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Comparison of flight interception traps in beetle sampling: Effects of design and material

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Abstract

Field studies of insects often involve insect trapping, and this is also the case when studying flying forest beetle communities. To sample this hyper-diverse taxon in sufficient detail is time consuming and demanding. Therefore, using effective traps is crucial.

In previous research, commonly used trap designs vary in size, shape, and construction material. A couple of recent studies has indicated large differences in trapping performance between trap designs, clearly impacting the sampling results. Comparing studies that use different trap types is therefore difficult. Still, research that compares the effect of different trap designs and materials on insect capture is surprisingly scarce, and the underlying reasons for these differences have been explored to a limited extent.

Given the need to understand the qualities of different designs, and work towards standardized trap designs, this study provides a systematic comparison of commonly used trap types in beetle sampling. My aim was to determine the impact of various trap designs and materials on beetle sampling performance in terms of abundance and species richness. In total, six trap types were compared during this study. Three trap designs: triangular single-pane, rectangular single-pane, and cross-pane, all made in two different commonly used transparent materials: polyethylene and polycarbonate. I deployed a total of 90 traps (15 of each type) during 8 weeks in a mixed deciduous forest in southeastern Norway.

The results show that the triangular trap in polyethylene clearly outperformed all the other trap types, when it comes to both abundance and species richness. In general, the traps made in polyethylene had higher catch rates than traps made with polycarbonate. However, the effect of material depended on the trap design: Triangular and cross-pane traps in polyethylene outperformed those made from polycarbonate, but there was no difference between the two materials for rectangular single-pane traps.

My results show that flight interception traps vary strongly in capture efficiency and demonstrates the need for taking trapping method into account when comparing studies. My findings further highlight the need for optimized and standardized sampling methods for flying forest beetles.

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1. Introduction

Beetles are a highly diverse group of insects, accounting for about 21 percent of all described arthropod species globally (Stork, 2018). They contribute to a variety of ecosystem functions, including services related to nutrient cycling, wood decomposition, seed and spore dispersal, pest control, and pollination (Ameixa et al., 2018; Ulyshen, 2014; Lunde et al., 2023).

Saproxylic beetles, which are beetles that rely on dead or dying wood at some point during their life cycle, are of extra importance in the decomposition of wood in ecosystems, because they recycle nutrients that would otherwise be locked in decay logs (Alexander, 2008; Stokland et al., 2012). Some species also contribute to pollination (Stefanescu et al., 2018). Saproxylic beetles are of special concern because today's intensive forest harvesting significantly reduces the volume of dead wood in forests (Gibb et al., 2005; Siitonen, 2001; Edelmann et al., 2022).

In Europe, at least 17.9 percent of the saproxylic beetles are threatened. Since the population trend to many of these species is unknown, the number of declining species could be even higher. Although most of the threatened species are in Central and Eastern Mediterranean regions (Cálix et al., 2018), beetles also make up a large proportion of the red-listed species in Fennoscandia. This has triggered a recent increase in beetle related research in the region (Rassi et al., 2000; Komonen et al., 2008). Saproxylic beetles are often used in inventories of forest biodiversity (Martikainen and Kouki, 2003; Lawton et al., 1998) and as tools for estimating the efficiency of forest conservation measures (Hammond et al., 2004; Lachat et al., 2006; Ohsawa, 2007).

Monitoring of beetle communities rely heavily on field studies involving sampling based on stationary traps. This also applies for knowledge on forest-dwelling insects, such as numerous beetle species (Leather, 2005; Siitonen, 1994; Økland et al., 1996). Sufficient sampling effort involves numerous traps that require emptying at 2–4-week intervals during the flight season. This is both time consuming and expensive. Hence, the use of effective trap designs is crucial for sampling communities of hyper-diverse groups like beetles.

In insect sampling, two common measurements are abundance and species richness, which often exhibit a strong relation (Gebert et al., 2023; Siemann et al., 1996). Still, both abundance and species richness are important metrics in the context of conservation. Population declines usually occur prior to the absence of a species (Beever et al., 2013). As Gebert et al. (2023) points out, abundance is most useful in conservation as a precursor of population changes, while species richness is more robust to short-term disturbances. Due to the high species richness of beetles, a large number of species occur in very low numbers. (Martikainen & Kouki, 2003). The more abundant beetle species tend to occur regardless of the management history of the sampling area (Martikainen et al., 2000). From a conservation viewpoint, it is the rare and threatened species that are of particular importance, but these species tend to miss out in scarce sampling efforts (Martikainen & Kouki, 2003; Hedgren & Weslien, 2007). Then comes the challenge to differentiate whether a species is absent from the location or present but not detectable, often referred to as false negatives. An obvious, yet challenging solution to false negatives is to increase the probability of detection (Allison & Redak, 2017).

When it comes to sampling forest beetle communities, the most frequently used and effective method is the flight interception traps, also known as window-flight traps (Allison & Redak, 2017; Bouget et al., 2008; Siitonen, 1994). These traps, first used by Chapman & Kinghorn (1955) and further developed by Peck & Davies (1980) are insect traps placed above ground, and when an insect flies into the material, it falls down in a container consisting of preservation liquid. Different window trap designs are used in beetle sampling, and their capture efficiency can vary significantly (Burner et al., 2021; Bouget et al., 2008). Additionally, different trap designs are optimal for certain insect taxa (Uhler et al., 2022). The use of window traps in insect research is not standardized. Additionally, several studies show clear differences in capture efficiency between different flight interception trap types (Burner et al., 2021; Bouget et al., 2008). As Montgomery et al. (2021) emphasizes, data collection in insect monitoring may fail to meet the ecological potential without a coordinated effort on standards and optimized practices in insect trapping.

Insect sampling with flight interception traps is used for different purposes and are widely used for monitoring insect populations. Hallmann et al. (2017) did a comprehensive study to determine the trend in insect biomass in nature protection areas in Germany. This initiated a trend which has been followed up in several countries, including Norway (Åström et al., 2024). To accurately assess trends in insect populations over time, it is essential that the methods remain consistent throughout the study period. This is equally crucial when comparing findings across different studies.

Insect sampling is also used to assess human impact on insect communities (Hammond et al., 2004; Alinvi et al., 2006). However, due to limited sampling efforts, rare species are frequently overlooked in such studies (Martikainen & Kouki, 2003). Moreover, the use of suboptimal traps contributes to this issue, and comparisons of studies using different sampling methods may result in the underestimation of our impacts on insect communities. Furthermore, insect sampling is used to assess the conservation value of a location. Nonetheless, the random results often yielded by sampling efforts can contribute to misleading conclusions, potentially undermining following conservation measures (Martikainen & Kouki, 2003).

For studies to be compared with each other, it is crucial that the sampling methods are equal. Montgomery et al. (2021) emphasized the need for standards in insects sampling. They highlighted that if window traps are used in a study, the color should be noted. Still, other trap qualities play a significant role in the capture efficiency as well (Burner et al., 2021; Bouget et al., 2008).

Considering how widespread window traps are used in insect sampling research, it is surprising that there is a scarcity of studies comparing the effects of different trap designs and materials on insect capture. This entails several challenges as there are clear differences in capture efficiency between different trap types, even with small adjustments between similar traps (Allison & Redak, 2017; Knuff et al., 2019; Parmain et al., 2013). Clarifying and studying these variations in insect sampling is key to interpreting and comparing results, but also to optimize the sampling methods for forest beetle communities.

Flight interceptions traps are either single-paned or cross-paned, in which cross-panes are often considered the most common (Siitonen, 1994; Bouget et al., 2008; Burner et al., 2021). Single-paned traps are in most cases triangular or rectangular. Several studies have shown that single-pane traps demonstrate better efficiency of species abundance and biomass compared to cross-pane traps (Bouget et al., 2008; Burner et al., 2021). Bouget et al. (2008) compared catches of beetle assemblages in rectangular single-pane traps with cross-pane traps, and they found the rectangular single-pane to catch significantly more species than the cross-pane. Likewise, Burner et al. (2021) compared the efficiency of cross-pane traps with a commonly used triangular-shaped trap. The triangular trap outperformed the cross-pane in both beetle abundance and species richness.

Two commonly used materials on flight interception traps are polyethylene and polycarbonate. The former is flexible, thin, and light, whereas the latter is non-flexible, thicker and weighs more. Based on available evidence, the only widely used trap in polyethylene is the triangular IBL-2 (Krzemiński, T, personal communication, April 26th, 2023; Burner et al., 2021). Cross-pane traps are usually either made in polycarbonate, but acrylic and polyvinyl chloride (PVC) is also used (Hanssen, O, personal communication, April 9th, 2023; Siitonen, 1994). Since the performance of triangular and cross-pane traps was shown to be clearly different on both abundance and species richness by Burner et al. (2021), investigating the effect of their materials on beetle sampling is needed.

The behavior of beetles when approaching flight interception traps is not well studied, but Boiteau (2000) described Colorado Potato Beetles (*Chrysomelidae*) just before and after the beetle hit a flight interception trap. A large portion of the beetles detected the window traps and avoided them by adjusting the direction of flight. The beetles reacted to the panes from within 1 meter, and if they reacted too late to change direction of flight some ended up landing on the traps without being caught. The findings of Boiteau (2000) highlight a potential factor when choosing trap material: light reflection of materials. Flying insects often maneuver based on visual motion (Egelhaaf & Kern, 2002), and Boiteau (2000) observed that beetles flying through an obstructed chamber typically avoid and fly past window traps.

The objective of this thesis is to test how material and design of flight interception traps affects capture efficiency on beetle abundance and species richness. In addition to the cross-pane and the triangular traps, this study also includes a rectangular single-pane trap similar to the one employed by Bouget (2005) and Bouget et al. (2008). The aim is to investigate if the captures of forest beetles are affected by differences in trap design by comparing rectangular cross-pane, rectangular single-pane and triangular (design), and if the catches in those three designs depend on whether the material is polyethylene or polycarbonate.

I expected the triangular trap made in polyethylene to perform best, based on the findings from Burner et al. (2021), since this trap is shown to catch considerably more than the cross-pane trap. Furthermore, I expected the rectangular panes to outperform the cross-panes in both abundance and species richness, like observed by Bouget et al. (2008). In turn, cross-panes are expected to perform most poorly of the three trap designs. Furthermore, the triangular IBL-2 traps used in research are made of polyethylene, and these are shown to perform better than cross-pane traps which usually are made of polycarbonate. Hence, for each trap design I expected the ones made of polyethylene to perform better than the ones in polycarbonate.

2. Materials and methods

2. 1 Study area

The traps were placed within a forest area of 1.8 hectares, located in Syverud (59°41'29.4"N, 10°45'07.2"E), close to the lake Årungen, in the municipality of Ås, Norway (Fig 1). The forest is owned by the Norwegian University of Life Sciences (NMBU), and is a mixed deciduous forest, containing mostly beech (*Fagus sylvatica*), aspen (*Populus tremula*), birch (*Betula spp.*), linden (*Tilia cordata*), oak (*Quercus spp.*), scots pine (*Pinus sylvestris*), and spruce (*Picea abies*) (Veidahl et al., 2017).

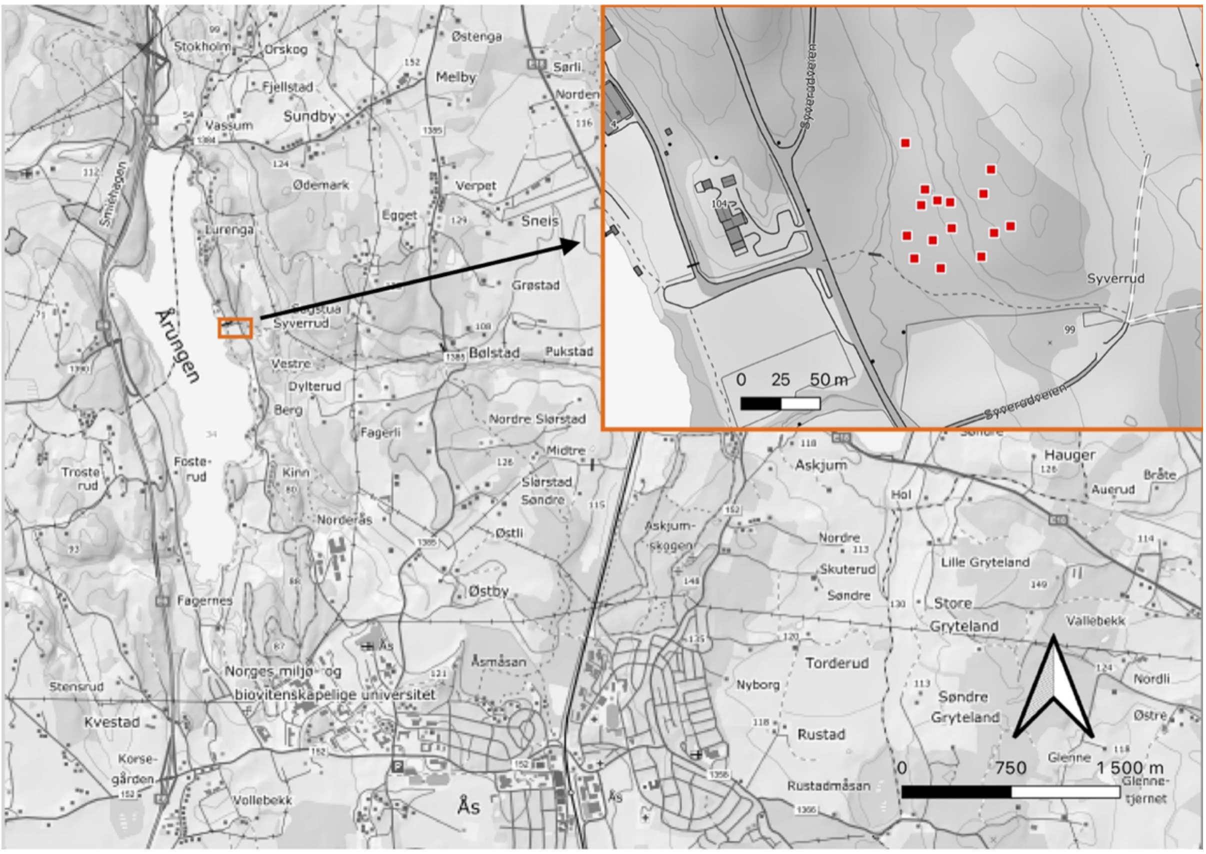


Figure 1. Map of the of the study area in Syverudskogen and the 15 beetle sampling locations. Each red dot represents a group of all 6 trap types. The map was made with QGIS-LTR (3.16.8-Hannover).

2. 2 Trap types

In total, six different traps were used in the study: three different trap designs, and each design in two different materials (Fig 2, table 1). The trap designs used were: two panes mounted as a cross-pane surface (4000 cm^2), single-pane triangular trapping surface (3950 cm^2), and a single-pane rectangular surface (4000 cm^2). All three trap designs were made in both polyethylene (PE) and polycarbonate (PC) (Fig 2, table 1), making up 6 different trap types, all with an approximately equal surface area. Each trap type was made in 15 replicates, so a total of 90 traps were used in the project.

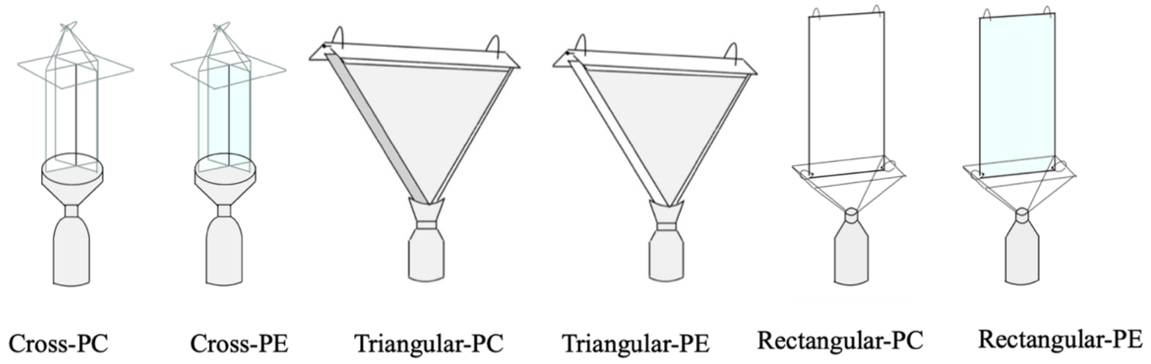


Figure 2: The six trap types placed at each location. The trap designs: Cross-pane, triangular, and rectangular pane, all in two different materials, polyethylene (PE), and polycarbonate (PC). Cross-PE and rectangular-PE had a blue tint due to available equipment.

Except for the triangular trap made from polyethylene (traded under the name IBL-2 and sold by CHEMIPAN, Warsawa, Poland), all the traps were custom made at the workshop on NMBU. I made the designs and had the traps made in collaboration with the workshop personnel. The cross-pane and rectangular pane trap in polyethylene was made in a light transparent material with blue tint as it was the only available material. The triangular traps made in polycarbonate had clear transparent side frames, while the triangular trap in polyethylene had white side frames (Fig 2). Collecting bottles for cross- and rectangular panes were painted green from an earlier experiment.

Table 1: Overview of the six different trap types, divided into design and material. For trap names, the material names are shortened: PE for polyethylene and PC for polycarbonate.

Trap name	Design	Material	Colour	Dimensions
Triangular-PE	Triangular	Polyethylene	Transparent w/ white frame	106 x 75 cm
Triangular-PC	Triangular	Polycarbonate	Transparent	106 x 75 cm
Cross-PE	Cross-pane	Polyethylene	Transparent w/ blue tint	20 x 100 cm (2x)
Cross-PC	Cross-pane	Polycarbonate	Transparent	20 x 100 cm (2x)
Rectangular-PE	Rectangular	Polyethylene	Transparent w/ blue tint	40 x 100 cm
Rectangular-PC	Rectangular	Polycarbonate	Transparent	40 x 100 cm

2. 3 Beetle sampling

In total, 90 traps were placed in 15 groups spread out over the study area, each group consisting of all the six trap types. The traps were hung on strings between tree trunks in duplets (Fig 3). Since the thick PC material was considerably heavier than the thin PE material each string was equipped with traps made from both materials. Except for this, the placement of each trap was randomized. The top of the trap windows were placed at a height of approximately 1.7 meters above ground. The distance between each string ranged from 0 to 4 meters, and there was 10-30 meters between each group of traps.

The traps were activated in two intervals: from the 13th of June to the 12th of July and from 13th of July to the 13th of August. A total of 180 samples were collected, 90 after the first and 90 after the second interval. I used 70% clear propylene glycol, 30% water, and a drop of dishwashing soap (to break the water surface) in all traps. In addition, all the bottles had two holes 3-4 cm up the edges for water to drain out when raining. The samples were stored in a freezer until species identification. The beetles were determined to species (when possible) by an expert taxonomist (Sindre Ligaard, independent consultant).

Figure 3. The set-up of all six trap types at one sampling location. From left: Cross-PC, triangular-PE, triangular-PC, rectangular-PE, rectangular-PC, and cross-PE.

2. 4 Data processing

All the collected samples from both intervals (n=180) were used in the data analysis, and when the trap type efficiencies were compared, the data from the two trapping periods were merged. Data was analysed with Rstudio (version 2023.06.2+561).

The abundance data was log transformed to homogenize the variance so it would fit into an ANOVA-test. This was not necessary for species richness. Furthermore, two two-way ANOVA tests were carried out to check if material and design significantly affects beetle capture. Trap material and design were included as explanatory variables in both tests. One was done with beetle abundance as the response variable, and another with species richness as the response variable. Interaction between material and design was included in the ANOVA-test to check whether the effect of design depends on the materials. A Tukey's Honestly Significant Difference (Tukey's HSD) post hoc test was then done on both ANOVA tests to determine which designs and materials are most effective. All p-value limits were set to 0,05.

3. Results

A total of 9093 individual beetles were caught represented by 467 different species, from 51 families. The five most abundant families were in order *Staphylinidae* (2647), *Scarabaeidae* (870), *Scraptiidae* (672), *Latridiidae* (602) and *Cryptophagidae* (511) (Appendix 3).

3. 1 Effect of trap design

The ANOVA-tests showed a significant difference in number of beetle species and individuals between the three designs (Table 2). When evaluating traps across both materials collectively, the Tukey's post hoc test revealed that the triangular design caught most beetle individuals. However, the cross-pane did not catch significantly different from rectangular pane trap (p=0.0732). Overall, for species richness, triangular traps caught more than both cross-panes (p=0.0004) and rectangular traps (p=0.0000). Cross-panes caught more than rectangular traps (p=0.0012).

Table 2. ANOVA analyses, one with beetle abundance as response variable, another with species richness. The explanatory variables in both tests are material, design, and material*design (interaction effect). Note that beetle abundance is log transformed, while species richness is not.

Explanatory variabel	F-value	SS	df	p-value
Beetle abundance (log)				
material	66.7	10.97	1	P<0.0001
design	45.86	15.09	2	P<0.0001
material*design	12.27	4.04	2	P<0.0001
Species richness				
material	60.09	17921	1	P<0.0001
design	29.14	17382	2	P<0.0001
material*design	17.58	10485	2	P<0.0001

3. 2 Effect of design given material

There was no significant difference in species richness between trap designs in polycarbonate (Fig 4). However, the Tukey's tests showed that the cross-pane trap outperformed the rectangular pane trap in terms of abundance (p=0.0005). Also, triangular traps in polycarbonate caught more species than rectangular panes (p=0.0218, Fig 4). Notably, there was no significant difference in individuals caught between triangular and cross-panes made in polycarbonate (p=0.8591).

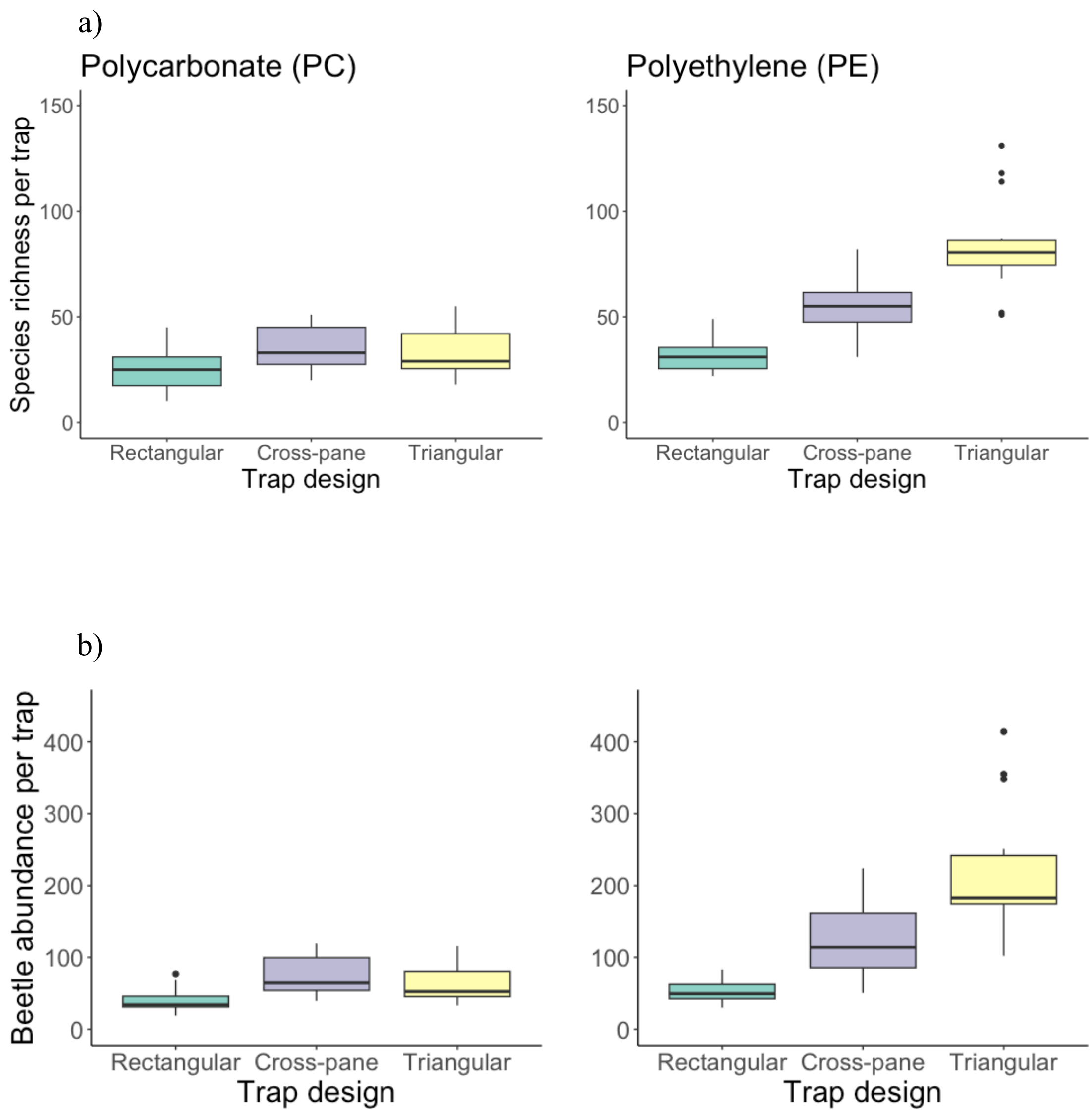


Figure 4. Boxplot comparing trap designs given material for catching performance on species richness per trap (a) and beetle abundance per trap (b). Abundance is not log transformed in the figure, only in the ANOVA-analyses. The middle line represents the median, the box shows the first quartile to the third quartile (the middle 50% of the data), and the whiskers extend 1.5 times the interquartile range from the upper and lower quartiles. Notice the identical y-axis scales for both figures in a, and correspondingly for both figures in b.

Overall, triangular traps in polyethylene significantly outperformed the other trap designs in the same material, for both abundance and species richness. In terms of species richness, all trap designs made in polyethylene caught significantly different from each other (Fig 4), in which triangular performed best, followed by cross-pane, which outperformed the rectangular pane (Fig 4, table 3). Cross-panes made in polyethylene caught significantly more than rectangular panes in the same material for both abundance ($p < 0.0001$) and species richness ($p=0.01$).

3. 3 Effect of trap material

The ANOVA-tests showed a significant difference in capture of beetle individuals and species between the two materials (Table 2). Traps with polyethylene generally captured more beetle species and individuals than the same designs in polycarbonate (Table 3, fig 5).

Table 3. Mean capture in abundance and species richness for all trap types, including standard errors.

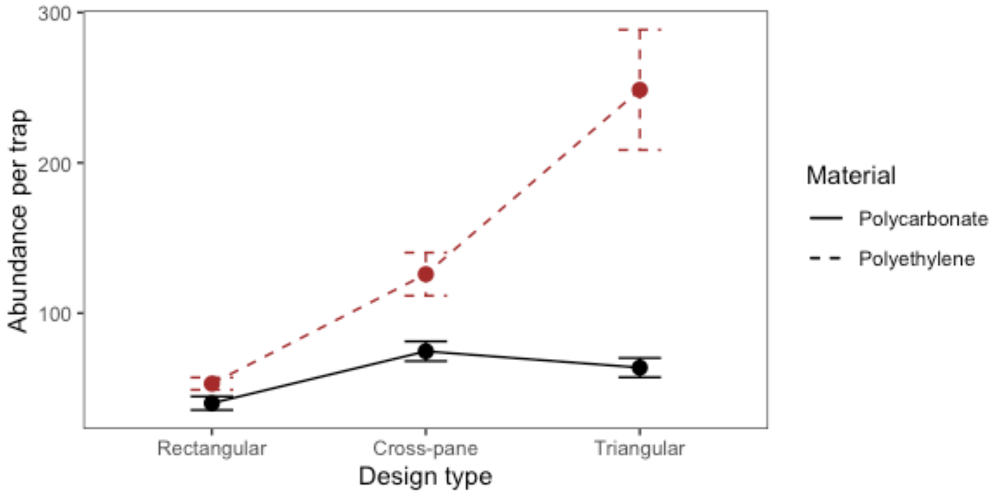
Trap type	Mean	SE
Abundance		
Rectangular PC	40.13	4.53
Rectangular PE	53.13	4.09
Cross PC	74.67	6.57
Cross PE	125.93	14.32
Triangular PC	63.8	6.42
Triangular PE	248.53	39.99
Species richness		
Rectangular PC	24.27	2.47
Rectangular PE	32	2.16
Cross PC	35.07	2.76
Cross PE	53.93	3.53
Triangular PC	33.13	2.83
Triangular PE	91.2	8.97

3. 4 Effect of material given design

Despite the overall effect of trap material, there was no significant difference between trap materials of the rectangular design (Tukey-test, abundance: p=0.2642, species richness: p=0.8227). Cross-panes made in polyethylene caught significantly better than those in polycarbonate for both abundance and species richness (p=0.0188, p=0.0409, fig 5). Finally, the separate test of the triangular traps significantly differed for both abundance and species richness (p=0.0000, p=0.0000), in which polyethylene outperformed polycarbonate (Fig 5, table 3).

3. 5 Interaction between design and material

a)



b)

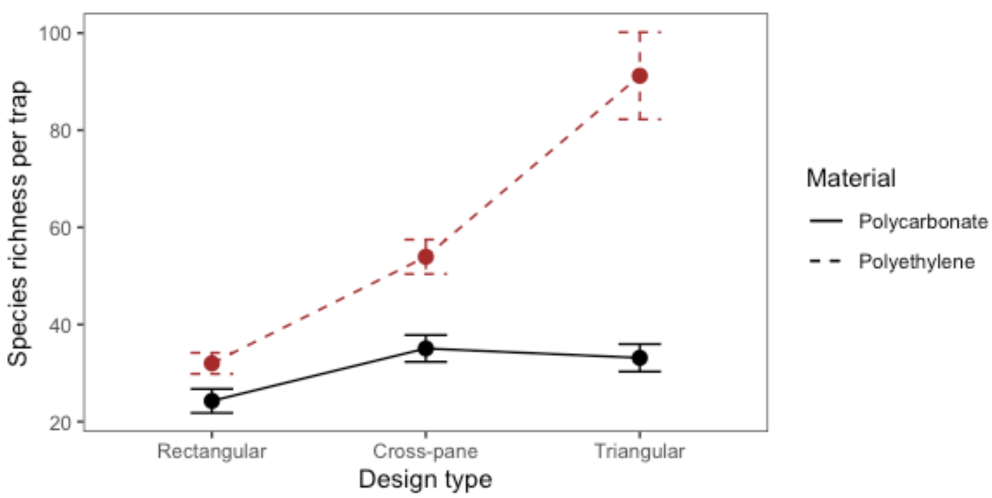


Figure 5. Interaction plots showing the difference in performance between materials for each trap design. The plots show the mean catch per trap of abundance (a) and species richness (b) for each of the three trap designs. Note that abundance is not log transformed in the figure, only in the ANOVA-analyses. The error bars show the standard error for each trap type.

The ANOVA-tests showed a significant interaction effect for trap material and design both for abundance and species richness (Table 2). The triangular trap design depends on what material you use, of which polyethylene perform significantly better than polycarbonate. Similarly, the cross-pane depends significantly on what material is used, although the effect is smaller than that of the triangular trap design (Fig 5).

3. 6 Material and design effect on species and family assemblage

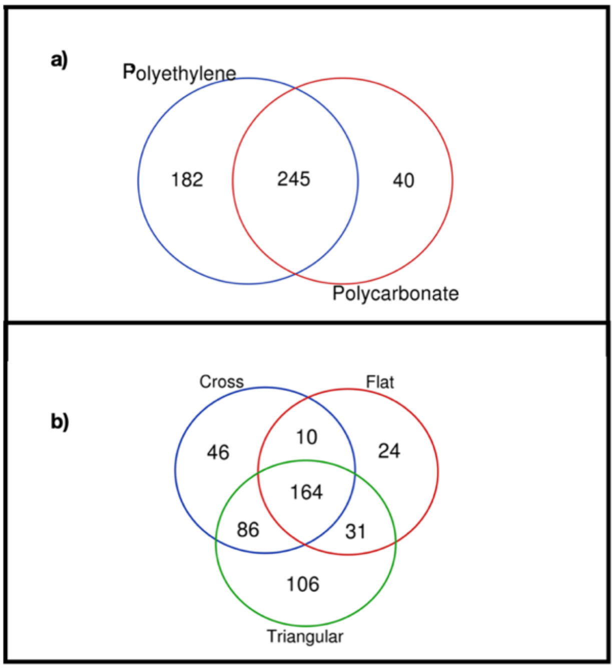


Figure 6. Venn-diagram showing the number of species caught in traps of different materials (a) and different trap designs (b). In diagram b, flat refers to the rectangular single-pane trap design.

As shown in figure 6, the larger proportion of the species were captured in both trap materials, but considerably more beetles were caught explicitly with polyethylene than polycarbonate. For both trap materials, the two most species rich families caught were *Staphylinidae* and *Curculionidae* (Appendix 3). In terms of abundance, *Staphylinidae* was most caught by both materials. The traps in polyethylene captured generally more in most families. Still polycarbonate caught considerably more individuals of *Scraptiidae* and *Cantharidae* (Appendix 4). For trap designs, the triangular trap captured most unique species, whereas the cross-pane captured considerably more unique species than the rectangular pane. Still, a large portion of the species caught were shared by all trap designs. Also, a great share of the species was caught by the triangular and the cross-pane traps only.

4. Discussion

4. 1 Summary of main results in relation to expectations

As expected, based on Burner et al. (2021), the triangular IBL-2 trap caught significantly more than the other two trap designs. I also hypothesized larger catches with rectangular traps than cross-pane traps based on Bouget et al. (2008), but this was not the case. Cross-pane traps caught significantly more species and individuals than the rectangular pane in both tested materials, with the only exception being species richness in polycarbonate where no significant difference was found.

Further, my results showed that traps made with polyethylene had higher overall catches than traps made with polycarbonate. This was also expected based on the high trapping efficiency of polyethylene-made triangular traps (Burner et al., 2021). However, when looking at rectangular panes alone, there was no significant difference in performance between the two materials.

Lastly, the choice of material significantly influenced the effectiveness of trap design: whereas both abundance and richness differed between the three different designs when traps were made in polyethylene. The only difference found in polycarbonate-made traps was the low abundance in rectangular traps.

4. 2 Effect of trap design

Polycarbonate is more frequently used in traps than polyethylene, although it was clear that the latter gave larger catches. Similarly, even though cross-panes in polycarbonate are more commonly used, they catch far less beetles than the triangular trap in polyethylene. Thus, many studies are carried out with suboptimal traps.

Overall, my results show that cross-panes catch better than rectangular single-panes. This contradict the findings of Bouget et al. (2008), where they found that of all the beetle species caught in the study, 88 percent was caught with the rectangular traps and only 45 percent was caught with the cross-pane traps. However, they emphasized that their results might be affected by their small dataset, and that the volume of attraction liquid (ethanol) was bigger in the rectangular than the cross-panes. Trapping liquids with baiting effect can potentially bias the results when assessing beetle abundance and richness (Nakládal et al., 2023).

Comparing triangular and cross-pane designs, Burner et al. (2021) found that the difference in capture rates was approximately proportional to the difference in surface area. Still, with 20 triangular traps they captured a total of 442 species, while a total of 80 cross-pane traps (equal to the surface area of 32 triangular traps) captured 307 species. However, my results showed that triangular traps had greater capture rate than cross-pane traps with the same surface area. Even though the cross-pane trap is shown to have less efficiency in number of species and abundance, there are several benefits of using the cross-pane trap. Like Bouget et al. (2008) points out: they are light, easy to transport and store, easily placed on a site, and less affected by wind than single-pane traps.

Furthermore, given the significant differences between trap types, as shown in my results, comparing studies in which different types are used is difficult. This was also pointed out by Burner et al. (2021). When comparing the two commonly used trap types, triangular in polyethylene and cross-pane in polycarbonate, the same number of traps (15) caught 373 species with the triangular trap versus 225 species with the cross-pane (1.7 times more species in the triangular). To collect the same number of species with the cross-panes as with 15 triangular, this would require 25.5 cross-pane traps, given that the same species caught by triangular traps would be caught with the cross-panes with the same effort.

While the traps in my study were shown to catch different numbers of species, the species accumulation curve (Appendix 1) shows that they would likely also flatten out at different levels. The cross-pane is often considered the most time and cost-effective option (Bouget et al., 2008), but the triangular trap can catch the same number of species with fewer traps (Appendix 1). If I used the triangular trap in polyethylene, I would estimate around 400 species in the study area based on how the curves flatten out. Conversely, I would estimate around 300 species with the cross-pane in polyethylene. For the rectangular pane made in polyethylene, and all three trap designs made in polycarbonate, I would probably not estimate more than about 200 species. Therefore, when using polycarbonate traps, high effort is needed to get high catch numbers, regardless of design.

4. 3 Why is polyethylene better than polycarbonate?

Since transparent polyethylene had a significantly better performance than transparent polycarbonate for both triangular and cross-panes, this suggests that material qualities other than color can have a strong impact on beetle capture. The materials used in beetle sampling with window traps is not standardized, and previous literature rarely specifies what material the window traps are made of. This underlines the low focus on trap-defined effects on beetle catches in past research.

While the difference in sampling performance between materials is clear in my study, the cause of this effect is unknown. Light reflection could potentially influence the material's efficacy. Beetles differ in their ability to detect wavelengths of light (Weiss et al., 1941), and different materials can reflect light differently, including transparent materials (Embrechts, 1995). If beetles captured by window traps are caught because they are unable to detect the light reflected from the trap material, then this is of potential significance on capture efficiency and the beetle assemblage caught by a window trap. This property of window traps is, based on available evidence, poorly explored. The clear difference in performance between the two transparent materials supports the possibility that light reflection influences capture performance. Different beetle species are attracted to different colors (Cavaletto et al., 2020; Sakalian & Langourov, 2004; Campbell & Hanula, 2007), indicating an ability to detect differences in wavelengths that might be reflected by different materials.

Another possible impact factor is the materials ability to adsorb ultraviolet light (UV). Many insects, including several beetles, are shown to be sensitive to UV-light, (Barghini & Souza de Medeiros, 2013; Singleton et al., 2024), and several studies indicate that they use it to navigate while flying (Antignus, 2000; Kring & Schuster, 1992). For instance, insects are shown to be disoriented and less active inside greenhouses covered by UV-blocking polyethylene (Antignus, 2000). If there is a difference in UV-light reflection and adsorption between trap materials, this may impact their capture performance. Although, as pointed out by Antignus (2000), polyethylene and polycarbonate are, due to the chemical structure, both known for their UV-adsorbing properties.

Potential difference in degree of polarization for reflected light between the trap materials can also affect whether the traps are detected by flying beetles. The ability to detect polarized light is shown in beetles, though primarily for scarab beetles (Pye, 2010; Warrant, 2010;

Horváth et al., 2014). It is also shown that many beetles living in water (*Hydrophilinae*, *Dytiscidae*, *Haliplidae*, *Hydraenidae*) and other moist substrates (*Sphaeridiinae*) are attracted to horizontally polarized reflected light from the ground in search for water (Schwind, 1984; Schwind, 1991). Light reflected at certain glossy surfaces, like water bodies or shiny leaves, is polarized in a direction parallel to the surface (Horváth, 1995; Horváth et al., 2002). If this is also the case with the trap surfaces, there is a possibility that reflected polarized light from the traps can have either a revealing or attracting effect on beetle species that are able to detect it. Studies on the difference in light reflection, polarization, and UV-adsorbing properties between the common window trap materials; polyethylene, polycarbonate, acrylic, and polyvinyl chloride is needed. Additionally, it is important to explore how these differences relates to the capture of abundance, species richness and beetle assemblage.

The effect of flexibility in window trap material has not been thoroughly investigated. Lamarre et al. (2012) discussed the possible effect of window traps with hard material compared to those in softer materials. They suggested that harder material traps, in this case made in acrylic, are more likely to stun the beetles when they hit the surface, leading to greater captures. They also point out that heavier beetles (i.e. *Scarabaeidae* and *Cerambycidae*) are more likely to be stunned by hard material than lighter beetles. Boiteau (2000), on the other hand, observed many of the beetles within the trap space to bounce off and fall without being trapped after hitting the trap surface. While hard material might stun the flying beetles, it is possible that softer trap materials decrease the proportion of beetles that bounce away from the collector, due to a dampening effect. My results do not support the suggestion of Lamarre et al. (2012) that beetles could be stunned by hard material leading to greater capture rates compared to soft plastic. Polyethylene as the softer material clearly performed better. Furthermore, my findings show that we should not expect greater catches even if the beetles were to be stunned by colliding with a harder material. However, it is possible that hard material makes the beetles bounce away from the collector, observed by Boiteau (2000), contributing to higher catches with softer materials, in this case soft polyethylene.

Material slipperiness might also affect the capture performance. For instance, Boiteau (2000) observed several Colorado Potato beetles that detected the window trap before flying into it. Consequently, they managed to land on the trap's surface, walk up the board and frame, and fly away, evading capture. Allison and Redak (2017) tested the effect of surface treatment to make the panel more slippery. The application of surface treatment significantly enhanced trap catches across trap types, guilds, and families. The treatment showed significant effect on bark- and woodboring beetles (Allison & Redak, 2017). Although none of the traps used in my study were treated to make the surface more slippery, there is potentially a small but impactful difference in slipperiness between the two materials used.

4. 4 Possible errors and future research

Many insects use color vision to find desirable habitats, to locate food sources and to recognize potential mates (Giurfa et al., 1997; Spaethe et al., 2001; Finkbeiner et al., 2014). Given that trap colors can resemble these cues, traps can have a color-induced attraction effect on beetles. Bouget et al. (2008) compared black and transparent cross-pane traps and found differences in abundance on family and species level, with some groups being caught more frequent in the black traps and some in the transparent ones. De Groot and Nott (2001) found black traps to capture significantly more pine longhorn beetles compared to transparent traps. Bark and ambrosia beetles use vision to distinguish host from non-host trees (Campbell et al., 2009; Campbell et al., 2006). Darker traps, resembling their tree hosts, tend to attract these beetles more effectively than light-colored traps (Strom and Goyer, 2001; Allison & Redak, 2017; Cavaletto et al., 2020). Also, certain darker metallic beetles, like *Chrysobothris affinis* and *Coroebus undatus*, are mainly attracted by darker trap colors, like purple and blue (Fürstenau et al., 2015; Meglič et al., 2020).

Flower visiting species on the other hand are usually more attracted to traps with typical flower colors, like yellow, white, blue as compared with colors such as green and black (Sakalian & Langourov, 2004; Campbell & Hanual, 2007). Green-colored trap bottles on the rectangular and cross-pane traps could possibly affected beetle capture. Triangular traps were the only ones with white collecting bottles, while the cross-panes and rectangular panes had collecting bottles painted green from an earlier experiment.

There is also a possibility that the polyethylene with a blue tint used for cross-panes and rectangular panes have affected their performance. The transparent traps with a blue tint used in this study were light coloured and have therefore possibly had little attraction effect on bark beetles compared to the clear transparent traps. However, some flower visiting beetles have been shown to be attracted to flower colours, including blue.

Therefore, traps with a blue tint could possibly have extra attraction effect compared to clear traps. The triangular trap was the only one which was clear transparent for both materials, and it was the trap design with highest difference in performance based on the material it was made of. Although the cross-pane performed significantly different with the two materials, there is a possibility that polyethylene made with a blue tint result in less captures than the transparent one.

The frames might also increase sampling performance due to their color. The triangular trap in polyethylene was the only trap with white side frames. Flower visiting beetles are attracted to typical flower colors, including white (Sakalian & Langourov, 2004; Campbell & Hanula, 2007). Therefore, this might give this trap an extra attractive effect compared to the other trap types. Also, the funnels differed in color between the trap designs. The triangular and cross-panes both had white funnels, while the rectangular had a transparent one. Since some beetles are proven to be attracted to light colors, including white, it is possible that the lack of any white components on the rectangular panes had an impact on the rectangular panes being outperformed by the other two designs.

The inclusion of side frames enables the capture of beetles from multiple angles, which could enhance the catch performance. The triangular trap has side frames, unlike most other window traps (Burner et al., 2021). Due to the triangular shape, it is necessary with frames that lead the falling beetles into the collector. Burner et al. (2021) showed a significant higher capture in both abundance and species richness with a trap design with frames, the triangular, compared to a design without frames, a cross-pane. Still, it is hard to tell whether the frames had an impact here, as other factors related to material and design distinguished the trap types. Because of the high catch with this trap compared to other window traps, it is not unlikely that the frame also has other effects on beetle capture. Boiteau (2000) investigated the effect of frames on flight interception traps, but there was no evidence to suggest that the presence of a frame increased trap avoidance. The triangular trap was the only design with a frame in my study. Even though cross-panes don't have a frame, they also have an increased directionality. Still, they don't perform nearly as good as the triangular design. It is also possible that the beetles fall more often into the collector with a frame, with the frames leading falling beetles down in the funnel.

Difference in trap design, like total surface area, width and height can also have an impact in capture performance given that all flying beetles are not evenly distributed in the open air. Several studies have shown insects to favor corridors during movements, including beetles (Várkonyi et al., 2003; Haddad et al., 2003; Hill, 1995). Noordijk et al. (2011) showed that small and linear forest clearings were intensely used by flying carabids as movement corridors. Thus, the difference in shape between the three trap designs are of potential influence on the capture performance, as the trap designs cover movement corridors of flying beetles differently. The triangular trap surface covers more width in higher layers, and less in the lower layers, compared to the rectangular flat-pane and cross-pane. The rectangular trap is evenly wide, while the cross-pane has the narrowest surface area compared to the other trap designs.

My results showed a clear difference in number of species caught exclusively for each trap design and material. Due to time constraints, I was unable to assess the differences in beetle assemblages between trap types in this study. Based on the findings of Bouget (2008), I would expect difference in beetle assemblages between the designs. Further investigations should be done for assemblages of species, families, guilds, and beetle size between trap types.

My findings also emphasize the lack of understanding as to why one transparent plastic material performs considerably better than the other one, and why this is only the case for certain trap designs, the triangular and cross-pane. I suggest that light reflection and collision impact should be further investigated as it is probable that they have a considerable impact on beetle sampling performance. Also, a similar study should be done with other transparent materials as well, including soft polyvinylchloride (PVC), which was used in cross-pane traps by Siitonen (1994), and acrylic, another material used in window traps (Lamarre et al., 2012; Hanssen, O, personal communication, April 9th, 2023).

5. Conclusion

My results show that material and design have a considerable impact on beetle sampling. Given the large differences of catches detected in this study, comparing studies which use different trap types are problematic. This also applies for studies using the same trap design, as trap material, which is rarely even specified in previous studies, may have a significant impact on the catches.

What caused the traps in polyethylene to outperform those in polycarbonate remains unclear, as does the effect of trap material on trap design. Thus, further studies should strive to understand why these differences have such an impact on beetle sampling. It is also of interest to understand how differences in material and trap design effect different functional and taxonomical groups.

Based on my results, it is clear that many investigations are carried out with suboptimal trap types which likely result in many false negatives. The triangular trap made in polyethylene (IBL-2) was superior to all other trap types. I recommend using this trap, if only one trap type is to be deployed and the goal is to capture most effectively. A coordinated effort towards a standard for window traps should take the superior performance of triangular designs combined with soft polyethylene into account.

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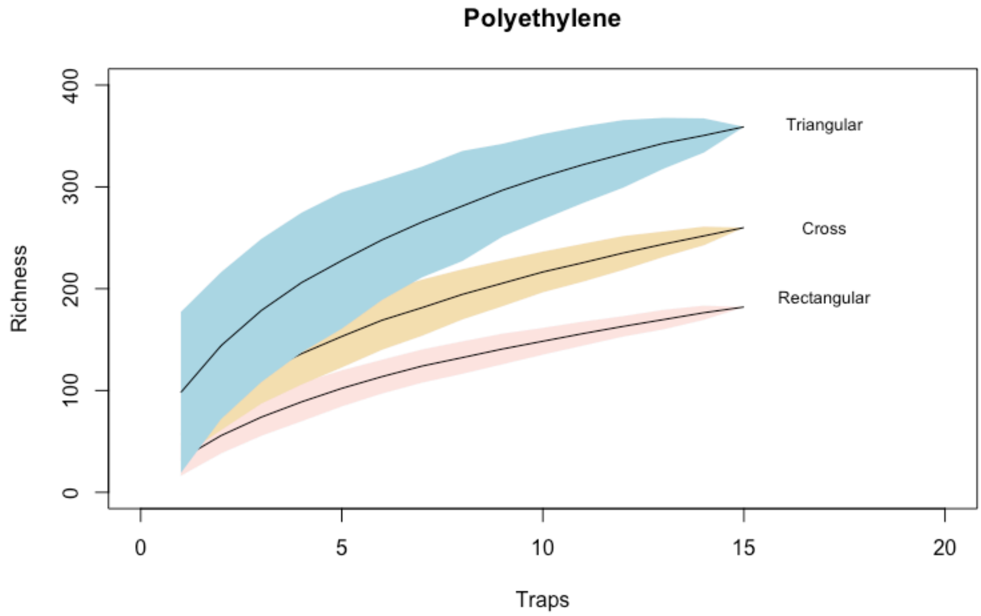
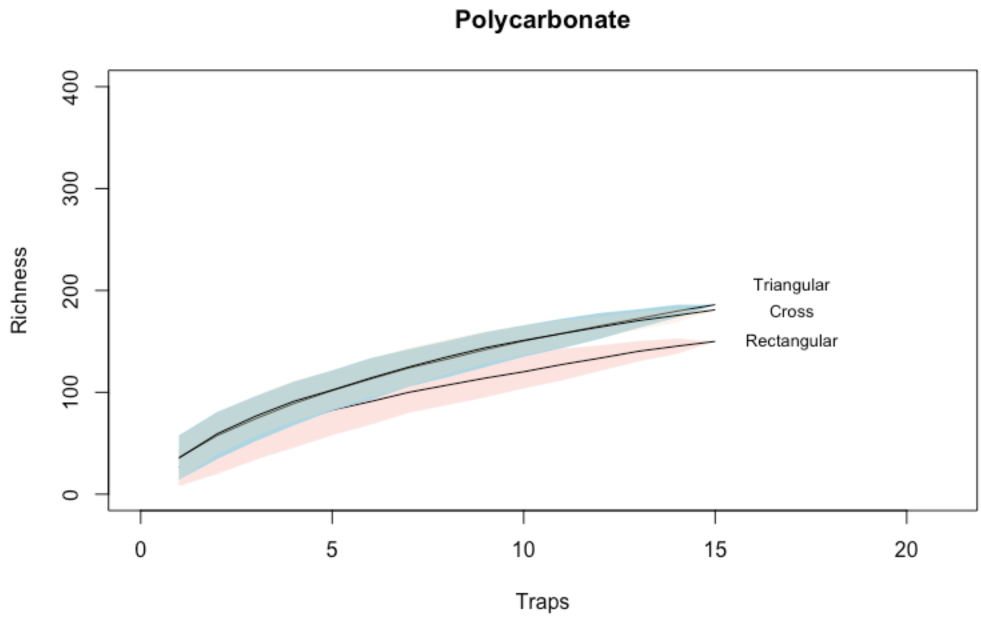
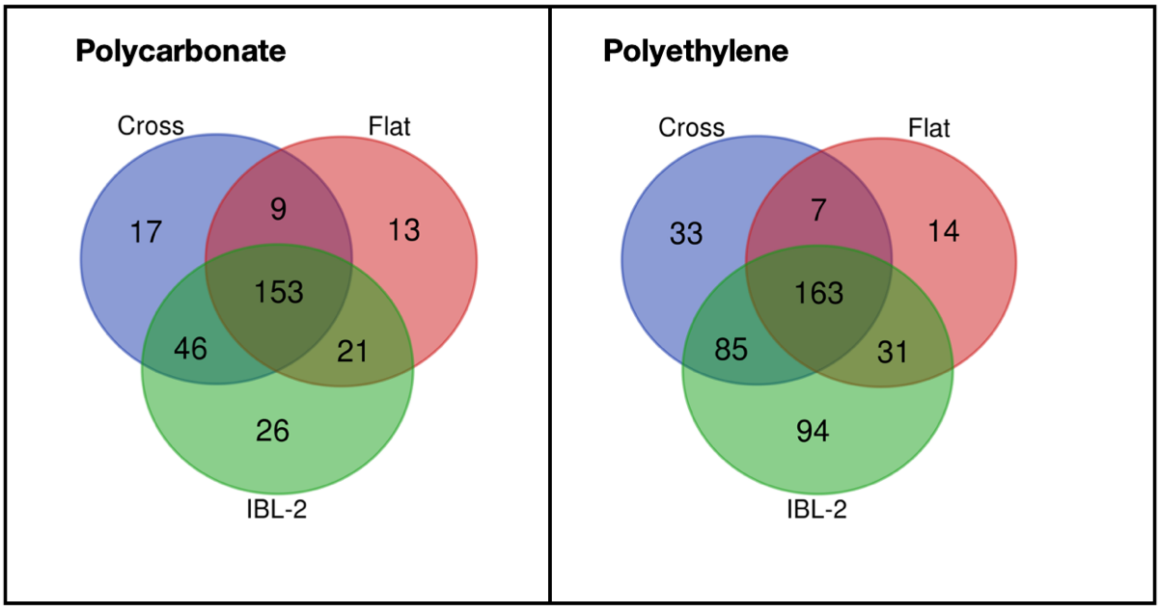
Appendix

Appendix 1. Species accumulation curve of each trap design, given the materials. The polygons represent 95% confidence intervals. The graphs for triangular and cross-panes in polycarbonate flattens out quite equally.





Appendix 2. VENN-diagram of species caught per trap design, given its materials.



Appendix 3. Number of individuals per family caught with each trap type. Polycarbonate is abbreviated as PC, and polyethylene as PE. Total abundance per family and the number of species caught per family is included.

Family	Cross PE	Cross PC	Rectangular PE	Rectangular PC	Triangular PE	Triangular PC	Total abundance	Number of species per family
Aderidae	0	0	0	0	2	1	3	1
Anthribidae	1	0	0	0	0	1	2	2
Apionidae	1	4	0	1	0	0	6	4
Byturidae	1	7	1	1	10	2	22	1
Cantharidae	22	62	14	41	43	86	268	17
Carabidae	3	2	1	2	5	0	13	10
Cerambycidae	4	2	2	2	6	1	17	8
Cerylonidae	128	40	25	7	140	38	378	4
Chrysomelidae	2	4	1	2	4	1	14	3
Ciidae	29	14	22	2	78	11	156	17
Clambidae	0	1	0	0	0	0	1	1
Cleridae	1	0	0	0	1	1	3	1
Corylophidae	3	1	0	0	4	0	8	1
Cryptophagidae	108	62	47	32	206	56	511	22
Curculionidae	98	23	27	14	182	16	360	30
Dasytidae	3	35	7	19	3	13	80	1
Elateridae	46	34	36	31	75	47	269	11
Endomychidae	2	0	0	0	3	1	6	2
Erotylidae	14	2	0	0	29	2	47	4
Eucnemidae	45	4	12	5	239	15	320	6
Geotrupidae	0	0	1	2	1	0	4	1
Helophoridae	2	1	0	1	12	2	18	1
Histeridae	3	0	8	2	26	1	40	8
Hydraenidae	0	0	0	0	2	0	2	1
Hydrophilidae	3	1	4	6	41	6	61	5
Laemophloeidae	0	0	0	1	2	0	3	1
Latridiidae	218	68	38	23	211	44	602	19
Leiodidae	60	29	54	26	87	11	267	20
Lucanidae	4	3	1	0	8	0	16	1
Lycidae	0	0	0	0	3	1	4	1
Melandryidae	14	5	4	1	22	5	51	6
Monotomidae	53	7	8	4	72	3	147	8
Mordellidae	9	0	1	0	2	1	13	2
Mycetophagidae	1	0	0	0	1	0	2	1
Nitidulidae	38	31	16	21	102	34	242	28
Orsodacnidae	0	0	0	0	0	1	1	1
Ptiliidae	126	14	24	5	247	41	457	13
Ptinidae	4	4	5	9	50	15	87	10
Rhynchitidae	0	0	0	0	1	0	1	1
Salpingidae	6	3	3	2	22	6	42	3
Scarabaeidae	141	118	141	109	232	129	870	8
Scirtidae	9	9	1	5	6	14	44	5
Scraptiidae	78	228	52	48	122	144	672	3
Silphidae	4	7	6	2	20	6	45	2
Silvanidae	1	3	1	0	3	0	8	2
Sphindidae	13	1	7	3	16	2	42	2
Staphylinidae	552	252	218	160	1301	164	2647	161
Tenebrionidae	0	0	0	1	3	0	4	2
Tetratomidae	4	3	0	3	13	2	25	2
Throscidae	32	36	9	9	67	32	185	2
Zopheridae	3	0	0	0	3	1	7	1

Appendix 4. Number of individuals per family caught with each trap material. Both lists are ordered in descending order.

Family	Polyethyelene
Staphylinidae	2071
Scarabaeidae	514
Latridiidae	467
Ptiliidae	397
Cryptophagidae	361
Curculionidae	307
Eucnemidae	296
Cerylonidae	293
Scraptiidae	252
Leiodidae	201
Elateridae	157
Nitidulidae	156
Monotomidae	133
Ciidae	129
Throscidae	108
Cantharidae	79
Ptinidae	59
Hydrophilidae	48
Erotylidae	43
Melandryidae	40
Histeridae	37
Sphindidae	36
Salpingidae	31
Silphidae	30
Tetratomidae	17
Scirtidae	16
Helophoridae	14
Dasytidae	13
Lucanidae	13
Byturidae	12
Cerambycidae	12
Mordellidae	12
Carabidae	9
Chrysomelidae	7
Corylophidae	7
Zopheridae	6
Endomychidae	5
Silvanidae	5
Lycidae	3
Tenebrionidae	3
Aderidae	2
Cleridae	2
Geotrupidae	2
Hydraenidae	2
Laemophloeidae	2
Mycetophagidae	2
Anthribidae	1
Apionidae	1
Rhynchitidae	1
Clambidae	0
Orsodacnidae	0

Family	Polycarbonate
Staphylinidae	576
Scraptiidae	420
Scarabaeidae	356
Cantharidae	189
Cryptophagidae	150
Latridiidae	135
Elateridae	112
Nitidulidae	86
Cerylonidae	85
Throscidae	77
Dasytidae	67
Leiodidae	66
Ptiliidae	60
Curculionidae	53
Ptinidae	28
Scirtidae	28
Ciidae	27
Eucnemidae	24
Silphidae	15
Monotomidae	14
Hydrophilidae	13
Melandryidae	11
Salpingidae	11
Byturidae	10
Tetratomidae	8
Chrysomelidae	7
Sphindidae	6
Apionidae	5
Cerambycidae	5
Carabidae	4
Erotylidae	4
Helophoridae	4
Histeridae	3
Lucanidae	3
Silvanidae	3
Geotrupidae	2
Aderidae	1
Anthribidae	1
Clambidae	1
Cleridae	1
Corylophidae	1
Endomychidae	1
Laemophloeidae	1
Lycidae	1
Mordellidae	1
Orsodacnidae	1
Tenebrionidae	1
Zopheridae	1
Hydraenidae	0
Mycetophagidae	0
Rhynchitidae	0

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