**Title**

Climate warming increases insect-driven seed removal of two eliaosome-bearing invasive thistle species

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**Abstract**

Ants and other insects are often an overlooked source of localised secondary dispersal for a variety of plants and play an important ecological role in the dispersal of plant propagules. While there is an increasing amount of literature on insect-mediated secondary dispersal, there is limited information regarding how climate change will affect such dispersal, as quantifying this dispersal can be quite challenging in the first place. Here, we investigate the effects of climate change on insect-mediated seed removal by examining the effects of increased growing temperatures on how attractive seeds from the invasive thistles *Carduus nutans* and *Carduus acanthoides* are to secondary insect dispersers. To accomplish this, we run an *in-situ* seed removal experiment to observe seed removal events from controlled locations and estimate the effects of warming treatments on rates at which seeds are removed. Our results indicate that seeds from maternal plants grown at temperatures 0.6 °C higher than ambient are removed at higher rates by insect dispersers than their unwarmed counterparts. We also observe that seed elaiosomes in these two species play an important role in dispersal, as seeds that had their elaiosomes removed were significantly less likely to be taken by insects over the same time period. These results provide evidence that climate change may alter aspects of the dispersal process such as seed removal, which could possibly affect how plants disperse their seeds in a changing world.

**Introduction**

For sedentary organisms such as plants, seed dispersal is essential to the movement of populations because it is the only stage in the life cycle that movement can occur. While plant propagules are often dispersed by abiotic vectors such as wind, water, and gravity, they are also often dispersed biotically by organisms such as insects, birds, and mammals. For example, the seeds of the mahaleb cherry *Prunus mahaleb* are ingested, moved, and defecated by a variety of mammals such as foxes and badgers as well as birds such as crows, thrushes, warblers, and robins (Herrera and Jordano 1981; Guitián *et al*. 1992; Jordano *et al*. 2007). The acorns of various oak trees (*Quercus* sp.) are often dispersed and cached by a variety of rodents such as mice and squirrels (Jensen and Nielsen 1986; Vander Wall 2001; Gómez *et al*. 2008). Some species can even be dispersed by carnivores when they prey on frugivores or granivores with seeds in their digestive tract (Hämäläinen *et al*. 2017). Humans are also often involved in the process of dispersing plant propagules, as numerous plants can be dispersed when propagules attach to clothing (Wichmann *et al*. 2009; Ansong and Pickering 2014), are caught in air currents generated by passing vehicles (Von Der Lippe *et al*. 2013) or on the vehicles themselves (Veldman and Putz 2010; Taylor *et al*. 2012), as a contaminant of horticultural stock (Hodkinson and Thompson 1997), and as impurities in agricultural produce such as grains (Shimono and Konuma 2008; Michael *et al*. 2010; Wilson *et al*. 2016). The prevalence in ecological literature of studies regarding these sorts of dispersal indicates a growing interest in identifying and quantifying dispersal by organisms such as insects, animals, and humans.

Such dispersal of seeds by biotic vectors typically occurs not in isolation, but as part of a larger network of parallel and serial dispersal events for any given species. For example, in the mahaleb cherry *Prunus mahaleb*, while seeds are often consumed directly from the tree by birds before primary dispersal via gravity, they may also be consumed off the ground and undergo secondary dispersal by birds and mammals after primary dispersal via gravity. Integration of these primary and secondary pathways and the vectors responsible into a total dispersal kernel, or probability distribution of how far seeds are dispersed when accounting for all possible dispersal vectors, can help us quantify how plant populations expand at a variety of different spatial scales (Nathan 2007). However, significant challenges in identifying these biotic dispersers and quantifying how they disperse seeds make it challenging to fully understand their role in seed dispersal, especially for smaller seeds that cannot be easily tracked through empirical means (Rogers *et al*. 2019).

For these smaller seeds, ants and other insects are often an overlooked source of localised secondary dispersal and are responsible for moving seeds after they have been dispersed by wind, water, gravity, or even another biotic dispersal vector (Vander Wall and Longland 2004). In particular, ant-mediated seed dispersal, or myrmecochory, has been shown to be a common occurrence in many plant species. In more than 80 plant families across the world, ant-dispersed plant species contain seeds that bear an elaiosome, a small structure on the seed achene that facilitates dispersal by ants (Edwards *et al*. 2006). The elaiosome has a high lipid content and likely serves as a reward for the ant dispersing the seed (Brew *et al*. 1989; Hughes and Westoby 1990, 1992), as ants will typically take the seeds back to their nest and consume the elaiosome, then store the seed achene in a midden (Berg 1975; Culver and Beattie 1978). This dispersal can be advantageous for a variety of different reasons, including moving propagules to areas with better germination and growing conditions as well as less competition from other plants (Handel and Beattie 1990).

Investigations of such ant-mediated secondary dispersal, as well as the primary dispersal that precedes it, is challenging in its own right. Even more complicated it to investigate how such processes are modified by climate change, such as climate warming, as climate change may affect various characteristics of these dispersal processes. For example, changes in the number of seeds that plant can produce may result from elevated growing temperatures (Sato *et al*. 2006, Hedhly *et al*. 2009, Caignard *et al*. 2017) and increased CO2 levels (Edwards *et al*. 2001, Thürig *et al*. 2003, Way *et al.* 2010). The dynamics of seed release can also be affected by increased growing temperatures, with some species more likely to release their seeds (Teller *et al*. 2016). Climate change may also cause shifts in the range or abundance of species that disperse a certain species’ seeds, as well as shifts in the traits that attract animal dispersers, and may thus affect its dispersal capabilities (Ruxton and Schaefer 2012, Mokany *et al*. 2014, Sales *et al*. 2021). Climate change also has the potential to affect seed nutrient content and a variety of studies, especially on agricultural crops, have shown changes in nutrient allocations and chemical makeup due to factors such as increased temperatures or elevated CO2 (Thomas *et al*. 2003, Caldwell *et al*. 2005, Singh *et al*. 2013). However, there is very little research on how these changes in seed shape, size, or nutrient allocations affect seed attractiveness to dispersers; the majority of the research addressing the effects of climate change on dispersal is focused on seed production and abiotic vectors of dispersal, with less known about how climate change may affect the dispersal of seeds by insects, animals, and humans.

Given the role that ants and other insects play in seed dispersal, a better understanding of how they move seeds can help us better understand how plant species dispersed by these insects spread. Such an understanding starts with quantifying seed removal, as this is the first step of dispersal via ants and other insects. A commonly used and straightforward experimental setup to quantify seed removal by secondary dispersers consists of so-called “cafeterias” or “depots” (e.g. Xiao *et al*. 2006, Fischer and Türke 2016, Gurney *et al*. 2015, Linabury *et al*. 2019), where seeds are aggregated in various locations and the number of seeds removed is closely monitored. When paired with video recording or exclusion treatments such as cages, these sort of seed removal experiments allow researchers to observe the types of animals or insects removing seeds and approximate their contribution of rates to seed removal (Jongejans et al. 2014, Griffiths *et al*. 2018). In the face of numerous challenges associated with quantifying secondary dispersal processes and documenting the ultimate fate of removed seeds (Vander Wall *et al*. 2005a), seed removal experiments provide an easily-manageable starting point for further inquiry into identifying secondary dispersal vectors and quantifying their contributions to the secondary dispersal process.

Here, we seek to develop a better understanding of how seeds are moved by secondary dispersal vectors, namely ants, with a focus on investigating the first step of this secondary dispersal process: seed removal. We also seek to explore the role of the elaiosome, as well as whether increased growing temperatures on maternal plants, in seed removal rates and overall attractiveness to insect dispersers. We thus investigate four questions. First, what are the approximate rates of seed removal via insect after a seed has experienced primary dispersal? Second, does the seed elaiosome affect the rate of removal? Third, are seeds from maternal plants that experienced increased growing temperatures any more or less likely to be removed by insects than their unwarmed counterparts? And fourth, does the effect of the seed elaiosome on removal rates change based on whether the maternal plant is warmed or unwarmed?

**Materials and Methods**

***Study Species***

*Carduus nutans* L. (“musk thistle” or “nodding thistle”) and *Carduus acanthoides* L. (“plumeless thistle”) are two closely-related invasive thistles in the Asteraceae family. Both species germinate in autumn or spring and bolt in the early summer (Zhang *et al*. 2012), reproduce exclusively by seed, and have monocarpic perennial life cycles that have been demonstrated to shift from biennial towards annual under warming conditions (Keller and Shea 2021). While sharing similar life histories, the two species display significant morphological differences in dispersal-related characteristics such as number of flower heads, flower head size, number of seeds produced per flower head, and distribution of flower heads across an individual (Desrochers *et al*. 1988). These invasive thistles have high reproductive potential and are a considerable agricultural pest since they thrive in pastures, are unpalatable to most grazers, and decrease pasture productivity (Trumble and Kok 1982). In addition to pastures, these thistles occur in other highly disturbed areas such as drainages and roadsides. Both species can be found across the U.S. and often co-occur (Allen and Shea 2006), and are listed as noxious weeds in several states (Skinner *et al.* 2000).

Wind serves as the primary dispersal vector in both *C. nutans* and *C. acanthoides*, as seeds of both species display a prominent pappus that increases hang time and makes it possible for them to be carried at long distances. However, dispersal of these seeds also extends beyond wind, with paths of secondary dispersal possible after seeds have hit the ground. Seeds from both species contain elaiosomes that are thought to play a role in ant-mediated dispersal (Pemberton and Irving 1990), and have been documented to be moved by insects and small mammals, with insects such as ants, crickets, and grasshoppers likely playing a significant role in the movement of seeds (Jongejans et al. 2014).

***Seed collection and preparation***

*C. nutans* and *C. acanthoides* from which seeds were harvested were grown under control and ambient warming treatments as part of an experiment in Drees and Shea (*in prep.*) to estimate the effects of warming on the distribution of flower heights; this publication discusses the methods and experimental setup in greater detail. In this experiment, individuals of each species were grown in a grid-like arrangement, and a subset of individuals within each species were randomly assigned a fibreglass open-top chamber. These chambers, built to specifications of the International Tundra Experiment Manual (Molau and Mølgaard 1996), have been demonstrated to increase the ambient temperature by approximately 0.6 °C on average over a year (Zhang *et al*. 2011) without significantly affecting other possible growth factors such as soil moisture and snow depth. When flowers set seed, mesh pollen bags were wrapped around the flowers endure that seeds from these invasive thistles did not escape and contaminate other parts of the study area, as seeds from these invasive thistles can stay dormant for years and could pose problems for future experiments once germination occurs.

Once individuals completed their life cycle, they were cut down, and bagged seed heads were collected from all individuals that produced five or more viable flowers. During this process, seed heads from all individuals of the same species were mixed together to randomise possible differences in seed size, shape, nutrient content, and any other factors that vary between individuals and may affect seed attractiveness to insects. The mesh pollen bags were then removed from the decapitated seed heads, and the heads were placed in a large paper bag and allowed to desiccate in a dry, low-light environment at approximately 24 °C. After approximately a month of desiccation, the bags were sealed and shaken vigorously to separate the seeds from the seed heads and pappi from the seeds; separated seeds were then sifted to remove spines, pappi, and other plant debris, and were then stored in an airtight container.

After seeds were successfully extracted, they were irradiated to ensure they could be freely dispersed by ants and other insects without spreading these invasive thistles and contaminating study site. Seeds from *C. nutans* and *C. acanthoides* were irradiated using a 1000 KR dosage of gamma radiation; this dosage was demonstrated by Jongejans *et al*. (2014) to prevent any germination without affecting how attractive seeds from either of these species are to insects.

Once seeds were irradiated, a subset of seeds from each species and warming/ambient treatment were assigned an elaoisome removal treatment. Elaiosomes were removed by holding the seed with a pair of forceps, aligning the flattest side of the seed parallel to the workbench, and then using a teasing needle to press the elaiosome against the workbench until it was severed from the seed achene. In instances where the elaiosome did not cleanly separate, the teasing needle was used to gently dig out the remainder of the elaiosome from the achene. Seeds not receiving the elaiosome removal treatment were handled with forceps in the same manner mentioned above, for approximately the same duration as the seeds whose elaiosomes were removed; this was done so that possible differences in experimental outcomes could not be attributed to differences in the way the seeds were handled. After seeds had their elaiosomes removed and the control seeds were handled appropriately, seeds were again placed in airtight containers based on treatment type.

Seed depots were then constructed to serve as points where insects could easily access and remove seeds. All depots were constructed in a similar manner to those in Jongejans *et al*. (2014), using 95 mm diameter petri dishes with a 15 cm tall edge and placing black sandpaper at the bottom to mimic the appearance of soil. Sandpaper was adhered to the bottom of the petri dish in order to negate any warping or movement of the paper due to wind, moisture, sunlight exposure, or insect activity. Note that unlike in Jongejans *et al*. (2014), we do not seek to exclude specific types of insects as a treatment, so Tanglefoot was not used when constructing these seed depots. Once the depots were constructed, each one was loaded with 25 seeds arrayed near the centre of the petri dish, though spread out enough so that seeds were not piled on top of each other. All depots were prepared in a controlled environment and were transported to the field site, rather than being constructed *in situ*.

***Experimental setup***

The seed removal experiment was conducted at the Russell E. Larson Agricultural Research Farm in Rock Springs, Pennsylvania, which is the same study site at which the experiment from which the seeds were derived was conducted. All seed depots were arranged over an 8 x 10 grid in a small field approximately 50 m from the location of the warming experiment, with individual seed depots spaced 1 m apart. Seeds within a particular seed depot represented one of eight unique combinations of species (*C. nutans* vs *C. acanthoides*), warming treatment (warmed vs unwarmed), and elaiosome treatment (present vs absent); each row of eight depots contained a randomised arrangement of these eight unique treatment combinations, for a total of 10 depots for each treatment combination across the 8 blocked rows. Before placing each depot, the small patch of vegetation below was trimmed and lightly compacted so that the petri dish could be easily fit in the grass canopy, reducing the chance of depots being disturbed by wind and ensuring that insects could access them easily.

Once all seed depots were placed, each seed depot was photographed from directly above by an observer at 30-minute intervals for the first 12 hours, from 09:00 to 21:00 on 07 September 2020; after 12 hours had elapsed, depots were then photographed once at 24 hours, again at 36 hours, and then once more at 48 hours. In instances where the sandpaper bottom of the dish was disturbed, it was fixed to the bottom of the petri dish again, and the remaining seeds gently placed back around the centre of the seed depot; such instances were extremely uncommon, however. No rain was observed over the duration of the experiment, and temperatures ranged between approximately 7°C and 27°C.

***Image processing***

All images were processed manually by counting the number of seeds for each seed depot at each recorded time; this was enabled by the contrast in colour between the seeds and the black sandpaper on the seed depots. Seeds were counted as removed only if they were completely removed from the seed depot; thus, even in instances where seeds were disturbed or scattered across the depot, they were still marked as present. For each image, the number of seeds was scored twice by the same observer across independent sessions to ensure accuracy of the data.

***Statistical Analyses***

All statistical analyses were conducted in R (R Development Core Team 2009). To assess significance of the three treatment variables (species, warming, and elaiosome removal), we used the **glmer** function from the package **lme4** (Bates *et al*. 2012) to fit a generalised linear mixed-effects model to the data, using a logit link and treating the number of seeds removed at a given time as a binomial response. Each of the three treatment variables were encoded as a two-level factor and treated as a fixed effect; interactions between treatments were treated as fixed effects as well, and treatment block was treated as a random effect. To examine significance of treatment at different points in time, the model was fit separately at the 6, 12, 24, and 48 hour marks, in a similar fashion to the analyses performed by Jongejans *et al*. (2014). The **lrtest** function from the package **lmtest** (Zeileis and Hothorn 2002) was used for conducting likelihood ratio tests to examine whether removal of interaction terms from each model was significant; only significant interaction terms were retained in the final models. Two-sided Kolmogorov-Smirnov tests were used to determine whether survival curves for a given combination of two treatments differed between levels of the third treatment.

**Results**

Over the course of the 48 hours that seed removal was documented, both photographs and direct observation suggest that insects were responsible for seed removal; no birds or mammals were documented in the vicinity of the study area or were observed removing any seeds. Throughout the entire duration of the experiment, seed removal by ants was observed and made up the vast majority of direct observations of seed removal, with the ants dragging individual seeds across the flat surface of the seed depot (Figure 1) before carrying the seed over the outer walls; these observations were especially common at the 30-minute observation periods during the daytime, but also occurred at several of the observation periods after sunset. Crickets were also observed on the seed depots (Figure 2), though mostly at night, where they would consume the seeds on the depot rather than carry them away and consume elsewhere. Grasshoppers frequently visited the depots during the daytime hours but were not observed consuming or removing seeds, though they consumed or attempted to remove the adhesive tape used to mark the depots. Though a variety of other small insects were observed at the depots as well, they were not identified, but none of them were observed removing any seeds.

Observed rates of seed removal were high; 48.4% of seeds were removed after 12 hours, 85.5% after 24 hours, and 94.6% after 48 hours. Out of the eight possible treatment combinations of species, warming, and elaiosome presence/absence, warmed *C. nutans* seeds with elaiosomes experienced the highest rates of removal, with 79.6% of seeds removed after 12 hours, 98.0% after 24 hours, and 98.4% after 48 hours; these observed values seem to differ only slightly from the respective model estimates of 76.3%, 97.5%, and 99.1%. On the other hand, unwarmed *C. acanthoides* seeds without elaiosomes experienced the lowest observed rates of removal at 13.8% after 12 hours, 75.0% after 24 hours, and 88.9% after 48 hours, with respective model estimates of 13.5%, 79.2%, and 93.5%.

Coefficient estimates from Table 1 suggest that both warming treatment and elaiosome removal significantly impacted the proportion of seeds removed, as the coefficient estimates for these treatments were both highly significant at the 6, 12, 24, and 48 hour marks. At these times, seeds from warmed maternal plants were more likely to have been removed than those from unwarmed maternal plants, and seeds with their elaiosomes intact were more likely to have been removed than those without their elaiosomes. Over the course of the experiment, seeds with their elaiosomes intact were generally removed at a faster rate than seeds without their elaiosomes for all combinations of warming and species, except for warmed *C. acanthoides* (Figure 3). Seeds from warmed maternal plants were removed at a faster rate than seeds from unwarmed maternal plants for all combinations of elaiosome presence/absence and species, except for *C. acanthoides* with intact elaiosomes (Figure 4). There is not substantial evidence that seed removal rates differed between species (Figure 5), as coefficient estimates for the species term in the mixed-effects model were not significant for three of the four time points at which the model was fit.

Interactions between species and warming treatment, between species and elaiosome treatment, and between warming treatment and elaiosome treatment were observed in the mixed effects models, though their direction and significance varied between the time marks. For example, while the interaction between species and elaiosome treatment was significant for the 6, 12, 24, and 48 hour marks, it was negative at the 48-hour mark and positive at the others. The interactions between species and warming treatment and between warming treatment and elaiosome treatment were consistent in direction between hour marks, but were only significant at a subset of those hour marks.

**Discussion**

Our results indicate that the rate of post-dispersal seed removal is quite high, with more than 85.5% of all seeds removed over the course of only 24 hours. These results are similar to observed removal rates of *C. nutans* and *C. acanthoides* in a similar study by Jongejans *et al*. (2014), who also demonstrate that up to 88% of seeds are removed in 24 hours when there is no impediment to the movement of insect dispersers. These extremely high rates of seed removal suggest that the majority of *C. nutans* and *C. acanthoides* seeds dispersed via wind also experience some sort of movement or consumption via insects or animals. Jongejans *et al*. (2014) also demonstrate that rates of seed removal were significantly lower when ant access to seed depots was restricted, indicating that ants were responsible for the majority of seed removal events; our observations of a disproportionately large number of ant visits to seed depots further support these results.

We also demonstrate that the elaiosome plays an important role in attracting seed removers, as seeds of both species had significantly higher rates of removal when the elaiosome was left intact compared to when it was removed from the seed achene. Previous studies have suggested that these elaiosomes in *C. nutans* and *C. acanthoides* are involved in myrmecochory, attracting ants and playing an important role in how they disperse seeds (Pemberton and Irving 1990, Alba-Lynn and Henk 2010); the differences in seed removal rates between elaiosome-present and elaiosome-absent seeds in our study lend further support to evidence of myrmecochory in these two thistle species. In addition to removal of the elaiosome significantly impacting seed removal rates, we find that exposing the maternal plant to increased growing temperatures also increases the rate at which its seeds are removed by insect dispersers, with seeds from warmed plants experiencing higher rates of removal. Why this is the case is unclear, as the effects of increased growing temperature on factors such as seed size or nutrient content, which likely play a role in how attractive insect dispersers find seeds, are not clear for *C. nutans* and *C. acanthoides*. Additional analyses are necessary to necessary to explore the link between increased growing temperatures and increased seed removal in order to highlight the underlying mechanisms responsible for these changes.

One of the limiting factors of our study is a lack of knowledge regarding how far seeds travel after removal; while we can easily observe seeds being removed from a controlled experimental area, it is significantly more challenging to find where dispersers move seeds after removing them from the seed depots. While not used in our study here, there are a variety of techniques to assess where animal-dispersed seeds are moved, with each having its own set of strengths and weaknesses. Some seeds are large enough to store electronic devices and can be tracked using telemetry (e.g. Pons and Pausas 2007, Hirsch *et al*. 2012), and can thus be found without visual cues, which can be particularly useful in areas with dense vegetation or when seeds are cached underground. Seeds of various sizes can be dyed with a fluorescent material or pigment that makes visual location easier (e.g. Levey and Sargent 2000, Reiter *et al*. 2006), but addition of pigment to seeds can significantly change their mass depending on the size of the seed and amount of pigment applied (Lemke *et al*. 2009), which could possibly alter the dynamics of seed removal or dispersal; such pigmentation could also possibly alter seed scent or taste. For ant-dispersed seeds such as *C. nutans* and *C. acanthoides*, fluorescent pigment may not be helpful in tracking seeds if they are taken underground to ant nests, where they are then no longer visible from the surface. Mapping emerging seedlings within the vicinity of a seed depot can also provide some information on secondary dispersal distances, though for invasive species such as *C. nutans* and *C. acanthoides* there are ethical concerns about allowing dispersal of viable seeds from an experiment into the environment (Jongejans *et al*. 2014), hence our use of gamma irradiation to render the seeds unviable. Also, this method would only provide dispersal distance information for only a fraction of dispersed seeds because it only examines the seeds that germinate, and would present the added challenge of ensuring that a particular seedling can be traced back to its source so that dispersal distance can be accurately quantified.

Given the difficulties with tracking how small seeds such as those from *C. nutans* and *C. acanthoides*, while our study helps shed light on the first part of the secondary dispersal by quantifying seed removal after primary dispersal, it does not document the fate of the seeds after they have been removed. Accurately assessing the fate of seeds after they are removed can be quite challenging, as removed seeds are typically exposed to some mixture of dispersal and predation; for example, while some seeds are consumed in a destructive manner after removal or are otherwise rendered inviable, others can be left intact by ants and scatter-hoarding animals (Hulme 1998, Vander Wall *et al*. 2005a, Penn and Crist 2018). Often, such caching and burial can improve chances of germination by protecting seeds from predation after secondary dispersal, though seeds germinating after cached at high densities may compete amongst each as seedlings (Hulme and Kollmann 2005). However, it is rarely known exactly what proportion of seeds are dispersed or cached without harm and what proportion experience predation. Despite this uncertainty in seed fate, many studies have conflated seed removal with predation, and often treat removed seeds as if they are consumed without substantial evidence indicating so (Vander Wall *et al*. 2005b). Such an assumption of seed fate may not only overestimate actual rates of seed predation, but also vastly underestimate secondary dispersal of seeds, as seed removal may not necessarily entail destruction but could instead be the first part of a series of secondary dispersal events (Vander Wall *et al*. 2005b). As such, we have framed our results in terms of seed removal, since our uncertainty in the proportions of removed seeds that are consumed or dispersed limits us from making any claims about post-removal seed fate.

A better understanding of seed removal rates also has implications for spatial plant population dynamics. For example, we demonstrate that the overwhelming majority of *C. nutans* and *C. acanthoides* seeds were removed after only 48 hours, indicating that almost all seeds that undergo primary dispersal have the possibility to travel even further from the parent plant than they already have, provided they are not subject to predation. This may mean that our current estimates of how quickly invasive species like *C. nutans* and *C. acanthoides* spread might be lower than actual rates depending on the extent of seed predation, as current estimates of these invasion rates (e.g. Skarpaas and Shea 2007, Jongejans *et al*. 2011, Zhang *et al*. 2016, Teller *et al*. 2016) only account for primary dispersal. Secondary dispersal may also affect the germination and recruitment of new individuals by moving seeds to locations that may be more favourable to germination than their original location; like with primary dispersal, the additional dispersal distance from the parent plant may possibly reduce any density-dependent mortality that may be associated with predation or parent-offspring competition (Janzen 1970, Connell 1971). Good sentence or two to end this paper on?

**Acknowledgments**

The authors would like to thank Professor Inger Nordal for helpful discussions on myrmecochory, as well as Dr. Candace Davison for assisting in the gamma irradiation of *C. nutans* and *C. acanthoides* seeds at the Penn State Breazeale Reactor.

**References**

Alba-Lynn, C. and Henk, S., 2010. Potential for ants and vertebrate predators to shape seed-dispersal dynamics of the invasive thistles Cirsium arvense and Carduus nutans in their introduced range (North America). Plant Ecology, 210(2), pp.291-301.

Allen, M. R., & Shea, K. (2006). Spatial segregation of congeneric invaders in central Pennsylvania, USA. Biological Invasions, 8(3), 509-521.

Ansong, M. and Pickering, C., 2014. Weed seeds on clothing: A global review. Journal of Environmental Management, 144, pp.203-211.

Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R. H. B., Singmann, H., ... & Scheipl, F. (2012). Package ‘lme4’. CRAN. R Foundation for Statistical Computing, Vienna, Austria.

Berg, R.Y., 1975. Myrmecochorous plants in Australia and their dispersal by ants. Australian Journal of Botany, 23(3), pp.475-508.

Brew, C.R., O'Dowd, D.J. and Rae, I.D., 1989. Seed dispersal by ants: behaviour-releasing compounds in elaiosomes. Oecologia, 80(4), pp.490-497.

Caignard, T., Kremer, A., Firmat, C., Nicolas, M., Venner, S. and Delzon, S., 2017. Increasing spring temperatures favor oak seed production in temperate areas. Scientific Reports, 7(1), pp.1-8.

Caldwell, C.R., Britz, S.J. and Mirecki, R.M., 2005. Effect of temperature, elevated carbon dioxide, and drought during seed development on the isoflavone content of dwarf soybean [Glycine max (L.) Merrill] grown in controlled environments. Journal of agricultural and food chemistry, 53(4), pp.1125-1129.

Connell, J.H., 1971. On the role of natural enemies in preventing competitive exclusion in some marine animals and in rain forest trees. Dynamics of populations, 298, p.312.

Culver, D.C. and Beattie, A.J., 1978. Myrmecochory in Viola: dynamics of seed-ant interactions in some West Virginia species. The journal of Ecology, pp.53-72.

Desrochers, AM, Bain, JF, & Warwick, SI (1988). The Biology of Canadian Weeds.: 89. Carduus nutans L. and Carduus acanthoides L. Canadian Journal of Plant Science , 68 (4), 1053-1068.

Edwards, G., Clark, H. and Newton, P., 2001. The effects of elevated CO2 on seed production and seedling recruitment in a sheep-grazed pasture. Oecologia, 127(3), pp.383-394.

Edwards, W., Dunlop, M. and Rodgerson, L., 2006. The evolution of rewards: seed dispersal, seed size and elaiosome size. Journal of Ecology, 94(3), pp.687-694.

Fischer, C. and Türke, M., 2016. Seed preferences by rodents in the agri‐environment and implications for biological weed control. Ecology and evolution, 6(16), pp.5796-5807.

Gómez, J.M., Puerta-Piñero, C. and Schupp, E.W., 2008. Effectiveness of rodents as local seed dispersers of Holm oaks. Oecologia, 155(3), pp.529-537.

Griffiths, H.M., Ashton, L.A., Walker, A.E., Hasan, F., Evans, T.A., Eggleton, P. and Parr, C.L., 2018. Ants are the major agents of resource removal from tropical rainforests. Journal of Animal Ecology, 87(1), pp.293-300.

Guitián, J., Fuentes, M., Bermejo, T. and López, B., 1992. Spatial variation in the interactions between Prunus mahaleb and frugivorous birds. Oikos, pp.125-130.

Gurney, C.M., Prugh, L.R. and Brashares, J.S., 2015. Restoration of native plants is reduced by rodent-caused soil disturbance and seed removal. Rangeland Ecology & Management, 68(4), pp.359-366.

Hämäläinen, A., Broadley, K., Droghini, A., Haines, J.A., Lamb, C.T., Boutin, S. and Gilbert, S., 2017. The ecological significance of secondary seed dispersal by carnivores. Ecosphere, 8(2), p.e01685.

Handel, S.N. and Beattie, A.J., 1990. Seed dispersal by ants. Scientific American, 263(2), pp.76-83B.

Hedhly, A., Hormaza, J.I. and Herrero, M., 2009. Global warming and sexual plant reproduction. Trends in plant science, 14(1), pp.30-36.

Herrera, C.M. and Jordano, P., 1981. Prunus mahaleb and birds: the high‐efficiency seed dispersal system of a temperate fruiting tree. Ecological monographs, 51(2), pp.203-218.

Hirsch, B.T., Kays, R. and Jansen, P.A., 2012. A telemetric thread tag for tracking seed dispersal by scatter-hoarding rodents. Plant Ecology, 213(6), pp.933-943.

Hodkinson, D.J. and Thompson, K., 1997. Plant dispersal: the role of man. Journal of Applied Ecology, pp.1484-1496.

Hulme, P.E., 1998. Post-dispersal seed predation: consequences for plant demography and evolution. Perspectives in Plant Ecology, Evolution and Systematics, 1(1), pp.32-46.

Hulme, P.E. and Kollmann, J., 2005. Seed predator guilds, spatial variation in post-dispersal seed predation and potential effects on plant demography: a temperate perspective. Seed fate: Predation, dispersal and seedling establishment, pp.9-30.

Hughes, L. and Westoby, M., 1990. Removal rates of seeds adapted for dispersal by ants. Ecology, 71(1), pp.138-148.

Hughes, L. and Westoby, M., 1992. Effect of diaspore characteristics on removal of seeds adapted for dispersal by ants. Ecology, 73(4), pp.1300-1312.

Janzen, D.H., 1970. Herbivores and the number of tree species in tropical forests. The American Naturalist, 104(940), pp.501-528.

Jensen, T.S. and Nielsen, O.F., 1986. Rodents as seed dispersers in a heath—oak wood succession. Oecologia, 70(2), pp.214-221.

Jongejans, E., Shea, K., Skarpaas, O., Kelly, D. and Ellner, S.P., 2011. Importance of individual and environmental variation for invasive species spread: a spatial integral projection model. Ecology, 92(1), pp.86-97.

Jongejans, E., Silverman, E. J., Skarpaas, O., & Shea, K. (2015). Post-dispersal seed removal of *Carduus nutans* and *C. acanthoides* by insects and small mammals. Ecological research, 30(1), 173-180.

Jordano, P., García, C., Godoy, J.A. and García-Castaño, J.L., 2007. Differential contribution of frugivores to complex seed dispersal patterns. Proceedings of the National Academy of Sciences, 104(9), pp.3278-3282.

Keller, J.A. and Shea, K., 2021. Warming and shifting phenology accelerate an invasive plant life cycle. Ecology, 102(1), p.e03219.

Lambert, J.E., Hulme, P.E. and Vander Wall, S.B., 2004. Seed fate: predation, dispersal, and seedling establishment. CABI.

Lemke, A., Von Der Lippe, M. and Kowarik, I., 2009. New opportunities for an old method: using fluorescent colours to measure seed dispersal. Journal of Applied Ecology, 46(5), pp.1122-1128.

Levey, D.J. and Sargent, S., 2000. A simple method for tracking vertebrate‐dispersed seeds. Ecology, 81(1), pp.267-274.

Linabury, M.C., Turley, N.E. and Brudvig, L.A., 2019. Insects remove more seeds than mammals in first‐year prairie restorations. Restoration Ecology, 27(6), pp.1300-1306.

Michael, P.J., Owen, M.J. and Powles, S.B., 2010. Herbicide-resistant weed seeds contaminate grain sown in the Western Australian grainbelt. Weed Science, 58(4), pp.466-472.

Mokany, K., Prasad, S. and Westcott, D.A., 2014. Loss of frugivore seed dispersal services under climate change. Nature Communications, 5(1), pp.1-7.

Molau U, P. Mølgaard P (1996). International Tundra Experiment Manual. Danish Polar Centre, Copenhagen.

Nathan, R., 2007. Total dispersal kernels and the evaluation of diversity and similarity in complex dispersal systems. Seed dispersal: theory and its application in a changing world, pp.252-276.

Pemberton, R. W., & Irving, D. W. (1990). Elaiosomes on weed seeds and the potential for myrmecochory in naturalized plants. Weed Science, 615-619.

Penn, H.J. and Crist, T.O., 2018. From dispersal to predation: A global synthesis of ant–seed interactions. Ecology and evolution, 8(18), pp.9122-9138.

Pons, J. and Pausas, J.G., 2007. Acorn dispersal estimated by radio-tracking. Oecologia, 153(4), pp.903-911.

R Development Core Team (2009) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Reiter, J., Curio, E., Tacud, B., Urbina, H. and Geronimo, F., 2006. Tracking Bat‐Dispersed Seeds Using Fluorescent Pigment 1. Biotropica: The Journal of Biology and Conservation, 38(1), pp.64-68.

Rogers, H.S., Beckman, N.G., Hartig, F., Johnson, J.S., Pufal, G., Shea, K., Zurell, D., Bullock, J.M., Cantrell, R.S., Loiselle, B. and Pejchar, L., 2019. The total dispersal kernel: a review and future directions. AoB Plants, 11(5), p.plz042.

Ruxton, G.D. and Schaefer, H.M., 2012. The conservation physiology of seed dispersal. Philosophical Transactions of the Royal Society B: Biological Sciences, 367(1596), pp.1708-1718.

Sales, L.P., Kissling, W.D., Galetti, M., Naimi, B. and M Pires, M., 2021. Climate change reshapes the eco‐evolutionary dynamics of a Neotropical seed dispersal system. Global Ecology and Biogeography, 30(5), pp.1129-1138.

Sato, S., Kamiyama, M., Iwata, T., Makita, N., Furukawa, H. and Ikeda, H., 2006. Moderate increase of mean daily temperature adversely affects fruit set of Lycopersicon esculentum by disrupting specific physiological processes in male reproductive development. Annals of Botany, 97(5), pp.731-738.

Shimono, Y. and Konuma, A., 2008. Effects of human‐mediated processes on weed species composition in internationally traded grain commodities. Weed Research, 48(1), pp.10-18.

Singh, R.P., Prasad, P.V. and Reddy, K.R., 2013. Impacts of changing climate and climate variability on seed production and seed industry. Advances in Agronomy, 118, pp.49-110.

Skarpaas, O. and Shea, K., 2007. Dispersal patterns, dispersal mechanisms, and invasion wave speeds for invasive thistles. The American Naturalist, 170(3), pp.421-430.

Skinner, K., Smith, L., & Rice, P. (2000). Using noxious weed lists to prioritize targets for developing weed management strategies. Weed Science, 48(5), 640-644.

Teller, B.J., Zhang, R. and Shea, K., 2016. Seed release in a changing climate: initiation of movement increases spread of an invasive species under simulated climate warming. Diversity and Distributions, 22(6), pp.708-716.

Taylor, K., Brummer, T., Taper, M.L., Wing, A. and Rew, L.J., 2012. Human‐mediated long‐distance dispersal: an empirical evaluation of seed dispersal by vehicles. Diversity and Distributions, 18(9), pp.942-951.

Teller, B.J., Zhang, R. and Shea, K., 2016. Seed release in a changing climate: initiation of movement increases spread of an invasive species under simulated climate warming. Diversity and Distributions, 22(6), pp.708-716.

Thomas, J.M.G., Boote, K.J., Allen, L.H., Gallo‐Meagher, M. and Davis, J.M., 2003. Elevated temperature and carbon dioxide effects on soybean seed composition and transcript abundance. Crop Science, 43(4), pp.1548-1557.

Thürig, B., Körner, C. and Stöcklin, J., 2003. Seed production and seed quality in a calcareous grassland in elevated CO2. Global Change Biology, 9(6), pp.873-884.

Trumble, J.T. and Kok, L.T., 1982. Integrated pest management techniques in thistle suppression in pastures of North America. Weed Research, 22(6), pp.345-359.

Vander Wall, S.B., 2001. The evolutionary ecology of nut dispersal. The Botanical Review, 67(1), pp.74-117.

Vander Wall, S.B. and Longland, W.S., 2004. Diplochory: are two seed dispersers better than one?. Trends in ecology & evolution, 19(3), pp.155-161.

Vander Wall, S.B., Forget, P.M., Lambert, J.E. and Hulme, P.E., 2005a. Seed fate pathways: filling the gap between parent and offspring. Seed fate: Predation, dispersal and seedling establishment, pp.1-8.

Vander Wall, S.B., Kuhn, K.M. and Beck, M.J., 2005b. Seed removal, seed predation, and secondary dispersal. Ecology, 86(3), pp.801-806.

Veldman, J.W. and Putz, F.E., 2010. Long‐distance dispersal of invasive grasses by logging vehicles in a tropical dry forest. Biotropica, 42(6), pp.697-703.

Von Der Lippe, M., Bullock, J.M., Kowarik, I., Knopp, T. and Wichmann, M., 2013. Human-mediated dispersal of seeds by the airflow of vehicles. PloS one, 8(1), p.e52733.

Way, D.A., Ladeau, S.L., McCarthy, H.R., Clark, J.S., Oren, R.A.M., Finzi, A.C. and Jackson, R.B., 2010. Greater seed production in elevated CO2 is not accompanied by reduced seed quality in Pinus taeda L. Global Change Biology, 16(3), pp.1046-1056.

Wichmann, M.C., Alexander, M.J., Soons, M.B., Galsworthy, S., Dunne, L., Gould, R., Fairfax, C., Niggemann, M., Hails, R.S. and Bullock, J.M., 2009. Human-mediated dispersal of seeds over long distances. Proceedings of the Royal Society B: Biological Sciences, 276(1656), pp.523-532.

Wilson, C.E., Castro, K.L., Thurston, G.B. and Sissons, A., 2016. Pathway risk analysis of weed seeds in imported grain: A Canadian perspective. NeoBiota, 30, p.49.

Xiao, Z., Wang, Y., Harris, M. and Zhang, Z., 2006. Spatial and temporal variation of seed predation and removal of sympatric large-seeded species in relation to innate seed traits in a subtropical forest, Southwest China. Forest Ecology and Management, 222(1-3), pp.46-54.

Zeileis, A. and Hothorn, T. (2002). Diagnostic Checking in Regression Relationships. R News 2(3), 7-10.

Zhang, R., Jongejans, E., & Shea, K. (2011). Warming increases the spread of an invasive thistle. PLoS One, 6(6), e21725.

Zhang, R., Post, E., & Shea, K. (2012). Warming leads to divergent responses but similarly improved performance of two invasive thistles. Population ecology, 54(4), 583-589.

**Table 1.** Estimates (1 standard error), -scores, and -values for the coefficients in the mixed-effects GLM with logit link fit to the proportion of seeds removed at 6, 12, 24, and 48 hours. The intercept (baseline) represents *C. acanthoides* seeds from unwarmed maternal plants and without elaiosomes. Estimates must be transformed using the inverse logit function to yield the proportion of seeds removed.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **6 Hours** | | | **12 Hours** | | |
|  | **Estimate** | ***z*** | ***p*** | **Estimate** | ***z*** | ***p*** |
| **Intercept** | -3.220 0.426 | -7.569 | <0.001 | -1.859 0.325 | -5.712 | <0.001 |
| **Species** | -0.365 0.290 | -1.259 | 0.208 | 0.282 0.159 | 1.770 | 0.077 |
| **Warming** | 1.767 0.275 | 6.426 | <0.001 | 1.888 0.171 | 11.053 | <0.001 |
| **Elaiosome** | 1.564 0.276 | 5.674 | <0.001 | 1.869 0.204 | 9.153 | <0.001 |
| **Species:Warming** | 1.170 0.270 | 4.338 | <0.001 |  |  |  |
| **Species:Elaiosome** | 1.242 0.270 | 4.593 | <0.001 | 0.738 0.213 | 3.459 | <0.001 |
| **Warming:Elaiosome** | -1.921 0.294 | -6.542 | <0.001 | -1.747 0.222 | -7.876 | <0.001 |
|  | | | | | | |
|  | **24 Hours** | | | **48 Hours** | | |
|  | **Estimate** | ***z*** | ***p*** | **Estimate** | ***z*** | ***p*** |
| **Intercept** | 1.339 0.343 | 3.901 | <0.001 | 2.666 0.456 | 5.853 | <0.001 |
| **Species** | -0.738 0.222 | -3.324 | <0.001 | -0.300 0.275 | -1.090 | 0.276 |
| **Warming** | 0.946 0.254 | 3.732 | <0.001 | 1.149 0.244 | 4.707 | <0.001 |
| **Elaiosome** | 1.124 0.260 | 4.328 | <0.001 | 2.406 0.547 | 4.400 | <0.001 |
| **Species:Warming** | 1.082 0.311 | 3.483 | <0.001 |  |  |  |
| **Species:Elaiosome** | 1.006 0.313 | 3.217 | 0.001 | -1.227 0.622 | -1.972 | 0.049 |
| **Warming:Elaiosome** | -1.115 0.317 | -3.521 | <0.001 |  |  |  |

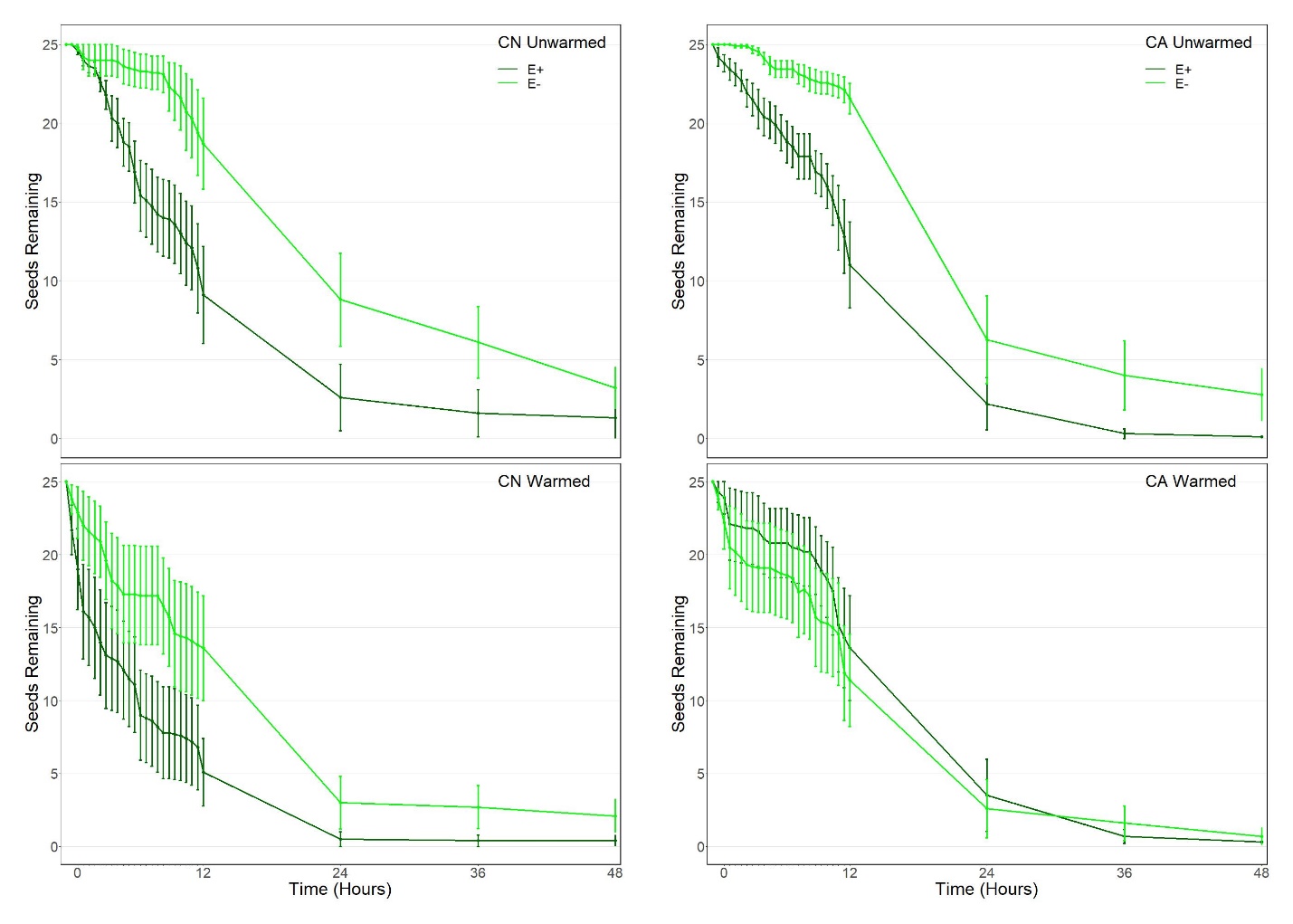
**Figure 1.** Ant removing a *C. acanthoides* seed with an elaiosome (11:30).



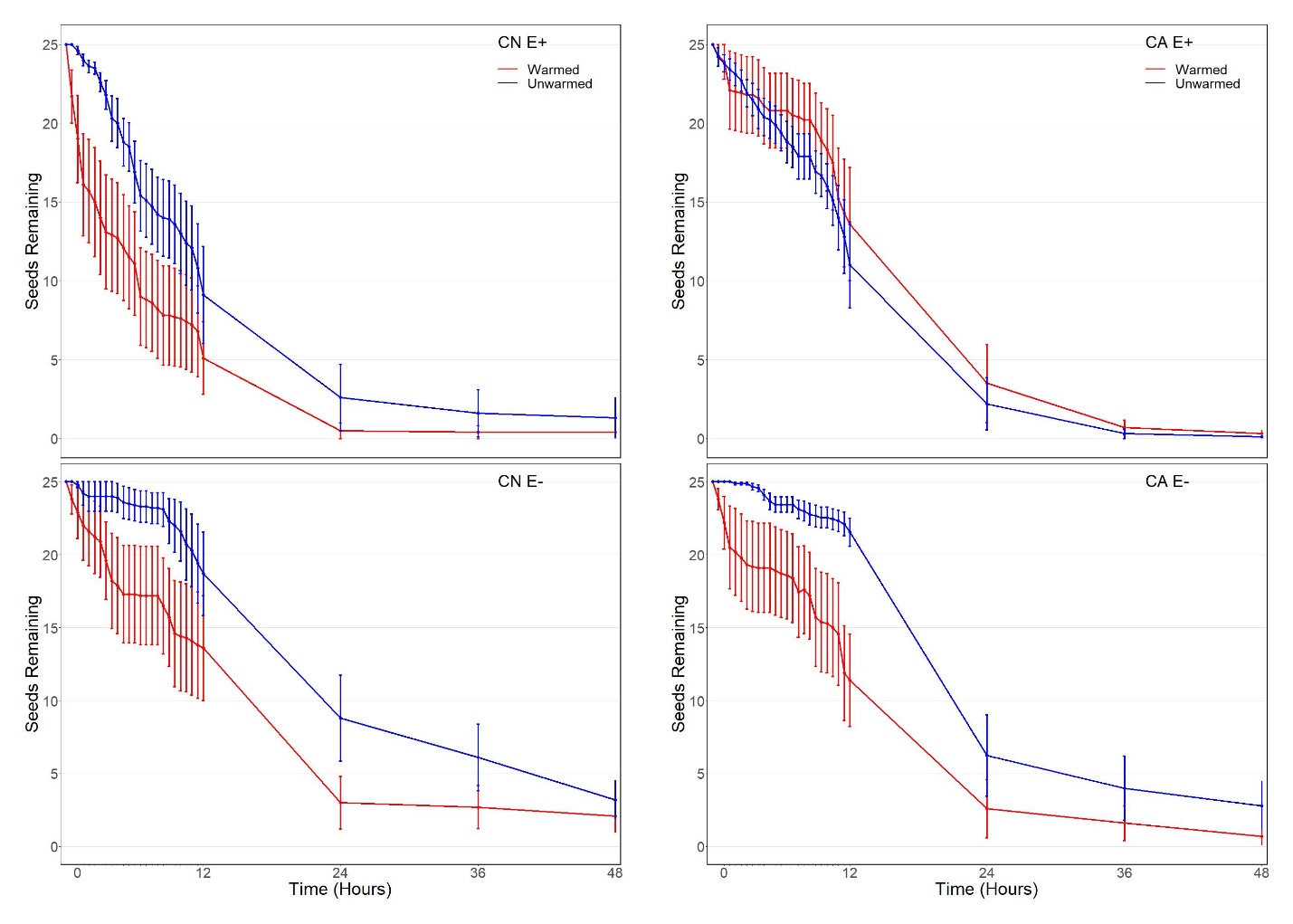
**Figure 2.** Cricket removing a *C. acanthoides* seed without an elaiosome (20:30).



**Figure 3.** Observed number of seeds remaining when elaiosome is present (E+) or absent (E-), conditioned on species (CN *Carduus nutans*, CA *Carduus acanthoides*) and warming treatment applied to the maternal plant. Error bars represent standard error on the mean.



**Figure 4.** Observed number of seeds remaining when maternal plant is warmed or unwarmed, conditioned on species (CN *Carduus nutans*, CA *Carduus acanthoides*) and elaiosome presence (E+ present, E- absent). Error bars represent standard error on the mean.



**Figure 5.** Observed number of seeds remaining between species species (CN *Carduus nutans*, CA *Carduus acanthoides*), conditioned on warming treatment applied to the maternal plant and elaiosome presence (E+ present, E- absent). Error bars represent standard error on the mean.

