps, even though the trapping performance changed depending on the taxon (Fig. 2D–F). Black-understory traps outperformed green-canopy traps for both longhorn beetles (Fig. 2D) and bark and ambrosia beetles (Fig. 2F), whereas the opposite trend was observed for jewel beetles (Fig. 2E).

**Table 1.** Analysis of deviance table from the generalized linear mixed models testing the effects of taxon (longhorn beetles, jewel beetles, and bark and ambrosia beetles), trapping methodology (black-understory multi-funnel traps and green-canopy multi-funnel traps) and their interaction on species richness (Poisson distribution; log link function) and abundance (negative binomial distribution; log link function). Nested random structure used for both models: ~1|Site/Cell/Trap. Type II Wald chi-square tests ($\chi^2$), degrees of freedom (df), *p*-values, and lognormal marginal ($mR^2$) and conditional ($cR^2$) pseudo R-squared are provided for both models.

| | $\chi^2$ | df | *p*-value |
|---|---|---|---|
| **Species richness** | | | |
| Taxon | 659.517 | 2 | < 0.001 |
| Methodology | 0.455 | 1 | 0.500 |
| Taxon × Methodology | 161.154 | 2 | < 0.001 |
| | | | $mR^2$ = 0.73, $cR^2$ = 0.87 |
| **Abundance** | | | |
| Taxon | 1040.747 | 2 | < 0.001 |
| Methodology | 20.737 | 1 | < 0.001 |
| Taxon × Methodology | 274.916 | 2 | < 0.001 |
| | | | $mR^2$ = 0.73, $cR^2$ = 0.86 |

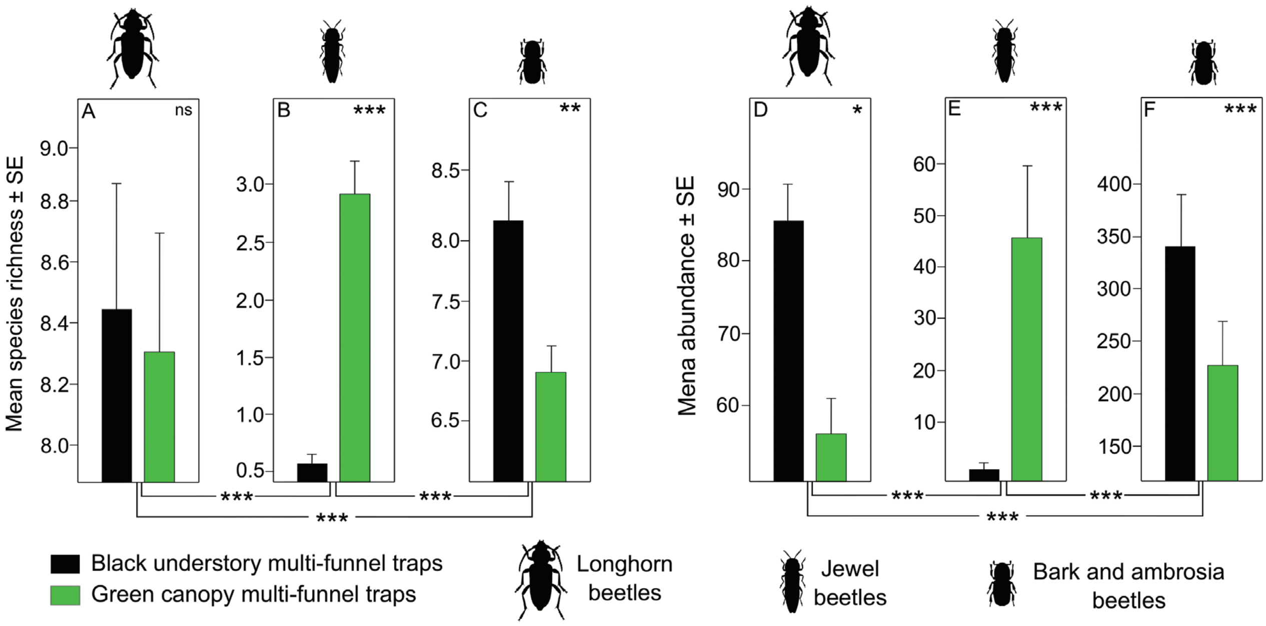


**Figure 2.** Mean (± standard error) species richness and abundance of longhorn beetles (**A, D**), jewel beetles (**B, E**), and bark and ambrosia beetles (**C, F**) for each trapping methodology. Asterisks within the plots indicate the statistical significance level from pairwise comparisons between the two trapping methodologies within each taxon from the generalized linear mixed models. Asterisks under the plots indicate the statistical significance level from pairwise comparisons among the three taxa from the generalized linear mixed models. *P*-values: * = 0.01 - 0.05; ** = 0.001 - 0.01; *** = < 0.001; ns = not significant (> 0.05). *P*-values were adjusted by Tukey correction. Model details are provided in Table 1.

### Effect of taxon and forest cover in the trap surroundings on dissimilarity indices

$\beta_{cc}$ and $\beta_{rich}$ were significantly affected by taxon and forest cover but not by their interaction, while $\beta_{-3}$ was significantly affected by taxon and by the interaction between taxon and forest cover (Table 2). Irrespective of the forest cover effect, jewel beetles showed higher $\beta_{cc}$ and $\beta_{rich}$ values, and lower $\beta_{-3}$ values compared to longhorn beetles and bark and ambrosia beetles (Fig. 3; Suppl. material 1: table S3). For all taxa, $\beta_{cc}$ slightly decreased with increasing amount of forest cover,

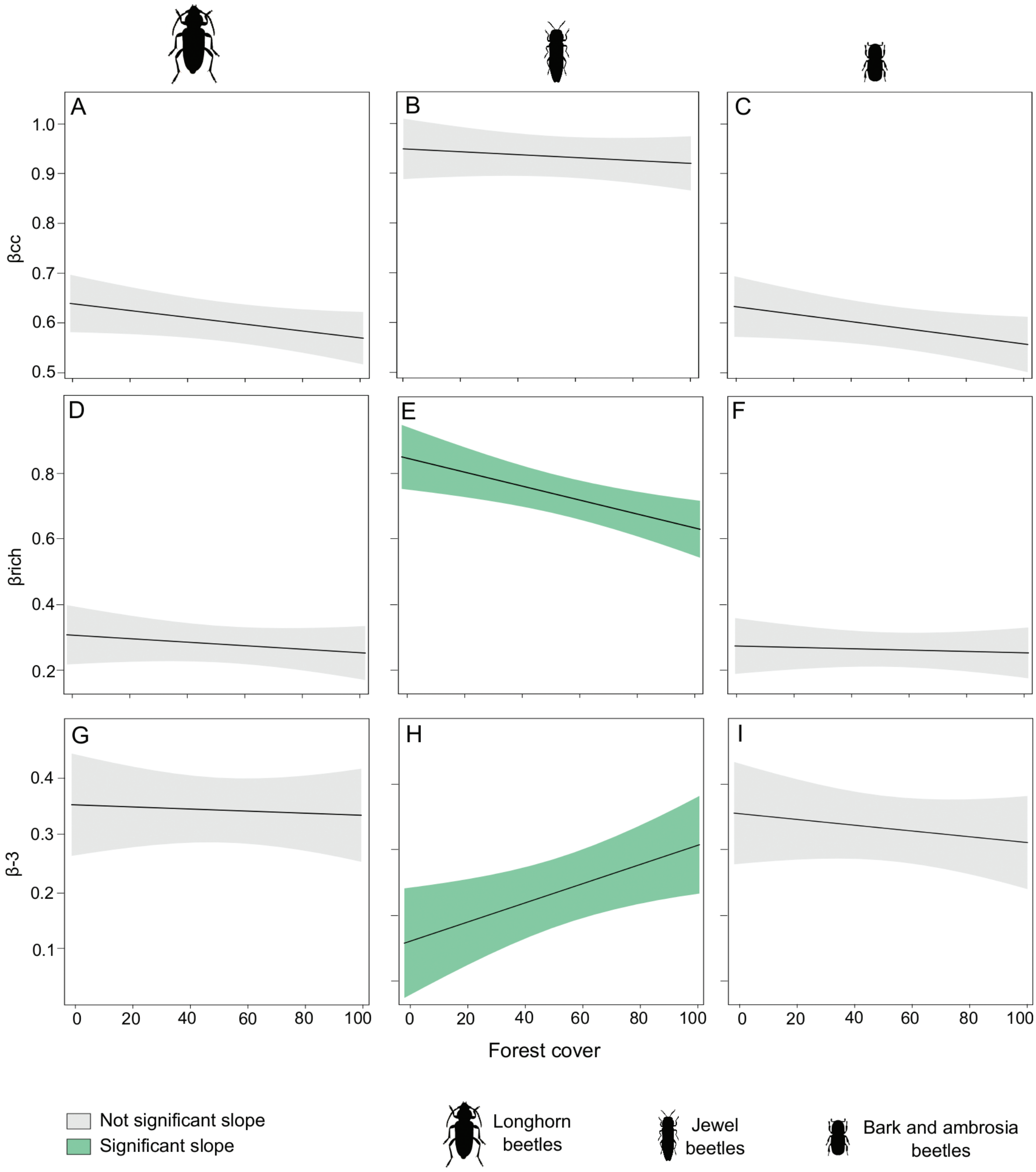


**Figure 3.** Effect of forest cover in a buffer of 250 m radius around the traps on the dissimilarity among wood-boring beetle communities found in black understory multi-funnel traps and green canopy multi-funnel traps, considering the total beta-diversity $\beta_{cc}$ (**A–C**) and its components species richness difference $\beta_{rich}$ (**D–F**) and species replacement $\beta_{-3}$ (**G–I**). Plots include model estimate (colored line) and 95% confidence intervals (colored shading). Model details are provided in Table 2. Pairwise comparisons among taxa are provided in Suppl. material 1: table S3. Slope estimates, along with their corresponding 95% confidence intervals, are provided in Suppl. material 1: table S4.

**Table 2.** Analysis of deviance table from the generalized linear mixed models testing the effects of taxon (longhorn beetles, jewel beetles, and bark and ambrosia beetles), forest cover (mean % in buffers of 250 m radius around the pair of traps) and their interaction on β-diversity ($\beta_{cc}$), species richness difference ($\beta_{rich}$) and species replacement ($\beta_{-3}$) indices (Gaussian distribution used for all models). Nested random structure used for all models: ~1|Site/Cell. Type II Wald chi-square tests ($\chi^2$), degrees of freedom (df), *p*-values, and delta marginal ($mR^2$) and conditional ($cR^2$) pseudo R-squared are provided for all models. Pairwise comparisons among taxa are provided in Suppl. material 1: table S3. Slope estimates, representing the relationship between each index and forest cover, along with their corresponding 95% confidence intervals, are provided in Suppl. material 1: table S4.

| | $\chi^2$ | df | *p*-value |
|---|---|---|---|
| $\beta_{cc}$ | | | |
| Taxon | 391.167 | 2 | < 0.001 |
| Forest | 4.282 | 1 | 0.039 |
| Taxon × Forest | 0.899 | 2 | 0.638 |
| | | | $mR^2 = 0.53$, $cR^2 = 0.58$ |
| $\beta_{rich}$ | | | |
| Taxon | 262.048 | 2 | < 0.001 |
| Forest | 4.617 | 1 | 0.032 |
| Taxon × Forest | 5.073 | 2 | 0.079 |
| | | | $mR^2 = 0.45$, $cR^2 = 0.47$ |
| $\beta_{-3}$ | | | |
| Taxon | 17.470 | 2 | < 0.001 |
| Forest | 0.426 | 1 | 0.514 |
| Taxon × Forest | 7.250 | 2 | 0.027 |
| | | | $mR^2 = 0.07$, $cR^2 = 0.10$ |

although the trend was not significant (Fig. 3A–C; Suppl. material 1: table S4). For jewel beetles, $\beta_{rich}$ decreased with increasing amount of forest cover (Fig. 3E; Suppl. material 1: table S4), whereas the opposite trend was found for $\beta_{-3}$ (Fig. 3H; Suppl. material 1: table S4). For longhorn beetles and bark and ambrosia beetles, both $\beta_{rich}$ and $\beta_{-3}$ showed no relationship with forest cover (Fig. 3D, F, G, I, Suppl. material 1: table S4).

## Discussion

Our study confirmed that the use of baited traps around high-risk sites represents an efficient approach for generic surveillance of wood-boring beetles (Brockerhoff et al. 2006; Rassati et al. 2015a, 2015b; Fan et al. 2019; Rabaglia et al. 2019; Mas et al. 2023). The simultaneous use of black-understory multi-funnel traps and green-canopy multi-funnel traps baited with a multi-lure blend of pheromones and host volatiles allowed us to catch 21 non-native species from all the three targeted families (i.e., longhorn beetles, bark and ambrosia beetles and jewel beetles), as well as more than 300 native species. In addition to the importance of records of newly introduced or expanding non-native species, knowledge of distribution and abundance data for native species in areas near entry/export sites represents a second key benefit of the application of this or similar trapping protocols (Rassati et al. 2015a, 2018; Mas et al. 2023). In fact, these data can be crucial not only to increase our ability to predict which species are at most risk from being introduced in other countries via exported commodities (Mas et al. 2023) but also to monitor range expansion or shifts of native species, which could become invasive within their native distributional range (Rassati et al. 2018; Ruzzier et al. 2023b).

Comparing the efficacy of the two trapping methodologies, we found that black multi-funnel traps baited with the multi-lure blend and set up in the understory caught significantly more bark and ambrosia beetle species and individuals than green multi-funnel traps baited with the same blend and set up in the canopy, but significantly less jewel beetle species and individuals. For longhorn beetles, a difference between the two trapping methodologies was found in the total number of individuals (more in black-understory traps), but not in the number of species. The trends observed in our study are likely explained by the combined effect of trap height and trap color (Dodds et al. 2024), two variables that are well known to affect trap efficacy towards the targeted taxa. Several studies, for example, showed an increasing abundance and richness of longhorn beetles and jewel beetles with increasing trap height (Ulyshen and Hanula 2007; Maguire et al. 2014; Flaherty et al. 2019; Rassati et al. 2019; Sheehan et al. 2019; Sweeney et al. 2020) and/or the opposite trend for bark and ambrosia beetles (Ulyshen and Hanula 2007; Hanula et al. 2011; Dodds 2014; Hardersen et al. 2014; Flaherty et al. 2019). Other studies showed that green colored traps are more efficient than black or dark colored traps in catching jewel beetles, especially *Agrilus* spp. (e.g., Crook et al. 2009, 2014; Francese et al. 2010a, b, 2011; Petrice and Haack 2015; Skvarla and Dowling 2017; Rassati et al. 2019; Tobin et al. 2021), and/or that black or dark colored traps are generally more or similar efficient than green colored traps in attracting bark and ambrosia beetles (Cavaletto et al. 2020; Marchioro et al. 2020) and longhorn beetles (Kerr et al. 2017; Rassati et al. 2019; Cavaletto et al. 2021). Although our study does not allow us to disentangle the individual contribution of trap color and trap height on beetle catches, it shows that the simultaneous use of black-understory and green-canopy multi-funnel traps in generic trapping programs targeting these three taxa at the same time is essential.

Analyzing dissimilarity indices, we also found that differences between beetle communities caught in black-understory traps and green-canopy traps were more evident for jewel beetles than for both longhorn beetles and bark and ambrosia beetles. For jewel beetles, these differences were mainly attributed to differences in species richness, while both differences in species richness and species turnover contributed to explain the dissimilarity of communities of longhorn beetles and bark and ambrosia beetles between trapping methodologies. These results are especially useful when planning surveillance activities targeting only one of the three taxa. For longhorn beetles and bark and ambrosia beetles, the simultaneous use of black-understory and green-canopy multi-funnel traps is always recommended, as different species with different flight patterns can be caught by these two trapping methodologies. Previous studies testing different trap types, environmental gradients, and/or lures (Skvarla and Dowling 2017; Flaherty et al. 2019; Rassati et al. 2019) confirmed that the diversification of trapping methodologies is always advantageous when targeting longhorn beetles and bark and ambrosia beetles (Dodds et al. 2024). For jewel beetles, especially *Agrilus* spp., green-canopy multi-funnel traps should be prioritized over black-understory traps in some, but not all, landscapes. In fact, jewel beetles were the only taxon for which dissimilarity indices were affected by the amount of forest cover in the trap surroundings. In particular, the difference in the number of jewel beetle species caught in black-understory and green-canopy multi-funnel traps decreased with increasing amount of forest cover, whereas the species turnover increased. In other words, jewel beetle species collected in black-understory traps were a subset of the species collected in green-canopy traps in urban-dominated landscapes, whereas the number of jewel beetle species exclusive to either black-understory or green-canopy traps increased in forest-dominated landscapes. Thus, the use of black-understory along with green-canopy multi-funnel traps is recommended only in forest-dominated landscapes.

## Conclusions

Baited traps are an essential component of both specific and generic surveillance programs around the world, making the development of efficient trapping protocols a research priority. Here we showed that the simultaneous use of black-understory and green-canopy multi-funnel traps baited with a multi-lure blend of longhorn beetle pheromones and host volatiles can be considered a very efficient approach for generic surveillance of longhorn beetles, jewel beetles and bark and ambrosia beetles in both urban-dominated and forest-dominated areas surrounding entry points. The only case in which this protocol can be simplified using only green-canopy multi-funnel traps is when targeting jewel beetles in urban-dominated landscapes. Despite the general efficiency of the trapping protocol we tested, it is very likely that not all longhorn beetle, bark and ambrosia beetle and jewel beetle fauna present in the sampled area was represented by trap catches. Fan et al. (2019), for example, using the same multi-lure blend, collected 48% of the 238 longhorn beetle species native to France, percentage that would be likely lower for bark and ambrosia beetles and jewel beetles. Overall, these results highlight that further improvements to the trapping protocol are possible. For example, the use of traps of different colors (e.g., yellow, blue) (Cavaletto et al. 2020, 2021) or traps integrated with more complex visual stimuli (Masaguè et al. 2024) is very likely to increase the diversity of species that can be collected, especially within those taxa strongly relying on color vision at the adult stage (e.g., Lepturinae). Similarly, advances in the knowledge of the chemical ecology of still understudied taxa (i.e., jewel beetles) will further improve trap attractiveness with direct benefits for national and international surveillance.

## Acknowledgments

We thank Enrico Ruzzier, Giacomo Cavaletto, Caterina de Sandre, Gianluigi Berardi, Ryan Lawson, Abigail Morton, Ifidion Ohiomah, Erika Ratcliff, and Ryan Rugg for helping in both lab and field activities. We are indebted to the managers of the Parc du Sausset at Aulnay/Bois (France) for authorizing the settlement of the traps in their urban park. This material was made possible, in part, by a Cooperative Agreement from the United States Department of Agriculture's Animal and Plant Health Inspection Service (APHIS). It may not necessarily express APHIS' views.

## Additional information

### Conflict of interest

The authors have declared that no competing interests exist.

## Ethical statement

No ethical statement was reported.

## Funding

This work was supported by the HOMED project (HOlistic Management of Emerging Forest Pests and Diseases) funded by the European Union's Horizon 2020 research and innovation program under grant agreement No. 771271 (https://homed-projecteu/). AMR received funding from the US Department of Agriculture Cooperative Agreement #AP18PPQS&T00C169 and #AP19PPQS&T00C082, and from the Xavier University Undergraduate Research Fund.

## Author contributions

GS: data curation, formal analysis, writing – original draft, writing – review & editing; AB: funding acquisition, writing – review & editing; CC: lure preparation, methodology; GC: beetle identification; MF: beetle identification, writing – review & editing; NF: investigation; JAF: funding acquisition, investigation, writing – review & editing; EKLF: beetle identification, investigation; FG: beetle identification; MMG: funding acquisition, investigation, writing – review & editing; CK: beetle identification, investigation; MM: conceptualization, investigation; DN: conceptualization, data curation, formal analysis; AMR: funding acquisition, investigation, writing – review & editing; AR: investigation, beetle identification, funding acquisition, writing – review & editing; JS: funding acquisition, investigation, writing – review & editing; KVR: beetle identification, investigation; VW: beetle identification, investigation; DR: conceptualization, data curation, project administration, validation, visualization, writing – original draft, writing – review & editing. All authors approved the text.

## Author ORCIDs

Giacomo Santoiemma https://orcid.org/0000-0002-3226-9253
Andrea Battisti https://orcid.org/0000-0002-2497-3064
Massimo Faccoli https://orcid.org/0000-0002-9355-0516
Martin M. Gossner https://orcid.org/0000-0003-1516-6364
Matteo Marchioro https://orcid.org/0000-0003-2301-1047
Alain Roques https://orcid.org/0000-0002-3734-3918
Jon Sweeney https://orcid.org/0000-0003-3391-2375
Davide Rassati https://orcid.org/0000-0001-7778-0349

## Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.

## References

Allison JD, Redak RA (2017) The impact of trap type and design features on survey and detection of bark and woodboring beetles and their associates: A review and meta-analysis. Annual Review of Entomology 62(1): 127–146. https://doi.org/10.1146/annurev-ento-010715-023516

Allison JD, Graham EE, Poland TM, Strom BL (2016) Dilution of fluon before trap surface treatment has no effect on longhorned beetle (Coleoptera: Cerambycidae) captures. Journal of Economic Entomology 109(3): 1215–1219. https://doi.org/10.1093/jee/tow081

Allison JD, Marcotte M, Noseworthy M, Ramsfield T (2021) Forest biosecurity in Canada – An integrated multi-agency approach. Frontiers in Forests and Global Change 4: 700825. https://doi.org/10.3389/ffgc.2021.700825

Aukema JE, Leung B, Kovacs K, Chivers C, Britton KO, Englin J, Frankel SJ, Haight RG, Holmes TP, Liebhold AM, McCullough DG, Von Holle B (2011) Economic impacts of non-native forest insects in the continental United States. PLoS ONE 6(9): e24587. https://doi.org/10.1371/journal.pone.0024587

Bashford R (2008) The development of a port surrounds trapping system for the detection of exotic forest insect pests in Australia. In: Oteng-Amoako AA (Ed.) New advances and contribution to forestry research. InTech, Rijeka, 85–100.

Bouget C, Brustel H, Brin A, Valladares L (2009) Evaluation of window flight traps for effectiveness at monitoring dead wood-associated beetles: The effect of ethanol lure under contrasting environmental conditions. Agricultural and Forest Entomology 11(2): 143–152. https://doi.org/10.1111/j.1461-9563.2008.00400.x

Brockerhoff EG, Jones DC, Kimberley MO, Suckling DM, Donaldson T (2006) Nationwide survey for invasive wood-boring and bark beetles (Coleoptera) using traps baited with pheromones and kairomones. Forest Ecology and Management 228(1–3): 234–240. https://doi.org/10.1016/j.foreco.2006.02.046

Brooks M, Bolker B, Kristensen K, Maechler M, Magnusson A, McGillycuddy M, Skaug H, et al. (2022) Generalized linear mixed models using template model builder. R package 'glmmTMB', version 1.1.5.

Byers J (2007) Chemical ecology of bark beetles in a complex olfactory landscape. In: Lieutier F, Day KR, Battisti A, Grégoire JC, Evans HF (Eds) Bark and wood boring insects in living trees in Europe, a synthesis. Springer, Dordrecht, 89–134. https://doi.org/10.1007/978-1-4020-2241-8_8

Carnegie AJ, Lawson S, Wardlaw T, Cameron N, Venn T (2018) Benchmarking forest health surveillance and biosecurity activities for managing Australia's exotic forest pest and pathogen risks. Australian Forestry 81(1): 14–23. https://doi.org/10.1080/00049158.2018.1433271

Carnegie AJ, Tovar F, Collins S, Lawson SA, Nahrung HF (2022) A coordinated, risk-based, national forest biosecurity surveillance program for Australian forests. Frontiers in Forests and Global Change 4: 756885. https://doi.org/10.3389/ffgc.2021.756885

Carvalho JC, Cardoso P, Gomes P (2012) Determining the relative roles of species replacement and species richness differences in generating beta-diversity patterns. Global Ecology and Biogeography 21(7): 760–771. https://doi.org/10.1111/j.1466-8238.2011.00694.x

Cavaletto G, Faccoli M, Marini L, Spaethe J, Magnani G, Rassati D (2020) Effect of trap color on captures of bark-and wood-boring beetles (Coleoptera; Buprestidae and Scolytinae) and associated predators. Insects 11(11): 749. https://doi.org/10.3390/insects11110749

Cavaletto G, Faccoli M, Marini L, Spaethe J, Giannone F, Moino S, Rassati D (2021) Exploiting trap colors to improve surveys of longhorn beetles. Journal of Pest Science 94(3): 871–883. https://doi.org/10.1007/s10340-020-01303-w

Collignon RM, Swift IP, Zou Y, McElfresh JS, Hanks LM, Millar JG (2016) The influence of host plant volatiles on the attraction of longhorn beetles to pheromones. Journal of Chemical Ecology 42(3): 215–229. https://doi.org/10.1007/s10886-016-0679-x

Crook DJ, Francese JA, Zylstra KE, Fraser I, Sawyer AJ, Bartels DW, Lance DR, Mastro VC (2009) Laboratory and field response of the emerald ash borer (Coleoptera: Buprestidae), to selected regions of the electromagnetic spectrum. Journal of Economic Entomology 102(6): 2160–2169. https://doi.org/10.1603/029.102.0620

Crook DJ, Francese JA, Rietz ML, Lance DR, Hull-Sanders HM, Mastro VC, Silk PJ, Ryall KL (2014) Improving detection tools for emerald ash borer (Coleoptera: Buprestidae): comparison of multifunnel traps, prism traps, and lure types at varying population densities. Journal of Economic Entomology 107(4): 1496–1501. https://doi.org/10.1603/EC14041

Cuthbert RN, Diagne C, Hudgins EJ, Turbelin A, Ahmed DA, Albert C, Bodey TW, Briski E, Essl F, Haubrock PJ, Gozlan RE, Kirichenko N, Kourantidou M, Kramer AM, Courchamp F (2022)

Biological invasion costs reveal insufficient proactive management worldwide. The Science of the Total Environment 819: 153404. https://doi.org/10.1016/j.scitotenv.2022.153404

De Groot P, Nott R (2001) Evaluation of traps of six different designs to capture pine sawyer beetles (Coleoptera: Scolytidae). Agricultural and Forest Entomology 3(2): 107–111. https://doi.org/10.1046/j.1461-9563.2001.00087.x

Dodds KJ (2014) Effects of trap height on captures of arboreal insects in pine stands of northeastern United States of America. Canadian Entomologist 146(1): 80–89. https://doi.org/10.4039/tce.2013.57

Dodds KJ, Ross DW (2002) Sampling range and range of attraction of *Dendroctonus pseudotsugae* pheromone-baited traps. Canadian Entomologist 134(3): 343–355. https://doi.org/10.4039/Ent134343-3

Dodds KJ, Dubois GD, Hoebeke ER (2010) Trap type, lure placement, and habitat effects on Cerambycidae and Scolytinae (Coleoptera) catches in the northeastern United States. Journal of Economic Entomology 103(3): 698–707. https://doi.org/10.1603/EC09395

Dodds KJ, Sweeney J, Francese JA, Besana L, Rassati D (2024) Factors affecting catches of bark and wood-boring beetles in traps. Journal of Pest Science. https://doi.org/10.1007/s10340-024-01774-1

Epanchin-Niell RS, Brockerhoff EG, Kean JM, Turner JA (2014) Designing cost-efficient surveillance for early detection and control of multiple biological invaders. Ecological Applications 24(6): 1258–1274. https://doi.org/10.1890/13-1331.1

Fan JT, Denux O, Courtin C, Bernard A, Javal M, Millar JC, Hanks LM, Roques A (2019) Multi-component blends for trapping native and exotic longhorn beetles at potential points-of-entry and in forests. Journal of Pest Science 92(1): 281–297. https://doi.org/10.1007/s10340-018-0997-6

Fenn-Moltu G, Ollier S, Caton B, Liebhold AM, Nahrung H, Pureswaran DS, Turner RM, Yamanaka T, Bertelsmeier C (2023) Alien insect dispersal mediated by the global movement of commodities. Ecological Applications 33(1): e2721. https://doi.org/10.1002/eap.2721

Flaherty L, Gutowski JMC, Hughes C, Mayo P, Mokrzycki T, Pohl G, Silk P, Van Rooyen K, Sweeney J (2019) Pheromone-enhanced lure blends and multiple trap heights improve detection of bark and woodboring beetles potentially moved in solid wood packaging. Journal of Pest Science 92(1): 309–325. https://doi.org/10.1007/s10340-018-1019-4

Fox J, Weisberg S (2019) An R companion to applied regression. 3rd edn., Sage publications. Thousand Oaks, California.

Francese JA, Crook DJ, Fraser I, Lance DR, Sawyer AJ, Mastro VC (2010a) Optimization of trap color for emerald ash borer (Coleoptera: Buprestidae). Journal of Economic Entomology 103(4): 1235–1241. https://doi.org/10.1603/EC10088

Francese JA, Fraser I, Rietz ML, Crook DJ, Lance DR, Mastro VC (2010b) Relation of color, size, and canopy placement of prism traps in determining capture of emerald ash borer (Coleoptera: Buprestidae). Canadian Entomologist 142(6): 596–600. https://doi.org/10.4039/n10-041

Francese JA, Fraser I, Lance DR, Mastro VC (2011) Efficacy of multifunnel traps for capturing emerald ash borer (Coleoptera: Buprestidae): effect of color, glue, and other trap coatings. Journal of Economic Entomology 104(3): 901–908. https://doi.org/10.1603/EC11038

Francese JA, Rietz ML, Mastro VC (2013) Optimization of multifunnel traps for emerald ash borer (Coleoptera: Buprestidae): influence of size, trap coating, and color. Journal of Economic Entomology 106(6): 2415–2423. https://doi.org/10.1603/EC13014

Google Inc.© (2023) Google Earth Pro. https://earth.google.com/

Graham EE, Poland TM (2012) Efficacy of fluon conditioning for capturing cerambycid beetles in different trap designs and persistence on panel traps over time. Journal of Economic Entomology 105(2): 395–401. https://doi.org/10.1603/EC11432

Hanks LM, Mongold-Diers JA, Atkinson TH, Fierke MK, Ginzel MD, Graham EE, Poland TM, Richards AB, Richardson ML, Millar JG (2018) Blends of pheromones, with and without host plant volatiles, can attract multiple species of cerambycid beetles simultaneously. Journal of Economic Entomology 111(2): 716–724. https://doi.org/10.1093/jee/tox373

Hanula JL, Ulyshen MD, Horn S (2011) Effect of trap type, trap position, time of year, and beetle density on captures of the redbay ambrosia beetle (Coleoptera: Curculionidae: Scolytinae). Journal of Economic Entomology 104(2): 501–508. https://doi.org/10.1603/EC10263

Hardersen S, Curletti G, Leseigneur L, Platia G, Liberti G, Leo P, et al. (2014) Spatio-temporal analysis of beetles from the canopy and ground layer in an Italian lowland forest. Bulletin of Insectology 67: 87–97.

Hartig F (2022) Residual diagnostics for hierarchical (multi-level/mixed) regression models. R package 'DHARMa', version 0.4.6.

Hoch G, Connell J, Roques A (2020) Testing multi-lure traps for surveillance of native and alien longhorn beetles (Coleoptera, Cerambycidae) at ports of entry and in forests in Austria. Management of Biological Invasions 11(4): 677–688. https://doi.org/10.3391/mbi.2020.11.4.04

Holusa J, Fiala T, Pyszko P (2023) Using ethanol and other lures to monitor invasive ambrosia beetles in endemic populations: Case study from the Czech Republic. Frontiers in Forests and Global Change 6: 1258729. https://doi.org/10.3389/ffgc.2023.1258729

Hughes CC, Johns RC, Sweeney JD (2014) A technical guide to installing beetle traps in the upper crown of trees. Journal of the Acadian Entomological Society 10: 12–18.

Isitt R, Liebhold AM, Turner RM, Battisti A, Bertelsmeier C, Blake R, Brockerhoff EG, Heard SB, Krokene P, Økland B, Nahrung HF, Rassati D, Roques A, Yamanaka T, Pureswaran DS (2024) Asymmetrical insect invasions between three world regions. NeoBiota 90: 35–51. https://doi.org/10.3897/neobiota.90.110942

Jactel H, Bonifacio L, Van Halder I, Vétillard F, Robinet C, David G (2019) A novel, easy method for estimating pheromone trap attraction range: Application to the pine sawyer beetle *Monochamus galloprovincialis*. Agricultural and Forest Entomology 21(1): 8–14. https://doi.org/10.1111/afe.12298

Kerr JL, Kelly D, Bader MKF, Brockerhoff EG (2017) Olfactory cues, visual cues, and semiochemical diversity interact during host location by invasive forest beetles. Journal of Chemical Ecology 43(1): 17–25. https://doi.org/10.1007/s10886-016-0792-x

Legendre P (2014) Interpreting the replacement and richness difference components of beta diversity. Global Ecology and Biogeography 11(11): 1324–1334. https://doi.org/10.1111/geb.12207

Lenth RV (2021) Estimated marginal means, aka least-squares means. R package 'emmeans', version 1.6.3.

Maguire DY, Robert K, Brochu K, Larrivée M, Buddle CM, Wheeler TA (2014) Vertical stratification of beetles (Coleoptera) and flies (Diptera) in temperate forest canopies. Environmental Entomology 43(1): 9–17. https://doi.org/10.1603/EN13056

Marchioro M, Rassati D, Faccoli M, Van Rooyen K, Kostanowicz C, Webster V, Mayo P, Sweeney J (2020) Maximizing bark and ambrosia beetle (Coleoptera: Curculionidae) catches in trapping surveys for longhorn and jewel beetles. Journal of Economic Entomology 113(6): 2745–2757. https://doi.org/10.1093/jee/toaa181

Mas H, Santoiemma G, Lencina JL, Gallego D, Pérez-Laorga E, Ruzzier E, Rassati D (2023) Investigating beetle communities in and around entry points can improve surveillance at national and international scale. NeoBiota 85: 145–165. https://doi.org/10.3897/neobiota.85.103904

Masaguè S, Bruchhausen A, Rozas G, Delavega G, Villacide J, Corely J, Martinez A (2024) The relevance of integrating multiple sensory modalities into capturing devices: The case of the global pest *Sirex noctilo*. Agricultural and Forest Entomology. https://doi.org/10.1111/afe.12637

McIntosh RL, Katinic PJ, Allison JD, Borden JH, Downey DL (2001) Comparative efficacy of five types of trap for woodborers in the Cerambycidae, Buprestidae and Siricidae. Agricultural and Forest Entomology 3(2): 113–120. https://doi.org/10.1046/j.1461-9563.2001.00095.x

Meurisse N, Rassati D, Hurley BP, Brockerhoff EG, Haack RA (2019) Common pathways by which non-native forest insects move internationally and domestically. Journal of Pest Science 92(1): 13–27. https://doi.org/10.1007/s10340-018-0990-0

Millar JG, Hanks LM (2017) Chemical ecology of cerambycid beetles. In: Wang Q (Ed.) Cerambycidae of the world: biology and pest management. CRC Press, Boca Raton, Florida, 161–208.

Miller DR, Rabaglia RJ (2009) Ethanol and (–)-α-pinene: Attractant kairomones for bark and ambrosia beetles in the southeastern US. Journal of Chemical Ecology 35(4): 435–448. https://doi.org/10.1007/s10886-009-9613-9

Miller DR, Crowe CM, Dodds KJ, Galligan LD, De Groot P, Hoebeke ER, Mayfield AE III, Poland TM, Raffa KF, Sweeney JD (2015) Ipsenol, ipsdienol, ethanol, and α-pinene: Trap lure blend for Cerambycidae and Buprestidae (Coleoptera) in pine forests of Eastern North America. Journal of Economic Entomology 108(4): 1837–1851. https://doi.org/10.1093/jee/tov126

Miller DR, Crowe CM, Mayo PD, Reid LS, Silk PJ, Sweeney JD (2017) Interactions between ethanol, syn-2,3-hexanediol, 3-hydroxyhexan-2-one, and 3-hydroxyoctan-2-one lures on trap catches of hardwood longhorn beetles in southeastern United States. Journal of Economic Entomology 110(5): 2119–2128. https://doi.org/10.1093/jee/tox188

Nahrung HF, Liebhold AM, Brockerhoff EG, Rassati D (2023) Forest insect biosecurity: Processes, patterns, predictions, and pitfalls. Annual Review of Entomology 68(1): 211–229. https://doi.org/10.1146/annurev-ento-120220-010854

Nguyen HTM, Chu L, Liebhold AM, Epanchin-Niell R, Kean JM, Kompas T, Robinson AP, Brockerhoff EG, Moore JL (2024) Optimal allocation of resources among general and species-specific tools for plant pest biosecurity surveillance. Ecological Applications 34(3): e2955. https://doi.org/10.1002/eap.2955

Nunes P, Branco M, Van Halder I, Jactel H (2021) Modelling *Monochamus galloprovincialis* dispersal trajectories across a heterogeneous landscape to optimize monitoring by trapping networks. Landscape Ecology 36(3): 931–941. https://doi.org/10.1007/s10980-020-01188-1

Oksanen J, Simpson GL, Blanchet FG, Kindt R, Legendre P, Minchin PR, et al. (2022) Community ecology package. R package 'vegan', version 2.6-4.

Petrice TR, Haack RA (2015) Comparison of different trap colors and types for capturing adult *Agrilus* (Coleoptera: Buprestidae) and other buprestids. Great Lakes Entomologist 48(1 & 2): 4. https://doi.org/10.22543/0090-0222.2310

Pinheiro D, Bates D, DebRoy S, Sarkar D, R Core Team (2021) Linear and nonlinear mixed effects models. R package 'nlme', version 3.1-152.

Podani J, Schmera D (2011) A new conceptual and methodological framework for exploring and explaining pattern in presence-absence data. Oikos 120(11): 1625–1638. https://doi.org/10.1111/j.1600-0706.2011.19451.x

Poland TM, Rassati D (2019) Improved biosecurity surveillance of non-native forest insects: A review of current methods. Journal of Pest Science 92(1): 37–49. https://doi.org/10.1007/s10340-018-1004-y

QGIS Development Team (2021) Quantum GIS geographic information system. http://qgis.osgeo.org/

R Core Team (2021) R: a language and environment for statistical computing. https://www.r-project.org/

Rabaglia RJ, Cognato AI, Hoebeke ER, Johnson CW, LaBonte JR, Carter ME, Vlach JJ (2019) Early detection and rapid response: A 10-year summary of the USDA Forest Service program of surveillance for non-native bark and ambrosia beetles. American Entomologist 65(1): 29–42. https://doi.org/10.1093/ae/tmz015

Ranger CM, Reding ME, Addesso K, Ginzel M, Rassati D (2021) Semiochemical-mediated host selection by *Xylosandrus* spp. ambrosia beetles (Coleoptera: Curculionidae) attacking horticultural tree crops: a review of basic and applied science. Canadian Entomologist 153(1): 103–120. https://doi.org/10.4039/tce.2020.51

Rassati D, Faccoli M, Petrucco Toffolo E, Battisti A, Marini L (2015a) Improving the early detection of alien wood-boring beetles in ports and surrounding forests. Journal of Applied Ecology 52(1): 50–58. https://doi.org/10.1111/1365-2664.12347

Rassati D, Faccoli M, Marini L, Haack RA, Battisti A, Petrucco Toffolo E (2015b) Exploring the role of wood waste landfills in early detection of non-native wood-boring beetles. Journal of Pest Science 88(3): 563–572. https://doi.org/10.1007/s10340-014-0639-6

Rassati D, Lieutier F, Faccoli M (2016) Alien wood-boring beetles in Mediterranean regions. In: Paine TD, Lieutier F (Eds) Insects and diseases of Mediterranean forest systems. Springer, Cham, Switzerland, 293–327. https://doi.org/10.1007/978-3-319-24744-1_11

Rassati D, Haack RA, Knížek M, Faccoli M (2018) National trade can drive range expansion of bark-and wood-boring beetles. Journal of Economic Entomology 111(1): 260–268. https://doi.org/10.1093/jee/tox308

Rassati D, Marini L, Marchioro M, Rapuzzi P, Magnani G, Poloni R, Di Giovanni F, Mayo P, Sweeney J (2019) Developing trapping protocols for wood-boring beetles associated with broadleaf trees. Journal of Pest Science 92(1): 267–279. https://doi.org/10.1007/s10340-018-0984-y

Rassati D, Marchioro M, Flaherty L, Poloni R, Edwards S, Faccoli M, Sweeney J (2021) Response of native and exotic longhorn beetles to common pheromone components provides partial support for the pheromone-free space hypothesis. Insect Science 28(3): 793–810. https://doi.org/10.1111/1744-7917.12790

Rice ME, Zou Y, Millar JG, Hanks LM (2020) Complex blends of synthetic pheromones are effective multi-species attractants for longhorned beetles (Coleoptera: Cerambycidae). Journal of Economic Entomology 113(5): 2269–2275. https://doi.org/10.1093/jee/toaa157

Roques A, Ren L, Rassati D, Shi J, Akulov E, Audsley N, Auger-Rozenberg M-A, Avtzis D, Battisti A, Bellanger R, Bernard A, Bernadinelli I, Branco M, Cavaletto G, Cocquempot C, Contarini M, Courtial B, Courtin C, Denux O, Dvořák M, Fan J, Feddern N, Francese J, Franzen EKL, Garcia A, Georgiev G, Georgieva M, Giarruzzo F, Gossner M, Gross L, Guarneri D, Hoch G, Hölling D, Jonsell M, Kirichenko N, Loomans A, Luo Y, McCullough D, Maddox C, Magnoux E, Marchioro M, Martinek P, Mas H, Mériguet B, Pan Y, Phélut R, Pineau P, Ray AM, Roques O, Ruiz M-C, Sartoi Monteys V, Speranza S, Sun J, Sweeney JD, Touroult J, Valladares L, Veillat L, Yuan Y, Zalucki MP, Zou Y, Žunič-Kosi A, Hanks LM, Millar JG (2023) Worldwide tests of generic attractants, a promising tool for early detection of nonnative cerambycid species. NeoBiota 84: 169–209. https://doi.org/10.3897/neobiota.84.91096

Ruzzier E, Haack RA, Curletti G, Roques A, Volkovitsh MG, Battisti A (2023a) Jewels on the go: exotic buprestid around the world (Coleoptera: Buprestidae). NeoBiota 84: 107–135. https://doi.org/10.3897/neobiota.84.90829

Ruzzier E, Martinez-Sañudo I, Cavaletto G, Faccoli M, Smith SM, Cognato AI, Rassati D (2023b) Detection of native-alien populations of *Anisandrus dispar* (Fabricius, 1792) in Europe. Journal of Asia-Pacific Entomology 26(4): 102137. https://doi.org/10.1016/j.aspen.2023.102137

Santoiemma G, Williams D, Booth EG, Cavaletto G, Connell J, Curletti G, de Groot M, Devine SM, Enston A, Francese JA, Franzen EKL, Giasson M, Groznik E, Gutowski JM, Hauptman T, Hinterstoisser W, Hoch G, Hoppe B, Hughes C, Kostaniwicz C, Peterson DL, Plewa R, Ray AM, Sallé A, Sućko K, Sweeney J, Van Rooyen K, Rassati D (2024) Efficacy of trapping protocols for Agrilus jewel beetles: a multi-country assessment. Journal of Pest Science. https://doi.org/10.1007/s10340-023-01728-z

Schroeder LM (2013) Monitoring of *Ips typographus* and *Pityogenes chalcographus*: Influence of trapping site and surrounding landscape on catches. Agricultural and Forest Entomology 15(2): 113–119. https://doi.org/10.1111/afe.12002

Seebens H, Blackburn TM, Dyer EE, Genovesi P, Hulme PE, Jeschke JM, Pagad S, Pyšek P, Winter M, Arianoutsou M, Bacher S, Blasius B, Brundu G, Capinha C, Celesti-Grapow L, Dawson W, Dullinger S, Fuentes N, Jäger H, Kartesz J, Kenis M, Kreft H, Kühn I, Lenzner B, Liebhold A, Mosena A, Moser D, Nishino M, Pearman D, Pergl J, Rabitsch W, Rojas-Sandoval J, Roques A, Rorke S, Rossinelli S, Roy HE, Scalera R, Schindler S, Štajerová K, Tokarska-Guzik B, van Kleunen M, Walker K, Weigelt P, Yamanaka T, Essl F (2017) No saturation in the accumulation of alien species worldwide. Nature Communications 8(1): 71314435. https://doi.org/10.1038/ncomms14435

Sheehan TN, Ulyshen MD, Horn S, Hoebeke ER (2019) Vertical and horizontal distribution of bark and woodboring beetles by feeding guild: Is there an optimal trap location for detection? Journal of Pest Science 92(1): 327–341. https://doi.org/10.1007/s10340-018-1026-5

Skvarla MJ, Dowling AP (2017) A comparison of trapping techniques (Coleoptera: Carabidae, Buprestidae, Cerambycidae, and Curculionoidea excluding Scolytinae). Journal of Insect Science 17(1): 7. https://doi.org/10.1093/jisesa/iew098

Sweeney J, Hughes C, Webster V, Kostanowicz C, Webster R, Mayo P, Allison JD (2020) Impact of horizontal edge–interior and vertical canopy–understory gradients on the abundance and diversity of bark and woodboring beetles in survey traps. Insects 11(9): 573. https://doi.org/10.3390/insects11090573

Tobin PC, Strom BL, Francese JA, Herms DA, McCullough DG, Poland TM, Ryall KL, Scarr T, Silk PJ, Thistle HW (2021) Evaluation of trapping schemes to detect emerald ash borer (Coleoptera: Buprestidae). Journal of Economic Entomology 114(3): 1201–1210. https://doi.org/10.1093/jee/toab065

Ulyshen MD, Hanula JL (2007) A comparison of the beetle (Coleoptera) fauna captured at two heights above the ground in a North American temperate deciduous forest. American Midland Naturalist 158(2): 260–278. https://doi.org/10.1674/0003-0031(2007)158[260:ACOTBC]2.0.CO;2

Ulyshen MD, Sheehan TN (2019) Trap height considerations for detecting two economically important forest beetle guilds in southeastern US forests. Journal of Pest Science 92(1): 253–265. https://doi.org/10.1007/s10340-017-0883-7

Wardhaugh CW, Pawson SM (2023) Multi-trap sampling of arthropod communities at ports of first entry informs biosecurity surveillance programs. Journal of Pest Science. https://doi.org/10.1007/s10340-023-01714-5

Wong JC, Mitchell RF, Striman BL, Millar JG, Hanks LM (2012) Blending synthetic pheromones of cerambycid beetles to develop trap lures that simultaneously attract multiple species. Journal of Economic Entomology 105(3): 906–915. https://doi.org/10.1603/EC11434

## Supplementary material 1

### Testing a trapping protocol for generic surveillance of wood-boring beetles in heterogeneous landscapes

Authors: Giacomo Santoiemma, Andrea Battisti, Claudine Courtin, Gianfranco Curletti, Massimo Faccoli, Nina Feddern, Joseph A. Francese, Emily K. L. Franzen, Filippo Giannone, Martin M. Gossner, Chantelle Kostanowicz, Matteo Marchioro, Davide Nardi, Ann M. Ray, Alain Roques, Jon Sweeney, Kate Van Rooyen, Vincent Webster, Davide Rassati

Data type: docx



Link: https://doi.org/10.3897/neobiota.95.129483.suppl1