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ORIGINAL PAPER

Evaluation of sampling methods for characterisation of post-fire beetle assemblages

Markus Franzén[1,2] · Anders Forsman[2] · Olof Persson[3]

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Abstract

This study evaluates five sampling methods for characterising saproxylic beetle assemblages in a recently burned (18–21 June 2021) boreal forest in southeastern Sweden. We compared species richness and community composition in samples collected using trunk traps, flight-intercept traps, pheromone traps, Malaise traps, and manual searches, deployed in the Finsjöbrännan nature reserve between 2022 and 2024. A total of 2258 beetle specimens were collected, representing 559 species, including 36 red-listed taxa. Flight-intercept traps yielded the highest species richness (331 species) and abundance, while trunk traps were most effective at detecting red-listed species (13.4% of species captured by trunk traps were red-listed). Coverage-based rarefaction indicated that deploying trunk and flight-intercept traps together could detect approximately 89% of the beetle species (by extrapolated richness); however, this two-method combination necessarily spans different succession stages. Notably, 61.1% of the red-listed species were captured exclusively by a single trap type, underscoring the complementary nature of different sampling approaches. Although non-overlapping sampling years may have confounded the comparisons between trap types, these results suggested that methodological choices, combined with temporal factors, may strongly influence biodiversity assessments in post-fire habitats. We provide evidence-based recommendations for effective sampling protocols, emphasising the need for multi-method approaches and temporal consistency in conservation-focused monitoring. Implications for insect conservation: Post-fire forests represent critical habitats for numerous saproxylic beetles, including many species of conservation concern that depend on recently burned wood. Our results demonstrate that no single sampling method adequately captures the full diversity of post-fire beetle assemblages, as red-listed species often occur exclusively in one type of trap. Therefore, conservation monitoring and biodiversity inventories in burned forests should employ a combination of complementary methods—particularly flight-intercept and trunk traps—to maximise species detection. Standardising temporal deployment and ensuring sampling continuity across years are essential for reliable comparisons among fires and regions. Incorporating such multi-method protocols into long-term monitoring will strengthen assessments of post-disturbance recovery and support evidence-based management of fire-dependent insect communities.

Keywords Biodiversity assessment · Coleoptera · Conservation monitoring · Fire ecology · Sampling efficiency · Saproxylic insects · Red-listed species · Post-fire succession

Introduction

Boreal forests are strongly influenced by wildfires, which play a pivotal role in maintaining ecological processes and habitat heterogeneity (Seidl et al. 2020; de Groot et al. 2013; Flannigan et al. 2009). As climate change intensifies the frequency and severity of fires, reliable biodiversity monitoring becomes increasingly crucial for conservation planning and adaptive management (Kelly et al. 2020). Wildfire has long been a natural disturbance in boreal ecosystems (indeed, many boreal species are fire-adapted) (Bond and

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✉ Markus Franzén
markus.franzen@liu.se

[1] Department of Physics, Chemistry and Biology (IFM), Linköping University, SE-581 83 Linköping, Sweden

[2] Department of Biology and Environmental Science, Centre for Ecology and Evolution in Microbial Model Systems (EEMiS), Linnaeus University, SE-391 82 Kalmar, Sweden

[3] Kvarnlyckan 114, 388 94 Vassmolösa, Sweden

Keeley 2005; Zumr et al. 2025), but modern climate change and fire-suppression efforts are changing fire regimes in unprecedented ways (Kelly et al. 2020). Post-fire environments, though disturbed, can offer critical refugia for rare and threatened taxa, particularly saproxylic beetles that rely on dead or decaying wood (Bond and Keeley 2005; Ray et al. 2019). These beetles underpin key ecological functions, including decomposition, nutrient cycling, and the maintenance of trophic interactions (Hébert 2023). Despite their ecological importance, effectively sampling beetle diversity in post-fire habitats poses methodological challenges.

Different sampling techniques tend to target distinct components of the beetle fauna and often produce divergent snapshots of community composition (Pryke and Samways 2012; New 2014). This can compromise the reproducibility of research findings and complicate comparisons of biodiversity assessments between sites, as well as comparisons of temporal shifts in biodiversity within sites. For example, flight-intercept traps primarily capture dispersing beetles (Økland et al. 1996), trunk traps collect species moving along tree trunks (Sverdrup-Thygeson et al. 2010), pheromone-baited traps specialise in attracting specific taxonomic or functional groups (Rassati et al. 2021), and Malaise traps broadly sample a range of flying insects (including many beetles) (Uhler et al. 2022). Many studies rely on a single sampling approach, potentially missing key taxa (Cardoso 2009; Hyvärinen et al. 2006). This limitation is particularly problematic for conservation assessments, as threatened saproxylic beetles with narrow habitat requirements may go undetected if standard sampling does not encompass their specific niches and behaviours (Standen 2000; VanTassel et al. 2015).

Detecting red-listed (threatened) saproxylic beetles is a special challenge given their low densities and specialised habitat needs (Jonsell et al. 2004; Seibold et al. 2015). Identifying which sampling methods are most effective for these conservation-priority species is essential for designing targeted monitoring programmes and guiding evidence-based management actions (Kouki et al. 2012; Heikkala et al. 2016). It is equally important to understand how sampling efficacy might vary across early post-fire succession stages, as beetle assemblages undergo rapid changes following a burn (Wikars 2002; Gutowski et al. 2020; Milberg et al. 2024). For instance, some highly pyrophilous species colonise immediately after a fire and may peak within the first year, while others arrive or persist in subsequent years as burnt wood ages (Wikars 2002; Hjältén et al. 2012).

Comparative evaluations of sampling techniques are thus critical for developing standardised protocols that yield accurate depictions of beetle diversity in post-fire settings. Such evaluations can reveal whether different traps provide complementary vs. redundant information, help optimise the use of limited monitoring resources, and enhance the detection of priority taxa (Hale and Swearer 2016). This work is increasingly urgent in light of novel fire regimes that alter species–habitat relationships and community assembly (McLauchlan et al. 2020; Coop et al. 2020). However, logistical constraints often necessitate deploying different methods across different time periods, which requires careful consideration of how temporal factors may influence apparent method performance.

Here, we compare five common sampling methods—trunk traps (TT), flight-intercept traps (FIT), pheromone traps (PT), Malaise traps (MT), and manual searching—to characterise saproxylic beetle assemblages in a recently burned boreal forest in southeastern Sweden. Due to practical constraints, different trap types were deployed in different years, meaning that each method's sample represents a unique post-fire successional stage. Evidence from boreal burns indicates that total beetle richness changes only modestly (approximately 5–15%) between years 2–3 and 3–4 post-fire, while dead-wood and fungal resources—and associated saproxylic assemblages—remain comparatively stable across these early years (Wikars 2002; Hjältén et al. 2012). In contrast, resources for foliage-feeding herbivores fluctuate rapidly with regrowth (Hjältén et al. 2012). We therefore expect trap-type selectivity to outweigh year effects, while acknowledging that our design conflates method with succession; against this backdrop, we address the following research questions:

Method-specific assemblages: How do samples collected using trunk traps, flight-intercept traps, pheromone traps, Malaise traps and manual searching differ in terms of the species richness, abundance, and community composition of post-fire saproxylic beetles?

1. Overall diversity capture: Which trap types, or combinations thereof, most effectively capture the overall beetle diversity in recently burned forests?
2. Red-listed species detection: Do particular trap types preferentially detect rare or red-listed beetle species, and what are the implications for conservation-focused monitoring?
3. Complementarity vs. redundancy: To what extent do these different sampling methods yield complementary (non-overlapping) versus redundant assessments of the beetle assemblage?

By answering these questions, we aim to provide evidence-based recommendations for designing and implementing effective sampling strategies in post-fire habitats. We focus on maximising the detection of threatened species while judiciously using limited resources and accounting for temporal dynamics in post-fire beetle communities.

Methods

Study area and sampling design

The study was conducted in the Finsjöbrännan nature reserve (57°10′1.4″N, 16°14′18.1″E), a 200-hectare protected area established in 2024 in Kalmar County, southeastern Sweden (Fig. 1A). This reserve encompasses a forest stand that burned 18–21 June 2021 under high-intensity crown and surface fire conditions. The climate in this region is oceanic, with mean annual precipitation of ~600 mm (spread over ~120 rain days) and mean daily temperatures ranging from 0 to 2 °C in winter to 17–18 °C in summer (Alexandersson 2002). Before the fire, the overstorey was dominated by Scots pine (*Pinus sylvestris* L.), with Norway spruce (*Picea abies* L.), aspen (*Populus tremula* L.), pedunculate oak (*Quercus robur* L.), and silver birch (*Betula pendula* Roth) present at lower densities. Following the fire, early-successional regeneration was dominated by birch (*Betula pendula* and *B. pubescens* Ehrh.), with aspen, goat willow (*Salix caprea* L.), and oak also resprouting. According to the Swedish biodiversity database (Artportalen.se), the burned area supports at least 39 red-listed insect species and numerous red-listed fungi, bryophytes, lichens, birds, and vascular plants. Fire-adapted herbs (*Geranium bohemicum*, *G. lanuginosum*) emerged en masse after the burn, indicating a persistent soil seed bank. Most species occurring in the area are assumed to have colonised after the 2021 fire (Fig. 2).

To evaluate the efficacy of different sampling methods for characterising post-fire beetle assemblages, we deployed four types of insect traps—trunk traps, flight-intercept (window) traps, pheromone traps, and Malaise traps—across the burned area, supplemented by manual searching (Fig. 1). Importantly, different trap types were operated in different years post-fire due to logistical constraints, resulting in a confounding of sampling method with successional stage. Flight-intercept traps (FIT) and Malaise traps (MT) were operated in 2022 (with MTs also in 2023), corresponding to roughly 1–2 years post-fire. Trunk traps (TT) and the pheromone trap (PT) were operated in 2024, about 3 years post-fire. All traps were spaced at least 30 m apart to ensure independent sampling and to capture variation in burn severity and microhabitat conditions across the site. The sampling methods employed represent two fundamentally different approaches to beetle detection. Pheromone traps are active sampling devices that use chemical attractants to draw beetles from extensive areas (potentially several kilometres), making a single trap sufficient to sample large spatial scales. In contrast, flight-- intercept traps, Malaise traps, and trunk traps are passive sampling methods that intercept beetles during their natural movement patterns—flight-intercept and Malaise traps capture beetles in flight, whilst trunk traps intercept beetles moving along tree trunks. This

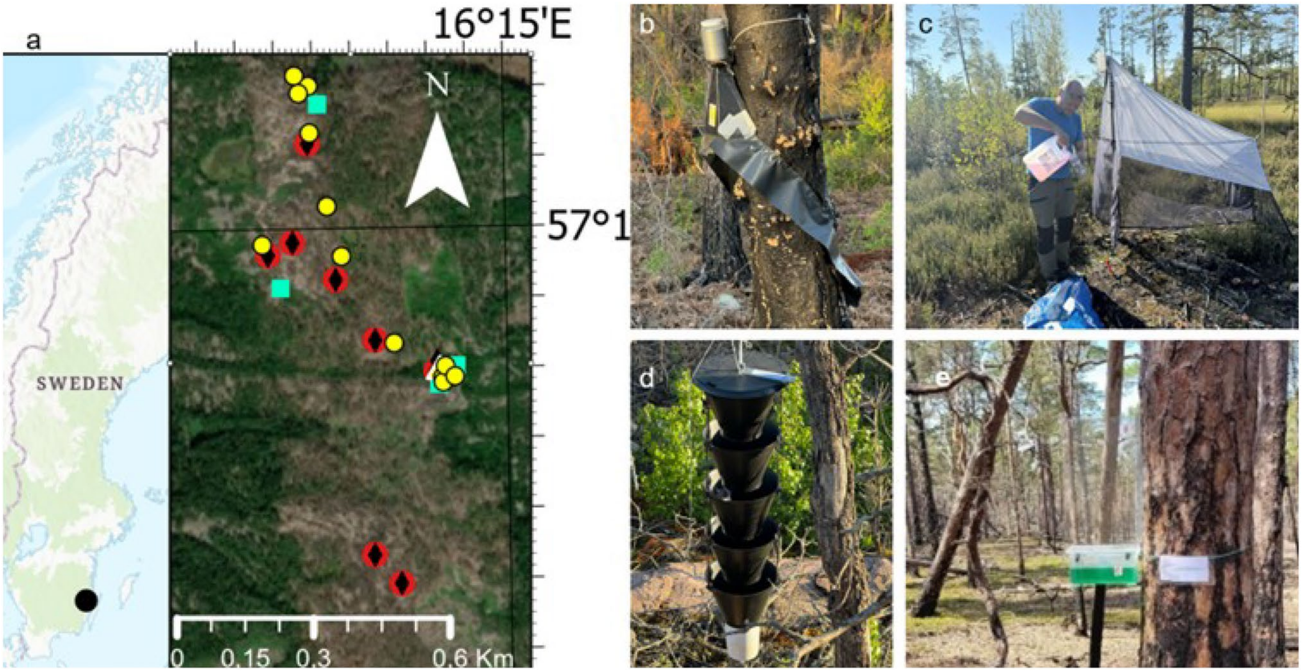

Fig. 1 Map showing the study sites in the Finsjöbrännan burned forest (southeastern Sweden). **a** Location of the study area in Sweden (inset) and aerial view of the Finsjöbrännan burn showing trap placements (blue quadrats—Malaisetrap, yellow rings with black border—trunk traps, red rings with black centroid—intercept traps, and triangle—pheromone trap, **b** A trunk trap attached to a charred pine snag. **c** A Malaise trap deployed on the burn site. **d** The multiple-funnel pheromone trap with lure. **e** A window flight-intercept trap installed in the burn. (Photographs by M. Franzén)

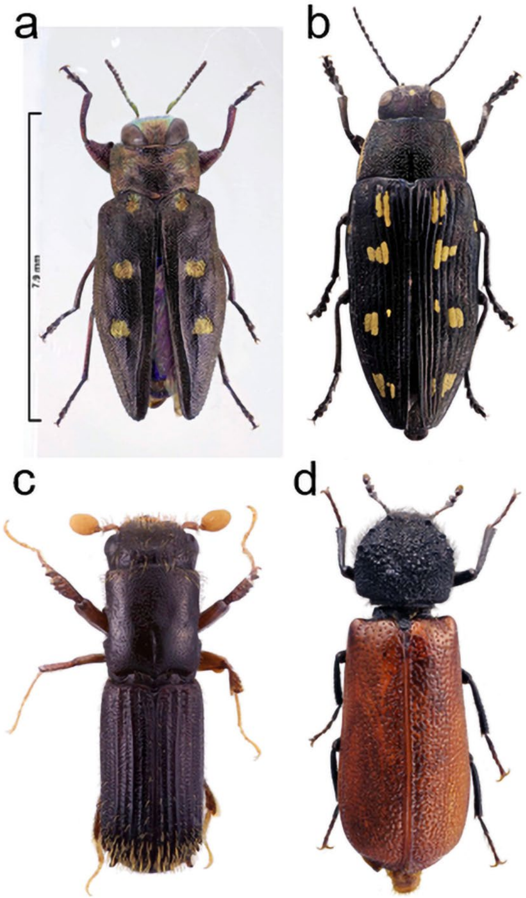

Fig. 2 Selected species detected in the burned forest. **a***Chrysobothris igniventris* (a jewel beetle new to Sweden), collected in a Malaise trap. **b***Buprestis novemmaculata* (VU), a fire-associated jewel beetle strongly tied to pines. **c***Platypus cylindrus* (RE), the oak pinhole borer, caught in flight-intercept and pheromone traps. **d***Bostrichus capucinus* (VU), a bostrichid beetle often found in hard oak wood. (All photographs by O. Persson)

distinction is critical for interpreting both species richness patterns and the spatial scale of sampling coverage.

Trunk traps (TT). Twelve trunk traps were installed at ~1.3 m above the ground on fire-killed trees (diameter at breast height≥15 cm, height≥7 m) to intercept beetles moving along the bole (Fig. 1B). Each trap consisted of a flexible 30 cm-wide polyethylene collar wrapped around the trunk and sealed tightly with neutral-cure silicone, funneling insects into a removable collection cup at the base. We deployed three trunk traps on each of four common tree species in the burn: pine (*Pinus sylvestris*), birch (*Betula pubescens*), aspen (*Populus tremula*), and oak (*Quercus robur*). Trunk traps were operated from 26 May to 1 December 2024 (189 days). Trap contents were collected on 26 May, 7 July, 16 August, 20 September, and 1 December 2024.

Flight-intercept traps (FIT). Nine flight-intercept (window) traps were set up at ~250 m intervals throughout the burned area (Fig. 1E). Each consisted of two transparent acrylic panels (30×40 cm) in a cross-frame, suspended above a metal tray (30×50 cm) filled with ~5 cm of 70% propylene glycol as a preservative (New 2014). The vertical panels intercept flying insects, which then fall into the preservative. FITs were deployed from 18 May to 15 August 2022 (89 days). Samples were collected from each trap on 18 May, 13 June, 13 July, 19 July, and 15 August 2022.

Pheromone trap (PT). We used one multi-funnel pheromone trap (five black funnels, 60 cm total height) hung ~2 m above the ground in an open, sun-exposed portion of the burn (Fig. 1D). To avoid cross-attraction, this trap was placed at least 50 m away from any other trap. It was baited with a blend of synthetic beetle pheromones targeting certain longhorn and click beetles (Rassati 2021). Specifically, we used a combination of general longhorn beetle attractants (3-hydroxy-2-hexanone, 2-methylbutan-1-ol, 3-hydroxy-2-octanone, C6 diol, fuscumol, and fuscumol acetate, plus their anti-isomers) along with a species-specific lure for the threatened click beetle *Elater ferrugineus* (Molander et al. 2019). Lure dispensers were replaced in early July to maintain efficacy. The pheromone trap was active from 27 May to 14 September 2024 (110 days), and we emptied the catch on 27 May, 7 July, 16 August, and 14 September 2024.

Malaise traps (MT). Four standard Malaise traps (tent-style flight-intercepttraps; Fig. 1C) were deployed at different locations in the burn. Each trap was 1.7 m tall and 1.8 m long, with a central mesh wall guiding flying insects upward into a collecting head containing preservative. Although Malaise traps are primarily used for flies and wasps, they also effectively capture many Coleoptera that fly into the mesh (Uhler et al. 2022). Our Malaise traps operated over two seasons: three sampling intervals in 2022 (mid-summer) and six in 2023 (spanning late winter to late summer), for a total of 165 trap-days. Specifically, samples were collected on 18 July, 19 July, and 15 August 2022, then on 26 February, 24 April, 18 June, 29 July, 23 August, and 10 December 2023.

All traps used 70% propylene glycol as a preservative, replenished as needed. Insects were retrieved from traps using fine strainers, then transferred to labelled vials and stored in 70% ethanol at 4 °C until identification. The total passive trapping effort was 2,268 trap-days for trunk traps (12 traps × 189 days), 801 trap-days for flight-intercept traps (9×89 days), 110 trap-days for the pheromone trap (1×110 days), and 660 trap-days for Malaise traps (4×165 days).

Manual searching. We complemented passive trapping with periodic manual searches to find additional species that traps might miss. On each trap-servicing visit, a team of five experienced coleopterists spent 3–4 h searching the burn site. Search methods included (i) inspecting under loose bark, in charred stumps, and within log hollows for larvae or adults, (ii) beating or sweeping low vegetation and dead branches over a white sheet, and (iii) hand-collecting beetles found by overturning debris or spotlighting at dusk. Any specimens encountered were captured using aspirators or forceps and placed in vials of ethanol. Manual searches were conducted on the same five dates per year as trap collections (coinciding with peak beetle activity periods in each season).

All beetles were identified to species by the authors (primarily O.P.), using available keys and comparison with reference collections. Nomenclature and red-list status follow the Swedish Red List 2020 (Eide et al. 2020) and the IUCN European Red List of Saproxylic Beetles (Nieto and Alexander 2010). Voucher specimens of notable or difficult taxa (especially red-listed species) were preserved in O.P.'s collection for future reference.

Data analysis

All statistical analyses were performed in R 4.4.3 (R Core Team 2024). We treated each trap type as a separate sample set. Our analyses focused on comparing these method–year combinations in terms of species richness, community composition, and capture of red-listed species. We did *not* pool data across years for formal statistical tests because the design was not orthogonal (each method corresponds to a unique year post-fire). Instead, we adopted a multi-faceted, primarily descriptive approach:

1. Species richness and rarefaction: We used the iNEXT package (v3.0.1) (Hsieh et al. 2024) to compute sample-size-based rarefaction and extrapolation curves for species richness for each method. To compare richness on an equal footing, we standardised sample coverage to 95%. We report the observed species counts and the asymptotic richness estimates (Chao) with 95% bootstrap confidence intervals for each method. We considered differences in richness between samples to be significant if their 95% CIs did not overlap.
2. Community overlap and ordination: We quantified the overlap in species composition between each pair of methods using the Sørensen similarity index. Sørensen similarity (qualitative Sørensen-Dice) is defined as:

$$S = \frac{2\,|A \cap B|}{|A| + |B|},$$

where A and B are the species sets captured by two trap types; |A ∩ B| is the number of shared species; and |A| and |B| are the total species counts for each trap type. We converted similarity to dissimilarity ($1 - S$) and performed a hierarchical cluster analysis (average linkage) to see how the method samples grouped by community similarity. We also conducted a non-metric multidimensional scaling (NMDS) ordination (using *metaMDS* in the vegan package) based on Sørensen distance to visualise differences in species composition. Points in the NMDS were labelled by trap type to examine how distinct each method–year assemblage was. We generated a Venn diagram to illustrate the number of species unique to or shared among the four trapping methods, using the VennDiagram package.

3. Red-listed species yield: For each method, we tallied the number of red-listed species captured and calculated the proportion of that method's species pool that were red-listed. We also computed the average number of red-listed species detected *per sampling event* (per trap per collection day, or per person-day for manual searching). This provides a simple index of how efficiently each method finds conservation-relevant species. For context, we compared these yields to the overall species richness per event. Because of the confounded design, we did not perform formal hypothesis tests on these values; instead, we present them with approximate 95% CIs obtained by bootstrapping the capture data 1,000 times.

We reiterate that because each trap type was used in a different year post-fire, we cannot statistically separate "method effects" from "year (successional) " effects. Any observed differences between trap samples may reflect, in part, true changes in the beetle community between 1–2 years vs. 3 years after fire, in addition to differences caused by the trap method itself.

Results

Overall beetle diversity

Across all four trapping methods and years, we collected 2,258 beetle specimens representing 559 species. This total includes 36 red-listed species: 23 Near Threatened (NT), 12 Vulnerable (VU), and 1 Regionally Extinct (RE). These conservation-priority taxa made up about 7.0% of the of trap-caught species , highlighting the high conservation value of the post-fire habitat. Different trap types were deployed in different post-fire years (2022–2024), so method-specific results are inherently confounded with successional stage.

Table 1 Summary statistics for beetle sampling by four trap types in a post-fire boreal forest

Method	Total individuals	Total species	Sampling events	Specimens per species	Red-listed species	Percentage red-listed	Unique species	Percentage unique
Flight-intercept trap	1,176	331	32	3.55	23	6.9	169	51.1
Malaise trap	580	232	14	2.50	7	3.0	107	46.1
Pheromone trap	181	123	4	1.47	11	8.9	30	24.4
Trunk trap	321	97	46	3.31	13	13.4	21	21.6
Total	2,258	515	96	4.38	36	7.0	327	63.5

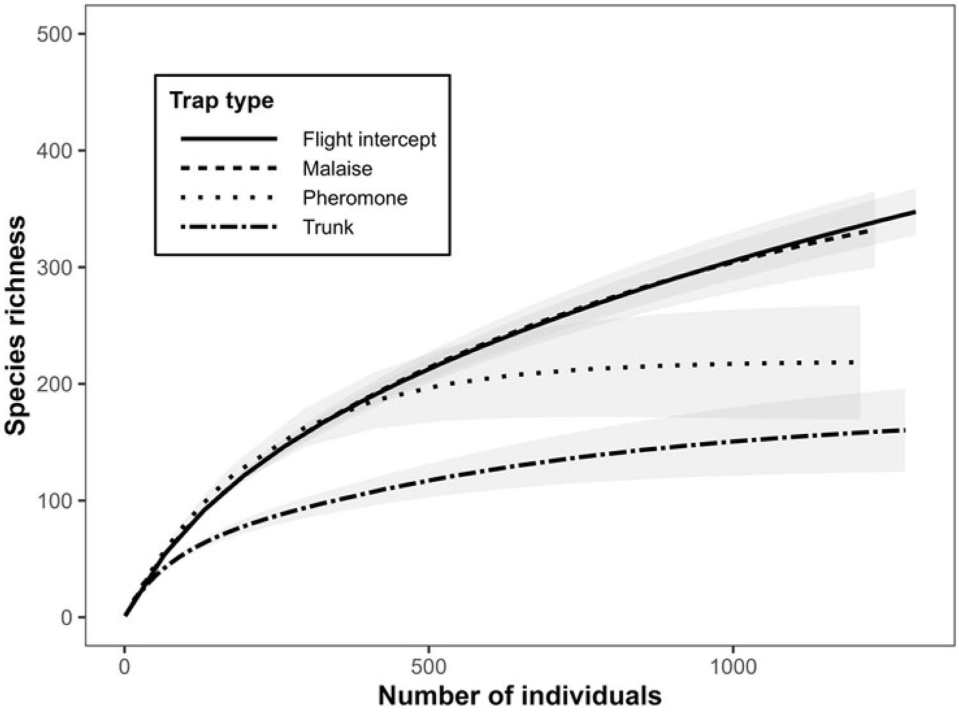

Fig. 3 Sample-based rarefaction (solid lines) and extrapolation (dashed lines) curves for saproxylic beetle species captured by each method. The x-axis is number of individual beetles sampled, and the y-axis is the estimated species richness. Shaded bands represent 95% confidence intervals. Curves are standardized to 95% sample coverage. A solid symbol marks the observed richness for each sample

Trap-specific patterns: richness and abundance

We observed marked differences in beetle catches among the four trapping methods, although it is important to remember these reflect both methodological and temporal variation (Table 1). Flight-intercept traps (2022) yielded the highest species count (331 species) and the greatest number of individuals (1,176 specimens, 52.1% of all individuals collected). Malaise traps (2022–2023) ranked second in species richness with 232 species (580 individuals, 25.7% of total specimens). The pheromone trap (2024) recorded 123 species (181 individuals; 8.0% of specimens), and trunk traps (2024) recorded 97 species (321 individuals; 14.2%).

Sample completeness varied by method. Trunk traps achieved the highest sample coverage (~86% of its estimated species pool), indicating that most species frequenting charred trunks in 2024 were captured. Flight-intercept trap samples were ~67% complete, while the pheromone trap and Malaise traps each reached about 55–56% of their asymptotic richness (despite the pheromone trap's lower species count, the estimator suggests many species attracted by the lures were captured). Rarefaction/extrapolation curves (Fig. 3) showed distinct diversity patterns for each method-year combination. When standardised to 95% sample coverage, flight-intercept traps were projected to have the highest asymptotic richness (~492 species; 95% CI: 419–565), followed by Malaise traps (~382 species; 95% CI: 323–440). The pheromone trap was projected to reach ~208 species (95% CI: 160–257) and trunk traps ~146 species (95% CI: 98–195). In other words, if sampling effort were increased to the point of ~95% completeness for each, the rank order of richness would remain FIT > MT > PT > TT.

Although trunk traps collected the fewest species overall, their steep initial species-accumulation curve (Fig. 3, yellow line) indicates efficient sampling of the available fauna within their deployment period. This reflects the targeted nature of trunk traps: they quickly captured many of the beetles active on burnt trunks in 2024, with relatively fewer new species appearing with additional effort. Manual

Table 2 Sørensen similarity indices between beetle assemblages captured by different trap types

Trap type comparison	Sørensen similarity index	Shared species	Total unique species
Fligh-intercept—Malaise	0.37	104	459
Pheromone—Flight-intercept	0.36	82	372
Malaise—Pheromone	0.31	55	300
Trunk—Pheromone	0.29	32	188
Trunk—Malaise	0.28	46	283
Trunk—Flight-intercept	0.26	56	372

searching contributed an additional set of species beyond what passive traps caught. In total, manual searches yielded 44 species (approximately 8.5% of the total fauna) that were *not* captured by any of the passive traps. These included several rare or cryptic beetles (e.g. in Buprestidae and Curculionidae) that likely escaped detection by the stationary traps.

Trap complementarity and overlap

The species composition captured by each method–year sample differed substantially. Pairwise Sørensen similarity indices between trap types were all low, ranging from 0.26 to 0.37 (Table 2). The lowest similarity was between trunk traps (2024) and flight-intercept traps (2022) (*S*=0.26), and the highest was between flight-intercept and Malaise traps (*S*=0.37). These values indicate that any two methods shared only about 26–37% of their species, underlining the high turnover between samples.

Venn diagram analysis further highlighted the limited overlap among methods (Fig. 4A). Out of 515 total species found in the four trapping methods, only 19 species (3.7%) were collected by all four sampling methods. In contrast, 327 species (63.5% of the total) were captured by only one method. Flight-intercept traps yielded the greatest number of unique species (169 species found exclusively by FIT and not by any other method), reflecting their broad catch of aerially dispersing beetles. Malaise traps contributed 107 unique species, the pheromone trap 30 unique species, and trunk traps 21 unique species. Thus, each method–year sample brought in a substantial portion of species not detected by other approaches.

This complementarity was even more pronounced for red-listed species (Fig. 4B). Only one threatened species, *Xylotrechus antilope* (NT; a longhorn beetle), was caught by all four methods. Notably, 22 of the 36 red-listed species (61.1%) were *exclusive* to a single method's sample. For example, several rare weevils and bark beetles were only found in trunk traps, and certain threatened longhorn and click beetles were only attracted to the pheromone lure. Clearly, each method had a unique strength in capturing particular red-listed taxa.

Detection of conservation-priority species

Flight-intercept traps recorded the highest absolute number of red-listed beetles (23 species; 63.9% of the total), whereas trunk traps detected the highest proportion of red-listed species relative to their overall yield (13.4%; Table 1). *Platypus cylindrus* (RE) (Fig. 2) and *Elater ferrugineus* (VU) was detected by both pheromone and flight-intercept traps. Other threatened taxa exhibited similar method-specific

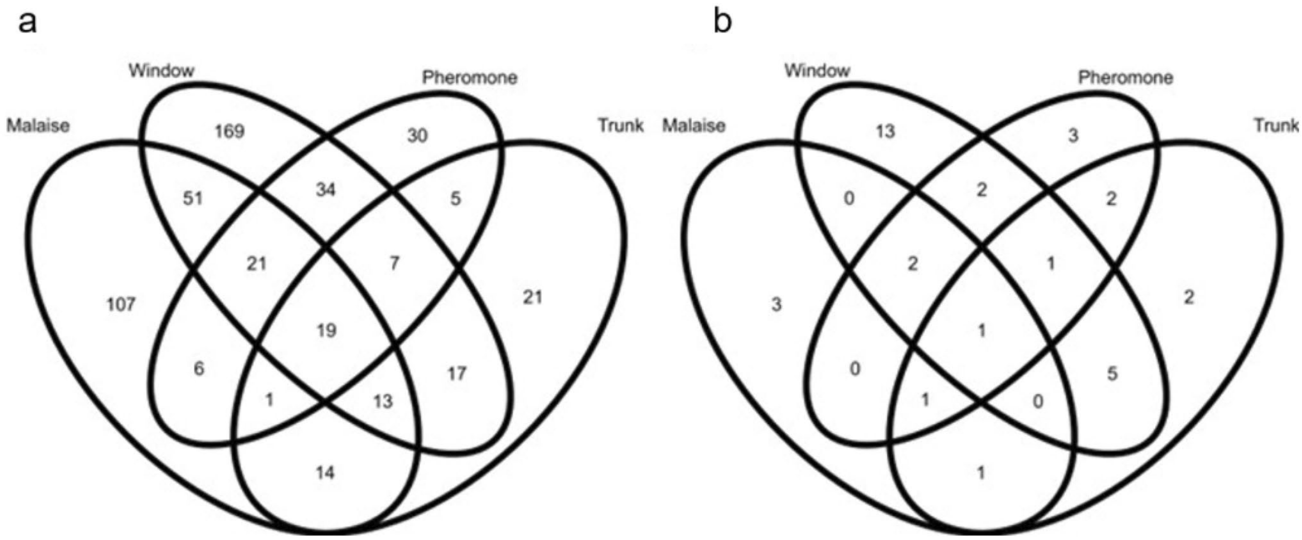

Fig. 4 Overlap in beetle species among the four trapping methods. **a** Venn diagram for all 515 species found in the four trap types. **b** Venn diagram for the 36 red-listed species. Numbers indicate how many species were unique to a given method (in each single-method circle segment) or shared by the methods represented by overlapping segments. Each method's circle is labelled with its trap type and year

Table 3 Sampling efficiency metrics for different trap types in post-fire beetle community assessment

Method	Individuals per sampling event	Species per sampling event	Red-listed species per sampling event
Flight-intercept trap	36.8	10.3	0.72
Malaise trap	41.4	16.6	0.50
Pheromone trap	45.3	30.8	2.75
Trunk trap	7.0	2.1	0.28

patterns, for example, *Dircaea australis* (VU) occurred only in trunk traps, and *Buprestis novemmaculata* (VU) (Fig. 2) was exclusive to flight-intercept traps.

Coverage-based analyses indicated that flight-intercept plus trunk traps detected 30 of 36 red-listed species (83.3%). Adding pheromone traps increased that figure to 34 (94.4%), leaving the remaining two requiring Malaise traps. Hence, different methods excelled at detecting particular threatened species, favouring a multi-method approach for capturing the full range of red-listed taxa in post-fire habitats.

Sampling efficiency and optimal combinations

Flight-intercept traps had the highest capture rates with 36.8 individuals and 10.3 species per sampling event (Table 3), followed by Malaise traps (41.4 individuals and 16.6 species per event). Although pheromone traps recorded fewer species overall, they demonstrated a high detection rate for red-listed taxa (2.75 conservation-priority species per sampling event vs. 0.72 for fligt--intercept traps).

Coverage-based accumulation curves of trap combinations revealed that flight-intercept and trunk traps together reached 89.3% of estimated total species richness (417 species) while requiring only ~ 40% of the total sampling effort. This combination detected 30 red-listed species. Adding pheromone traps increased coverage to 94.1% (438 species), capturing 34 red-listed taxa. Employing all four methods pushed coverage to 96.7% but required more than twice the effort of the two-method combination.

Discussion

Our study provides insights into the comparative effectiveness of various sampling methods for post-fire saproxylic beetles, while also underscoring a critical limitation: the confounding of sampling method with year. Because different methods were used in different years after the fire, we cannot conclusively attribute differences in catches to the trap method alone. Literature suggests that beetle richness in boreal burns might change by roughly 5–15% between the second/third and the third/fourth year post-fire (Wikars 2002). In the first few years after a burn, dead-wood resources and associated beetle communities can remain relatively stable – the main pulse of herbaceous vegetation and deciduous regrowth (which could spur insect population explosions) typically occurs a bit later (Hjältén et al. 2012). In other words, the essential saproxylic habitat (charred wood colonised by fungi) is fairly constant across these early years, unlike the rapidly changing food resources for leaf herbivores (Wikars 2002; Hjältén et al. 2012). Thus, it is plausible that many of the differences we observed were driven more by methodological biases than by successional turnover (Lindenmayer et al. 2019). Even so, our results must be interpreted as reflecting the combined effects of sampling method and successional timing, rather than pure method performance. Despite these limitations, two main conclusions emerge. First, multiple trap types are required to capture the full breadth of post-fire beetle diversity. Each sampling method contributed a distinct assemblage, with relatively low overlap in species. Second, careful selection of complementary methods can greatly enhance biodiversity detection (including red-listed species) while optimising effort. Below, we discuss each method's contributions and consider implications for survey design and conservation.

Trap performance and beetle guild specificity

Each trapping method sampled a unique subset of the beetle community, reflecting differences in both trap selectivity and beetle behavior. Flight-intercept traps intercepted a broad spectrum of flying beetles and, not surprisingly, yielded the highest overall species richness and abundance. This method was especially effective for groups that disperse widely through the habitat, such as longhorn beetles (Cerambycidae), checkered beetles (Cleridae), and many rove beetles (Staphylinidae). Trunk traps, in contrast, collected fewer species overall but were disproportionately effective at capturing certain rare, saproxylic specialists. Over 13% of species in trunk traps were red-listed, indicating that these traps target the conservation-important fauna inhabiting charred trunks. For instance, we caught *Xylotrechus antilope* in our oak trunk traps, consistent with its preference for oak wood rather than any special fire affinity. Malaise traps contributed substantially to total species richness by sampling many small or fast-flying beetles that might evade other traps – including various Latridiidae, Cryptophagidae, and minute Staphylinidae. However, Malaise traps detected relatively few red-listed species; their broad catch is less focused on the large, wood-dependent beetles that tend to be of conservation concern. Finally, the pheromone trap had the lowest total catch, but it excelled at targeting specific elusive taxa. It efficiently attracted certain longhorn and click beetles that were otherwise rarely encountered, such as *Elater ferrugineus* (VU), an elusive click beetle associated with old hollow trees, which would likely have gone undetected without pheromone lures. In fact, the pheromone trap yielded the highest number of red-listed species per trap of any method, demonstrating the value of chemical lures for boosting detection of target species (Harvey et al. 2017; Kadej et al. 2015).

The existence of so many threatened species in our samples (36 in total) highlights the significant conservation value of recently burned forests. High-intensity fire events create habitat conditions (e.g. abundant sun-exposed dead wood, reduced competition, fresh fungal substrates) that favor a suite of rare organisms (Kelly et al. 2020). However, our results show that *how* one samples such habitats will strongly influence which of those organisms are recorded. Each method had biases: flight-intercept traps tended to catch incoming dispersers, trunk traps caught those dwelling on burned trees, Malaise traps picked up many incidental fliers, and pheromones zeroed in on particular taxa. It is notable that 22 of our 36 red-listed species were each captured by only one method. If a survey had omitted any one of these methods, it would have likely missed multiple threatened species. Thus, for a thorough evaluation of post-fire sites (e.g. for conservation or restoration decisions), using a combination of methods is essential.

Manual searching as a complementary approach

Manual searching proved to be a useful complement to passive trapping, adding 44 species that were not caught in any trap. By actively targeting microhabitats – peeling bark, checking wood crevices, and examining scorched logs – human collectors can find cryptic, non-attracted beetles that traps might miss (Siitonen 1994). For example, our team manually discovered several jewel beetles and weevils hidden under bark that never appeared in the traps. That said, manual collecting is labor-intensive and inherently less standardised than trapping. The yield of manual searches can vary widely with the effort, time of day, weather, and individual skill. In our case, manual searches were limited to about five person-days per year, which is a fairly small effort compared to the thousands of trap-days logged by passive methods. Thus, while manual searching can boost species tallies (and is especially valuable for detecting certain rare species), it is not a stand-alone solution for large-scale monitoring. We recommend using it as a supplementary strategy – for instance, to target specific habitats or taxa that traps are known to under-sample – rather than as a primary survey method.

Sampling efficiency and optimal method combinations

Our results demonstrate that combining different sampling methods yields a much more complete picture of the beetle community than any single method alone. In fact, the assemblages captured by each method were so distinct that one could almost treat each as a separate “window” into the post-fire ecosystem. The combination of flight-intercept and trunk traps emerged as particularly powerful: together, these two methods (even though deployed in different years for us) would have captured about 90% of all species we detected, and the majority of red-listed ones. These two methods complement each other well. Flight-intercept traps sample broadly among flying beetles, casting a wide net that includes both common and vagile species as well as some rarities that happen to disperse through (Lamarre et al. 2012). Trunk traps, on the other hand, focus on the beetles that are actively using the burned trees – many of which are saproxylic specialists of conservation interest. Adding a pheromone trap to this mix further boosts the likelihood of detecting certain target species (notably large click beetles and some longhorns) that neither flight nor trunk traps are likely to catch. In practical terms, a resource-limited monitoring program could prioritize deploying several flight-intercept traps and trunk traps to cover the broad diversity and specialist fauna, and include one or two pheromone traps if particular high-priority species are expected. This multi-method strategy would yield a far more comprehensive inventory than relying on any single method (Parmain et al. 2013), yet it would still be more efficient than trying to deploy every possible method.

Our findings align with those of other researchers who have examined insect sampling methodologies. For example, Bouget et al. (2008) showed that even subtle differences in trap design can influence the catch: single-panel window traps caught significantly more saproxylic beetles than cross-vane traps, and traps placed in the understory captured more species than those in the canopy (Sbaraglia et al. 2025). These results highlight that combining trap types (and placement heights) can increase total yields. Similarly, a study by Parmain et al. (2013) found that increasing sampling effort – whether by adding a second trap of the same type or sampling across additional years – markedly improved the detection of saproxylic beetle diversity. In their work, adding a second window trap or a second year of sampling increased the number of species detected by 50–75%, and a multi-year survey captured an assemblage that was only ~ 50% overlapping with a single-year survey (Nageleisen and Bouget 2009; Bouget et al. 2008). These insights echo our results: rigorous post-fire beetle monitoring should employ standardised multi-method, multi-occasion sampling to reliably capture species richness and community composition. The gains in information from such an approach far outweigh the additional effort or cost.

Methodological considerations for post-fire environments

The low overlap in species among our trap samples (only 3.7% of species were common to all four methods) suggests that post-fire beetle communities exhibit a high degree of niche partitioning and asynchronous colonisation. The intense resource pulse and open conditions after a wildfire attract specialists from various guilds, each exploiting different niches (Saint-Germain et al. 2004). For instance, some beetles are drawn immediately to heat and smoke (e.g. certain *Melanophila* jewel beetles), while others arrive later to breed in decaying wood (Wikars 2002). Very few species were missing from the catches; one potential species that we did not find is the "fire beetle" *Euracmaeops marginatus* (EN), which is very rare in Sweden. Notably, the black multi-funnel traps baited with ethanol/pheromone lures are very effective for many bark beetles and longhorn beetles. Still, they tend to capture few Buprestidae (jewel beetles) (Thurston et al. 2022). We also observed a large bycatch of non-target insects in the pheromone traps, likely due to the broad-spectrum attractants and trap design – the traps mimic standing tree trunks and the ethanol-based preservative or pheromone odors draw in many other saproxylic insects and even predatory species (Miller and Crowe 2011; Miller and Duerr 2008). This heavy bycatch underscores that our traps were not specific to fire-specialists and could have contributed to certain expected species being missed. In the future, more research on trap design and lure specificity (e.g. trap colour, height, and alternative attractants) is needed to reduce non-target catches and improve detection of low-abundance fire-adapted beetles (Bonifácio and Sousa 2025).

Sampling designs for post-fire insects should incorporate multiple methods across multiple time frames to account for the diverse ecological strategies of saproxylic beetles. A one-size-fits-all approach—using just one trap type, or sampling only in one particular year post-fire—will almost certainly yield an incomplete and possibly misleading picture. It is also worth noting that methodological consistency is crucial when comparing results across studies or monitoring programs. Small differences in how traps are set up or when they are deployed can affect catches (Sbaraglia et al. 2025). For example, trap colour, panel size, or height can each bias the sample toward certain taxa (Bouget et al. 2008). In the context of post-fire monitoring, researchers should carefully document trap configurations and deployment periods, and ideally implement concurrent sampling (using the same methods at the same time) when comparing multiple areas or treatments.

Conservation and management implications

Our results have direct implications for biodiversity conservation in fire-affected forests. First, we have shown that multi-method surveys are necessary to accurately assess the conservation value of a burned site. A single-method survey would have missed a substantial fraction of the fauna, including many red-listed species, potentially underestimating the site's importance. Land managers and conservation biologists should therefore employ a combination of trapping methods to ensure that management decisions (such as whether to protect a burn site from salvage logging) are based on comprehensive data. The high complementarity among methods means that each additional method can reveal new species that fundamentally change our understanding of the site's biodiversity.

Second, our finding that 61% of the threatened species were each detected by only one method means that survey methodology could bias conservation outcomes. For example, trunk traps highlighted the presence of several rare saproxylic beetles that specifically require fire-killed trees (some of which were overlooked by flight or Malaise traps). This underscores the ecological importance of retaining standing burnt trees of various species after a wildfire. Managers should take note that heterogeneity in tree species and decay stages is key to conserving saproxylic beetle diversity.

Third, we propose a tiered monitoring strategy for post-fire beetle assemblages: (1) use flight-intercept traps to broadly sample the flying insect community (covering a wide taxonomic range and many dispersing species); (2) deploy trunk traps on a variety of burned trees to target the wood-inhabiting specialists, including many threatened species; and (3) include pheromone traps if particular high-priority beetles are of interest (for instance, if historical records or habitat suggests the presence of certain endangered longhorn or click beetles, use their lures). In addition, incorporating a modest amount of manual searching can help detect extremely cryptic species that might slip past passive traps. This multi-faceted approach balances thoroughness with efficiency. It is more effective than any single-method survey, yet avoids the diminishing returns (and high labor) of trying to use all possible methods everywhere. Such an approach can be implemented in adaptive monitoring programs where initial surveys identify which methods yield the most new information for a given site, allowing efforts to be focused accordingly in subsequent surveys (Ranius and Jansson 2002).

Finally, as climate change alters wildfire regimes and more forests experience severe fires, having robust monitoring protocols in place will be increasingly important. Our work suggests that standardised, multi-method sampling can serve as an "early detection system" for post-fire biodiversity responses. By routinely applying these methods after fires, conservationists can quickly identify burns that harbor rare species or exceptionally high diversity, and prioritize them for protection or further study. Conversely, areas that show depauperate fauna might be candidates for restoration actions (like creating habitat structures or translocating wood substrates). In essence, effective monitoring is the first step toward evidence-based management of fire-prone landscapes under climate change.

Future research directions

Our study highlights several avenues for further research to improve post-fire insect monitoring:

1. Concurrent multi-method sampling: Future studies should deploy multiple trap types *in the same post-fire year and location* to directly quantify methodological biases without confounding by succession. This would allow statistical separation of method effects from year effects, and test whether the patterns we observed (e.g. FIT catching more species than TT) hold when traps operate simultaneously.
2. Longer-term chronosequence sampling: Extending comparative sampling across a post-fire chronosequence (e.g. 1, 3, 5, 10 years after fire) would clarify how each method's efficacy changes as the burned habitat evolves. For instance, trunk traps might be most productive in the first few years while bark remains intact on snags, whereas later on, emergence traps on downed logs might capture more new species.
3. Quantitative manual survey methods: Investigating standardized manual search protocols (such as fixed-time searches or transect-based searches) could help evaluate the effort-to-yield ratio of active searching versus trapping. This would refine the role of manual surveys in long-term monitoring and determine how much added value they provide for detecting rare species.
4. Effects of fire severity and scale: It would be insightful to test these sampling methods under different fire conditions (e.g. low-intensity prescribed burns vs. high-intensity wildfires, small burns vs. mega-fires). Beetle communities can respond differently to fire severity (Doherty et al. 2022), and certain traps might perform better or worse depending on habitat structure. Understanding these interactions could guide method selection for various post-fire scenarios.
5. Emerging technologies: New techniques such as collecting environmental DNA (eDNA) from soot, or using automated flight-intercept traps with image recognition, hold promise for surveying insect diversity (Van Klink et al. 2022). Research should explore how these technologies can complement traditional traps. For example, could eDNA detect presence of species that are otherwise missed, or could machine-learning trap cameras identify nocturnal beetles that avoid day-active collectors? Integrating such tools may greatly enhance the accuracy and efficiency of saproxylic beetle inventories in the future.

Conclusions

Our comparative assessment—while limited by temporal confounding—illustrates that each sampling method captures a distinct component of the post-fire beetle assemblage. Flight-intercept traps provided broad coverage of dispersing beetles, trunk traps disproportionately detected red-listed saproxylic specialists on burnt wood, Malaise traps augmented overall species counts by collecting many small fliers, and pheromone traps efficiently targeted certain elusive threatened species. Using these methods in combination enabled us to approach a nearly complete inventory of the beetle community with substantially less effort than would be required if each method were used in isolation. As wildfire activity and its ecological impacts increase under climate change, deploying efficient multi-method sampling protocols—with careful attention to timing and standardisation—will be crucial for evidence-based conservation and adaptive management in fire-affected forests.

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Data availability Data are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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