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Research Article

Proximity to wind turbines altered plant–pollinator dynamics in prairie and sagebrush ecosystems in Wyoming, USA

Michelle Weschler[1,2], **Brenna Martin**[1] **and Lusha Tronstad**[1–3]

[1]Wyoming Natural Diversity Database, University of Wyoming, Laramie, WY, USA
[2]Department of Zoology and Physiology, University of Wyoming, Laramie, WY, USA
[3]Program in Ecology and Evolution, University of Wyoming, Laramie, WY, USA

Correspondence: Michelle Weschler (mweschle@uwyo.edu)

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Wind turbines influence several abiotic conditions in the environments they are sited in and may influence the behavior and movement of insect pollinators. It is unknown how operating turbines influence plant–pollinator interactions. To investigate if pollination dynamics could be affected by the presence of wind turbines, we recorded videos of pollinating insects visiting flowers on blooming, native plants within a wind energy facility, and at five sites located 4–28 km from operating turbines. We calculated the length of interactions between insect pollinators and flowers, and identified individual behaviors exhibited by visiting insects. Insects interacted with flowers for longer periods of time when closer to wind turbines. As distance to turbine increased, the probability that pollinating insects would crawl into blooms or drink nectar decreased, while the probability that they would rest on plants increased. These behaviors also varied with changes in wind speed, air temperature, and the number of flowers on plants. Our study is one of the first to offer evidence that plant–pollinator interactions could be altered by turbines or abiotic changes caused by turbines. This topic merits further investigation to help land managers and conservation organizations make informed decisions about future turbine siting, restoration, and conservation efforts.

Keywords: bees, behavior, ecology, native flora, pollination, renewable energy

Introduction

Insect pollinators such as butterflies (Van Dyck et al. 2009, Nakamura 2011, Swengel et al. 2011, Warren et al. 2021), moths (Fox 2013, Bell et al. 2020, Green et al. 2021), and wild bees (Goulson et al. 2008, Potts et al. 2010) are declining regionally or throughout their range (Grixti et al. 2009, Potts et al. 2010, Hallmann et al. 2017, Harvey et al. 2023). Threats to pollinators include climate change, pesticide use, the introduction and spread of pests and pathogens, pollution, and changes in land-use (Grixti et al. 2009, Halsch et al. 2021, Brunet and Fragoso 2024). Landscape-scale disturbance that results in habitat loss and fragmentation may be one of the

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prominent drivers of decline (Vanbergen and Initiative 2013, Goulson et al. 2015). For example, conversion of flower-rich habitat to farmland in the UK and North America has contributed to lower floral abundance and diversity, driving bumble bee species declines (Goulson et al. 2008, 2015). Loss of wild pollinators will likely negatively impact the reproductive success and genetic diversity of many crops and native plants by destabilizing plant–pollinator networks (Ramos-Jiliberto et al. 2020).

Pollinator behavior, such as movement and diet preference, is one aspect of pollination ecology influenced by landscape disturbance (Hadley and Betts 2012). Invertebrates alter their behavior in response to abiotic environmental conditions such as air temperature (Martini et al. 2018, Leith et al. 2021) and wind speed (Withers and Harris 1997, Chen et al. 2018), both of which can be affected by landscape disturbance. These external stimuli often interact with one another, the biotic environment, and the insect's internal state, resulting in context-specific behavior (Dahake et al. 2023). Insect pollinators exhibit foraging behaviors that are correlated with reproductive success, speciation or reproductive isolation in plants (e.g. floral constancy, preference, visitation time, visitation rate, and nectar robbing; Ne'eman et al. 2010, Hopkins 2022) that may be context-dependent. Renewable energy infrastructure, such as wind turbines, cause disturbance that has measurable effects on the abiotic conditions of environments they are sited in; however, information on how insect pollinators respond to these specific landscape disturbances is scarce (Weschler and Tronstad 2024).

The wind industry has seen rapid growth in the past several decades, a trend that is predicted to continue (Wiser et al. 2024). Wind energy facilities require large amounts of land, and the area around turbines is often reseeded, grazed, or used for agriculture (Manwell et al. 2010). Wind turbines can affect abiotic factors in an ecosystem. Generally, turbines increase ambient temperatures and decrease wind speed downwind, and some of these effects can persist for several kilometers downwind of turbines (Miller and Kleidon 2016, Whalen et al. 2019). These environmental changes may influence insect behavior; for example, insects may be attracted to turbines because of their color, shape, and heat output (Weschler and Tronstad 2024), potentially reducing time spent at nearby floral resources. Wild pollinators modify their behavior as a result of environmental changes due to the installation of infrastructure used to generate electricity (i.e. solar panels; Guiller et al. 2017, Grodsky et al. 2021), but no previous studies have addressed how their foraging behavior may be altered at wind energy facilities. Therefore, understanding how wind turbines influence pollinator–plant interactions may be crucial to conserving both groups.

The goal of this research was to investigate how the behavior of insect pollinators changed with distance from turbines and changes in abiotic conditions associated with turbine operation. Because abiotic changes due to turbines, such as shifts in infrasound prevalence, average temperature, and wind speed, can be measured up to 20 km downwind of turbines in windy conditions (Marcillo et al. 2015), we wanted to observe how behaviors specific to pollination efficacy may be altered along the same gradient. Our questions were: 1) do aspects of insect pollinator behavior, such as visitation rate at flowers and the amount of time spent at flowers, differ with distance to turbines? 2) Does the distance to turbines and associated abiotic factors influence the frequency of specific behaviors on and around flowers? To address these questions, we analyzed video footage of pollinators foraging at several sites located at varying distances from operating wind turbines in Wyoming, USA.

Study sites

We assessed pollinator behavior at six sites located at varying distances from wind turbines in mixed-grass prairie and sagebrush steppe ecosystems in southeastern Wyoming, USA. One site was an operating wind energy facility with 74 turbines and a power generation capacity of 136.9 megawatts (MW). The turbines at this facility had a hub height of 80 m, a rotor diameter of 91 m, and a total height of 125.6 m (Hoen 2018). Four other sites ~ 3.9, 7.2, 10.7, and 13.2 km downwind from the nearest turbines, were undeveloped lands selected because they were accessible, publicly owned (i.e. managed by the state of Wyoming or the Bureau of Land Management), and slated for potential wind energy development in the future. The final site was an undeveloped, publicly owned reference location 28.1 km from the nearest operating turbine, selected to minimize downwind effects that persist for long distances. Flowering plants with pollinator activity observed at the sites included *Cirsium* sp., *Erysimum* sp., *Mertensia* sp., *Pediocactus* sp., *Sphaeralcea* sp., *Opuntia* sp., *Senecio* sp., *Cleomella* sp., *Crepis* sp., *Antennaria* sp., *Phlox* sp. and *Thermopsis* sp. (Table 1). The average monthly precipitation in the area during our study was 2.5–5.0 cm, and the average temperature range was 1.1 to 28.3°C. The average daily temperature across our study period was 15.7°C (National Oceanic and Atmospheric Administration, National Weather Service, weather.gov).

Material and methods

We recorded video footage to measure the behavior of insects visiting flowers within an operating wind facility and at sites ≤ 28.1 km from wind facilities. We visually verified that the nearest turbines were operating before each recording session. We aimed a GoPro Hero5 camera at a flowering plant for 1–5 h between May and July 2022 on fair weather days (little to no precipitation and air temperatures > 17°C) during daylight hours (06:00 to 20:00 h). The order of site visitation across each week and on individual days when more than one site was visited was randomized. One camera was attached to a tripod and positioned to record flowering plants that were selected haphazardly at sites during each field visit. Subsequent recording sessions at the same site were ≥ 50 m from the previous camera location. Wind speed (to the

Table 1. The number of successful recording sessions, dates of recording sessions, total amount of footage watched, and genera of plants observed at each site based on their distance from operational wind turbines.

Site (distance from turbines, km)	No. of recording sessions	Recording dates (2022)	Total amount of footage (h)	Blooming plant genera observed
0	1	9 June	2	*Artemisia*, *Astragalus*, *Erigeron*, *Erysimum*, *Linum*, *Opuntia*, *Xylorhiza*
3.9	4	26 May, 7 June, 22 June, 5 July	13	*Alyssum*, *Artemisia*, *Astragalus*, *Castilleja*, *Chaenactis*, *Cirsium*, *Cleome*, *Cryptantha*, *Erigeron*, *Machaeranthera*, *Oxytropis*, *Physaria*, *Senecio*, *Thermopsis*, *Vicia*, *Xanthisma*
7.2	2	13 June, 29 June	7	*Artemisia*, *Cryptantha*, *Erysimum*, *Opuntia*, *Sphaeralcea*
10.7	2	27 June, 17 July	2	*Artemisia*, *Astragalus*, *Cirsium*, *Machaeranthera*, *Musineon*, *Phlox*, *Senecio*, *Xanthisma*
13.2	3	8 June, 23 June, 7 July	12	*Antenarria*, *Artemisia*, *Cirsium*, *Crepis*, *Erigeron*, *Phlox*, *Sedum*, *Taraxacum*
28.1	3	2 June, 14 June, 16 June	9	*Artemisia*, *Astragalus*, *Castilleja*, *Cerastium*, *Erigeron*, *Grindelia*, *Mertensia*, *Oxytropis*, *Pediocactus*, *Phlox*

nearest 0.1 m s^{-1}) and ambient temperature (to the nearest 0.1°C) were measured at the start and finish of each recording session with a Neilsen–Kellerman Kestrel 2000 weather meter to assess wind turbine effects on abiotic conditions at our sites.

We assessed pollinator behaviors by directly observing video footage in response to wind speed, temperature, plant characteristics, and the distance to the nearest turbines. Flowering plants that were interacted with were identified to the best of our ability and ultimately categorized based on the number of flowers visible in the frame of the video footage per plant as high (> 20), medium (10–20), or low (1–9 flowers). Plants were categorized this way because we were unable to identify all our plants to species and had a variety of genera represented without much overlap between sites, and because it was difficult to get an accurate total flower count due to the video resolution. Pollinator behavior was recorded based on individual insects' visits with flowers, henceforth called 'interactions'. Interactions were defined as an individual insect visiting a flower. An interaction started when an insect contacted a flower and ended when the insect left the camera's field of vision. An insect touching multiple flowers was considered part of a single interaction and the number of flowers they interacted with was recorded. The duration of interactions was calculated by recording the camera timestamps at the beginning and end of an interaction. Duration included flight time, if an insect moved to multiple flowers, and flower-handling time. A single interaction could also consist of multiple types of behaviors, and the number of behaviors exhibited per interaction was recorded. Types of behaviors we recorded included collecting pollen, drinking nectar, nectar robbing, contacting the flower for ≤ 3 s without displaying another behavior (also known as 'touching'), resting, crawling into the flower, interacting with an individual of the same species, and interacting with an individual of a different species. Behaviors displayed during an interaction were recorded as a '1' while those that were not displayed were recorded as a '0'.

We compared behavior using generalized linear models (GLM) with the *glm()* function in Program R (www.r-project.org) to estimate the effect of distance from turbine. Our first set of analyses focused on response variables including duration of interactions, proportion of time that pollinators were present during individual recording sessions, number of pollinators observed, number of flowers visited, and number of behaviors observed per interaction. We used the distance to the nearest turbine in kilometers as a fixed effect. Wind speed and temperature were also included as fixed effects to account for abiotic factors affecting insect flight and seasonality. Finally, the categorical variable of flower count (where high flower count was the reference level) was included as a fixed effect as a proxy for flower availability to add statistical power. The continuous variables were scaled to assist with analysis. We present information on flower count separately from abiotic variables because our questions focused on abiotic factors. Our data involving time insects spent interacting with flowers were not normally distributed, and most closely matched a gamma distribution after inspecting histograms of our response variables. We summarized the mean interactions duration with *ddply()* based on site and date (i.e. recording session) as well as flower count for the two videos that contained multiple species of flowers in the frame, and analyzed it using a gamma distribution. For response variables that relied on count-data (e.g. number of insect visitors, number of behaviors, etc) we used a Poisson distribution, and we used beta regression for the proportion of time pollinators were present throughout our videos.

Our second set of analyses used the presence of specific behaviors as the response variable. We used *glm()* with the *logit()* function to calculate log-odds to compare the differences in the probabilities of individual behaviors based on the same model variables listed previously. We used the binomial distribution to analyze our data because behaviors were recorded as present (1) or absent (0). Instances of nectar robbing, interacting with an individual of the same species, and interacting with an individual of a different species were recorded but ultimately not analyzed due to a lack of sufficient statistical power. We used the 'lme4' package (Bates et al. 2015) in Program R to run our models and the 'plyr' package (Wickham 2011) to summarize data. Packages 'sjPlot' (Lüdecke 2023) and 'ggplot2' (Wickham 2016) were used to visualize the results.

Results

Variation in temperature and wind speed among our sites was partially explained by distance to wind turbines. Wind speed decreased as distance to turbine increased (glm; $\beta = -0.330$, $T = -16.527$, $p < 0.0001$), although the correlation between wind speed and distance to turbines was weak (correlation = −0.55). Temperature slightly increased as distance to turbine increased (glm; $\beta = 0.014$, $T = 3.544$, $p = 0.0004$) and was also weakly correlated (correlation = 0.32). We collected and watched 45 h of footage and recorded 472 interactions with flowers over 15 different days. The average length of the recording sessions was 2.95 h. Most of the insect visitors to flowers were Hymenoptera (64%, n = 302). Diptera (6%, n = 29), Coleoptera (1%, n = 5), and Lepidoptera (0.6%, n = 3) were less abundant; we were unable to identify 28.4% (n = 133) to order. The average interaction was 43 s long and composed of 1.7 behaviors. Interactions with flowering plants closer to turbines were longer than those farther away (glm; $\beta = -0.264$, $T = -2.116$, $p = 0.034$; Fig. 1A). The mean duration of interactions was also longer near turbines (glm; $\beta = -0.455$, $T = -2.892$, $p = 0.012$; Fig. 1D). Total interaction time decreased as wind speed increased (glm; $\beta = -0.185$, $T = -2.302$, $p = 0.021$; Fig. 1B) and as air temperature increased (glm; $\beta = -0.226$, $T = -2.942$, $p = 0.003$; Fig. 1C). The mean duration of interactions was not influenced by wind speed (glm; $\beta = -0.320$, $T = -2.05$, $p = 0.061$; Fig. 1E), but decreased as temperature increased (glm; $\beta = -0.379$, $T = -2.781$, $p = 0.015$; Fig. 1F). The number of individuals observed per day and plant type increased as temperature increased (glm; $\beta = 0.409$, $Z = 7.681$, $p = < 0.001$). The number of flowers visited per interaction decreased as wind speed increased (glm; $\beta = -0.141$, $Z = -3.372$, $p < 0.001$) and as temperature increased (glm; $\beta = -0.114$, $Z = -2.965$, $p = 0.003$). The proportion of time when pollinators were present in our videos based on recording session and flower taxa decreased as distance to turbine increased (betareg: $\beta = -0.803$, $Z = -3.467$, $p < 0.001$). Variation in the number of behaviors exhibited per interaction was not explained by any of our fixed variables.

Several specific behaviors were related to proximity to turbines, air temperature, and wind speed (Fig. 2). Insects were more likely to crawl into flowers (glm; $\beta = -0.897$, $Z = -4.334$, $p < 0.001$) and drink nectar (glm; $\beta = -1.704$, $Z = -3.431$, $p < 0.001$) closer to turbines (Fig. 3A). Insects were more likely to rest during interactions at sites farther from turbines (glm; $\beta = 1.745$, $Z = 5.525$, $p < 0.001$; Fig. 3A). Counterintuitively, crawling into the flower was less

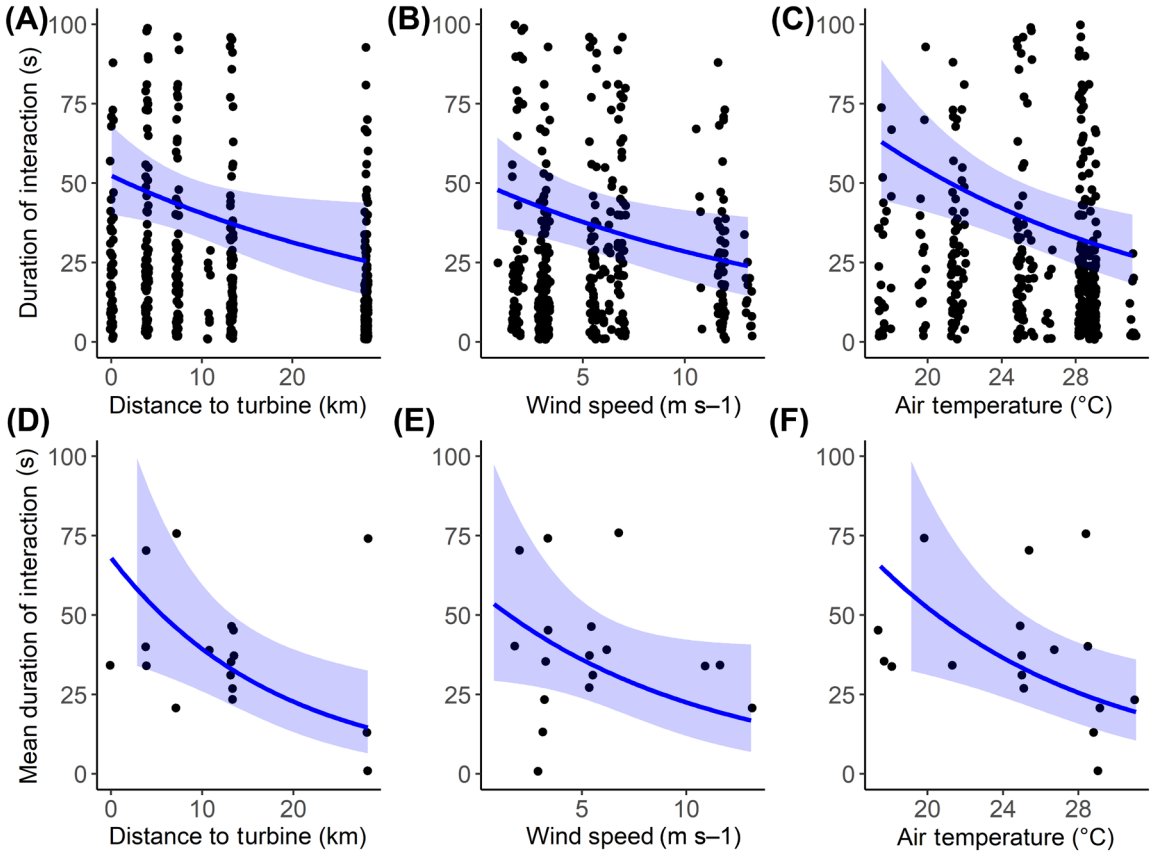

Figure 1.The duration of interactions in seconds (n = 472) decreased as the distance to turbines (A), wind speed (B), and air temperature (C) increased. The mean duration of interactions, as calculated for each recording session (n = 17), also decreased as distance to turbines (D), wind speed (E), and air temperature (F) increased. Shaded blue areas represent uncertainty based on a 95% confidence interval.

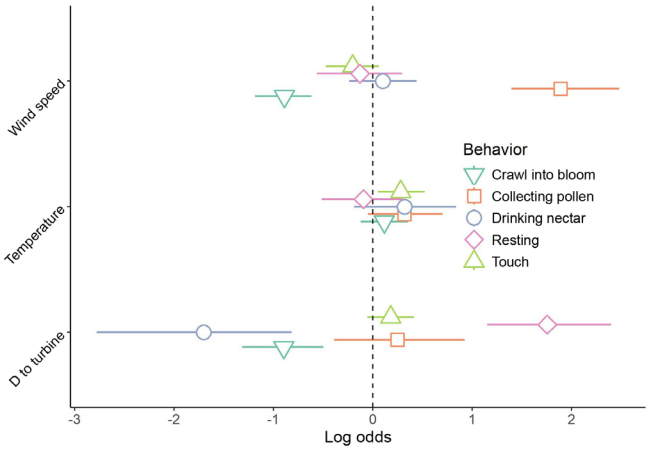

Figure 2. The log odds of collecting pollen, crawling into flowers, drinking nectar, contacting the flower for < 3 s (touch), or resting during an insect's interaction with a flower based on changes in wind speed, air temperature, and distance to turbine (D to turbine). Positive correlations appear to the right of zero, while negative correlations appear to the left. Error bars overlapping zero indicate no significance. Larger positive numbers indicate a stronger positive correlation, while lower negative numbers indicate a stronger negative correlation. Error bars represent a 95% confidence interval.

likely at high wind speeds (glm; $\beta = -0.890$, $Z = -6.160$, $p < 0.001$; Fig. 3B) despite higher wind speeds occurring closer to turbines. Insects collected pollen more often at high wind speeds (glm; $\beta = 1.890$, $Z = 6.904$, $p < 0.001$; Fig. 3B) and were more likely to touch flowers at high temperatures (glm; $\beta = 0.282$, $Z = 2.009$, $p = 0.044$; Fig. 3C).

Flower availability in the frame (i.e. flower count) explained the variance in several of our response variables when included as a fixed effect. Flower availability significantly influenced the duration of interactions (glm: $\beta = 0.509$, $T = 3.063$, $p = 0.002$), with longer interactions taking place when flower counts were low (emmeans: $p < 0.007$). The number of individuals per recording session and flower taxa (glm; $\beta = -0.317$ to 0.306, $Z = -3.056$ to 2.623, $p < 0.008$) was highest at medium flower counts (emmeans; $p < 0.02$). The number of flowers visited per interaction ($\beta = -0.891$, $Z = -9.489$, $p < 0.0001$) was lowest at low flower counts (emmeans; $p < 0.0001$). The probability of some specific behaviors was also influenced by flower availability (Supporting information). We saw variation in flower abundance, richness, and density among our sites based on floral quad measurements performed by Tronstad et al. (2025; Supporting information). Floral density reduced slightly as distance to turbine increased (glm: $\beta = -0.072$, $T = -2.564$, $p = 0.02$) but we did not see significant differences among our sites when analyzed as a categorical variable. Floral richness slightly increased as distance to turbine increased (glm: $\beta = 0.009$, $T = 2.218$, $p = 0.03$) but also was not significant when sites were compared categorically. Flower abundance (total number of flowers) decreased as distance to turbine increased (glm: $\beta = -0.05$, $Z = -43.31$, $p < 0.0001$) and differed among sites (glm: $\beta = -0.661$ to 1.138, $Z = -9.131$ to 33.761, $p < 0.0001$), with our 3.9 km site having the highest abundance (emmeans: $p < 0.0001$).

Discussion

Our data suggest the probability of certain behaviors being displayed changed with distance to turbines in our system. We also found that the proportion of time we observed insects interacting with flowers increased closer to turbines, and that interactions with plants tended to last longer when occurring closer to turbines, including the combined time spent flying between flowers and time spent on flowers (i.e. flower-handling time). Longer flower-handling time can increase the pollination success of some plants and the effectiveness of pollen transfer in some taxa (Conner et al. 1995, Ivey et al. 2003). In some cases, longer handling time on a single plant can also lead to pollen waste and an increased chance of geitonogamy or self-pollination (Fishbein and Venable 1996). Duration of interactions with flowering plants can be influenced by a number of factors such as insect order, species, and characteristics of individuals such as proboscis length (Herrera 1989), which we were not able to assess due to the limitations of our equipment. Vane and net trapping, however, showed there was no significant difference in pollinator assemblages among our sites (Tronstad et al. 2025). Our study shows that wind turbines may directly or indirectly influence this plant–pollinator relationship, but further study that separates flower handling time from time spent traveling between flowers is necessary to understand the effects of this factor with more certainty.

Wind energy facilities are often constructed within agricultural settings, such as row crop fields, orchards, and rangelands, which highlights the importance of understanding the behaviors of wild pollinators and how they are influenced by wind energy to maximize crop pollination and yield. All five of the most common behaviors we observed were potentially influenced by distance to turbine, wind speed, air temperature, or a combination of these variables within our system. Specific flower-handling behaviors can influence pollination success. For example, wild bees, which are more likely to collect nectar by approaching flowers in a way that causes them to come into contact with flower reproductive parts, contribute more to seed set in apple orchards than honeybees (Russo et al. 2017). Honeybees are more likely to obtain nectar by working the side of the flower (i.e. land on the flower but avoid the reproductive parts) and therefore collect pollen less often when foraging for nectar. Variation in pollination behavior among individuals of the same species could also influence pollinator effectiveness. Foraging behavior at artificial donor flowers was found to influence the amount pollen deposited at subsequently visited flowers of three different plant species *Begonia odorata, Exacum affine*, and *Solanum houstonii* by *Bombus impatiens*, a common generalist bumble bee (Russell et al. 2021). One behavior we did not measure because our video footage mainly focused on a single plant species at a time, but is vital to plant reproductive success,

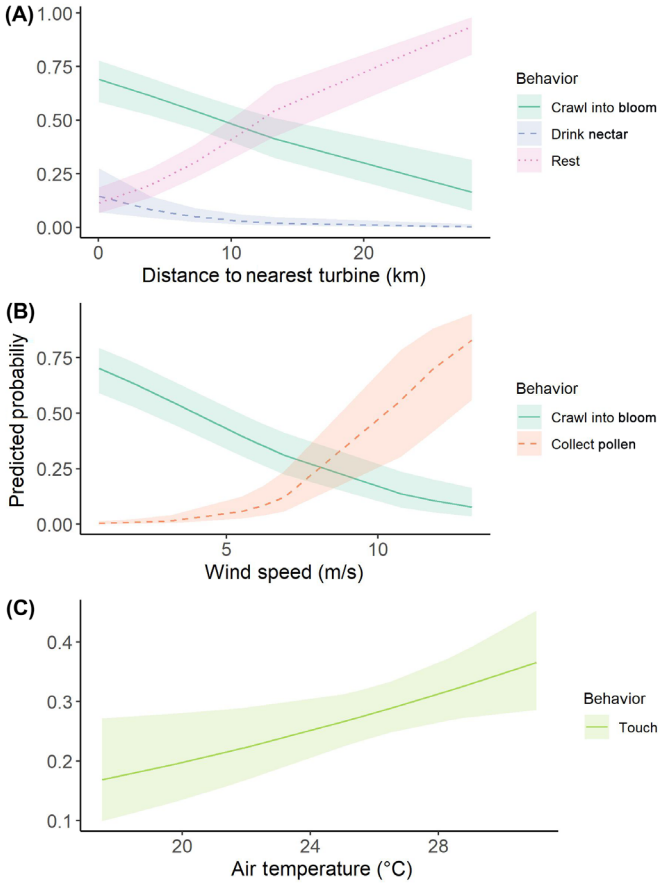

Figure 3. The change in predicted probabilities that insects would perform specific behaviors during an interaction with plants as distance from turbines increased (A), wind speed increased (B), or temperature increased (C). Shaded areas represent uncertainty based on a 95% confidence interval.

is flower constancy. Behavior studies that place constancy in the context of wind energy development would be especially useful for managing these lands.

Turbines have measurable effects on the average wind speed and temperatures of the environments they are sited in (Weschler and Tronstad 2024). Generally, turbine operation increases ambient temperature and decreases average wind speed downwind of turbines. Our system showed slightly different results, with temperature increasing as distance from turbine increased. Our data showed that increases in temperature and wind speed resulted in decreased interaction duration; however, we also saw longer interactions closer to turbines, where there tended to be higher wind speeds. Insect activity is typically lower during high winds (Taylor 1974) and small-bodied species are more vulnerable to changes in wind speed (Peng et al. 1992). Hennessy et al. (2021) and Balfour and Ratnieks (2025) found that honey bees *Apis mellifera* reduce their foraging efforts by visiting fewer flowers and increasing flower handling time as wind speed increases. Our results contradict this by showing an overall decrease in interaction duration during high winds, which would include flower-handling time. A direct comparison is difficult, however, because we did not separate the duration of flight between flowers from flower-handling time, and data were collected over multiple pollinator species. Not all bees are influenced by wind and temperature equally. The buff-tailed bumblebee *Bombus terrestris* prefered foraging for pollen over nectar during warm, dry and windy conditions, potentially because pollen loads on their legs increased flight stability (Mountcastle et al. 2015). *Osmia cornuta* foraging activity at an apple orchard occurred at lower temperatures and in more variable wind conditions than the foraging activity of honeybees (Vicens and Bosch 2000). Similarly, *B. impatiens* were the main pollinators of highbush blueberries in poor weather conditions (10–15°C), while honeybees only visited during good weather (> 15°C) (Wilson and Isaacs 2010). High wind speeds drastically decreased flower visitation in almond orchards with a low diversity of pollinators, more so than those with a high diversity (Brittain et al. 2013).

Floral traits and plant characteristics can also influence pollinator foraging behavior. For example, floral abundance and the spatial arrangement of plants can affect foraging constancy of pollinators, altering pollination efficiency (Ghazoul 2006, Bruninga-Socolar et al. 2022). Flower count explained substantial deviance in our models (6–20% of deviance) which agrees with previous studies that the flower abundance can alter pollinator behavior (Schmitt 1983, Sjödin 2007, Cohen et al. 2021). Insects in our study tended to

spend more time at a flower when the plants they were foraging on had low flower counts, but we saw more individuals when flower counts were in the medium range. Data from our study also suggests that insects were more likely to drink nectar and collect pollen when flower availability was low. Bees prefer traveling short distances when foraging, and as a result may stay at a flower longer when there is a larger average distance between flowers (Bruninga-Socolar et al. 2022). Similarly, medium-sized patches of flowers may offer more efficient foraging, attracting more individuals. This does not, however, explain why we saw more individuals in medium flower-count recordings than those with high-flower counts. The wind energy facility site in our study had a low overall abundance of flowers compared to most of our other sites, which may explain some of our variability across distance to turbine (Tronstad et al. 2025). Furthermore, flower size, shape, and reward availability can determine the different behaviors a pollinator may exhibit during an interaction. For example, nectar levels and nectar renewal rates can influence pollinator behavior by altering time spent in flower patches and the amount of time spent moving between flowers (Dreisig 2012, Forster et al. 2023). Including these measurements and categorizations would improve interpretations of the connection between wind energy and pollinator behavior. Wind turbines can have varying effects on plant communities depending on the ecosystem they are sited in (Tang et al. 2017, Xu et al. 2019, Urziceanu et al. 2021, Qin et al. 2022), but little is known about effects on flower abundance. Our system showed variation in seed set in relation to distance from turbines (Tronstad et al. 2025) and differences in flower abundance, richness, and density, but these could be due to abiotic factors, changes in pollination dynamics, or other influences that we did not measure. Future investigations should compare the same species of plant at varying distances from wind turbines and include measures of pollination efficacy (e.g. seed set or yield) to understand this relationship more thoroughly.

To gain a better understanding of the impacts of wind energy facilities and turbines on insect behavior, it may be important to measure changes in climate on a finer scale. For example, turbines may alter the temperature of flower heads and leaf surfaces that insects are directly interacting with, thus potentially altering insect behavior at those specific plants (Weschler and Tronstad 2024). It is important to note that our study only included a single system (i.e. distance gradient) and a single wind energy facility, therefore our observed correlations are specific to this system and may not fully explain the relationship between insect behavior and distance to turbines. Future investigations should include multiple independent systems and multiple wind energy facilities to avoid pseudoreplication. Wind speed measurements taken throughout the observation period, rather than just a few times during the day would be useful because wind speed is highly variable throughout the day. These measurements would also allow for determination of wind speed effects when specific species are active. Furthermore, our equipment made it difficult or at times impossible to accurately identify all observed taxa and behaviors. Using a camera that can capture higher resolution footage or accommodate the use of a macro lens may increase the accuracy of the data and analysis in the future and allow for the analysis of individual behaviors based on taxa. Our response variables, even when significantly influenced according to our models, still showed high variability, which could indicate that some taxa are more acutely affected by our fixed variables than others.

Our study offers some evidence of pollinating insects displaying altered behavior patterns within a system influenced by wind turbines. While it is impossible to suggest broad causation because of the limitations of the study (i.e. a single, non-replicated study system, technological limitations, inability to control or measure other abiotic variables) we believe our data support the need for further investigation into this phenomenon. Wind energy, along with other renewable energy infrastructure, is being built throughout the world to combat climate change. Although moving away from less sustainable forms of electricity production will be vital to preserving insect habitat and biodiversity (Goulson et al. 2015, Duffy et al. 2022, Harvey et al. 2023), it is important to understand the immediate and long-term impacts of these solutions on ecosystems. Pollinating insects play a critical role in food systems for people, livestock, and wildlife (Potts et al. 2010, Chopra et al. 2015). Aspects of these systems such as crop yields (Hoehn et al. 2008, Woodcock et al. 2019), seed viability (Herrera 1989), and plant diversity (Ollerton et al. 2011) can be negatively impacted by changes in plant–pollinator networks and pollinator behavior. Our study provides a framework and potential methodology for further studies that can gather information on pollinator behavior in the field that can be used to better manage wind facilities for diverse pollinator assemblages, and maximize pollination of nearby crops and rangelands. Improved understanding of how foraging behaviors change because of anthropogenic disturbance may be important for managing ecosystems to support and strengthen beneficial plant–pollinator relationships.

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Author contributions

Michelle Weschler: Data curation (lead); Formal analysis (equal); Investigation (lead); Methodology (equal); Project administration (equal); Resources (equal); Supervision (equal); Validation (equal); Writing – original draft (lead);

Writing – review and editing (equal). **Brenna Martin:** Conceptualization (equal); Formal analysis (supporting); Funding acquisition (equal); Methodology (equal). **Lusha Tronstad:** Conceptualization (equal); Formal analysis (equal); Funding acquisition (equal); Project administration (equal); Resources (equal); Supervision (equal); Writing – review and editing (equal).

Data availability statement

Data are available from the Zenodo Digital Repository: https://doi.org/10.5281/zenodo.20670290 (Weschler et al. 2026).

Supporting information

The Supporting information associated with this article is available with the online version.

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