Erosion Control and Habitat Restoration of Retired Farmland in the Anza-Borrego Desert

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Abstract

Improving agricultural water management in response to diminishing groundwater resources is crucial for sustainable land use. In Borrego Springs, California, state-mandated water reductions are prompting farmers to retire or fallow their farms permanently. However, without proper management, retired farmlands are vulnerable to wind erosion and dust emissions, which hinder restoration efforts and pose risks to human health. Our team conducted a study where we implemented four different erosion control treatments in two blocks of permanently retired citrus orchards. The treatments included (1) rows of mulch (the standard practice), (2) felled citrus trees scattered across the site, (3) fences made from felled citrus trees, and (4) commercial sand fences, each consisting of ten rows oriented to face the dominant wind direction. Preliminary results show average dust control efficiencies of 93% and 94% for the Scattered Trees and Tree Fences respectively, implying that most dust emissions are controlled within these two treatments. The Scattered Tree treatment creates the most effective wind barrier with porosity in a range (28-37%) known to reduce wind speeds while minimizing soil scouring. The Tree Fences showed the most significant reductions in wind speeds. Overall, the Tree fence and Scattered Tree treatments are the most cost-effective choice for controlling erosion, dust emissions, and promoting restoration.

Table of Contents

Executive Summary

Purpose

The community of Borrego Springs has a Groundwater Management Plan (GMP) that aims to significantly reduce groundwater pumping in the Borrego Springs Subbasin over the next 16 years (by 2040). Borrego Springs relies entirely on groundwater for its water supply, which has been overdrafted largely due to agricultural operations. To achieve the reduction goals, many farmers will need to decrease their groundwater use. Consequently, it will not be feasible for all farmers to continue their current operations long-term. In turn, some farmers are selling or permanently retiring their land.

When left unmanaged, retired farmland can cause adverse impacts such as airborne dust emissions, the spreading of invasive species, and an unattractive landscape with low ecosystem function. These impacts can have serious consequences for human and ecological health, and impede the tourism-dominated economy of this location. To find a solution that best addresses these concerns, UCI's Environmental Collaboratory, in collaboration with Land IQ, set up a dust control experiment aimed at minimizing erosion while simultaneously promoting the ecological restoration of functional landscapes that support native flora and fauna communities. To study the restorative potential of the sites, we tested the composition of the soil seed bank, assessed soil salinity levels, and launched a pilot seeding study.

Methods

Four dust control treatments were explored in this study: Mulch Rows, Scattered Trees, Tree Fences, and Sand Fences (Figure 1). The first treatment involves mulching the site in rows with chipped orchard tree material. This treatment is similar to the current fallowing standard (using mulch or ash spread evenly across the site) set forth by the GMP for erosion and dust control, but its effectiveness for plant recruitment is unknown. While mulching in rows is not standard practice, this was done to allow for comparison to the other treatments which were installed in rows. The second treatment involves scattering felled whole orchard tree material across the site evenly, mimicking the arrangement of naturally occurring shrubs in the surrounding desert landscape. The third involves using the same type of tree material to build contiguous stretches of fencing. The fourth treatment consists of commercial Sand Fences in the same layout as the Tree Fences.

The effectiveness of each erosion control treatment was tested directly through dust collections and indirectly through wind speeds and porosity analyses. To determine the composition of plant seeds in the soil seed bank and to test soil salinity, we collected soil samples from the two fallowed farm sites. We propagated a set of soil seed bank samples in a greenhouse setting and studied the composition of the sprouts. The remaining soil samples were taken to a lab where we measured salinity. We also seeded replicate 1 m^2 plots with native species at the two fallowed farm sites to see how well native plants could establish throughout the treatments.

Key findings

- The Scattered Tree and Tree Fence treatments had the highest dust control efficiencies, with average dust control efficiency rates of 93% and 94% respectively.
- The Tree Fence treatment displayed the most significant reduction of wind speed.
- The Scattered Trees had a mean porosity of 28.1% and a maximum porosity of 38.2%, falling closest to the ideal porosity range (30-50%) compared to other treatments.

- The soil seed bank at the sites was dominated by non-native plants with very few native seeds that germinated, demonstrating the importance of seeding and managing weeds after farmland retirement.

Table 1. Summary table of all the erosion metrics and which treatments were the most and least effective for each.

Metric	Most Effective Treatment	Least Effective Treatment
Dust Emissions	Tree Fences and Scattered Trees	Mulch Rows
Porosity	Scattered Trees	Mulch Rows
Wind Speed Reduction	Tree Fences	Mulch Rows
Lowest Cost	Tree Fences	Sand Fences

Table 2. Cost of treatment implementation including selling of excess plant material, labor, transportation, and use of fuel to operate machinery necessary for installation.

Treatment	Estimated Price Range (Cost per acre)
Tree Fences	**$2,250 to $3,000**
Scattered Trees	**$2,500 to $3,250**
Mulch Rows	**$2,500 to $3,750**
Sand Fences	**$3,750 to $4,750**

Conclusion

Given that the Scattered Tree and Tree Fence treatment performed equally well in terms of controlling dust, but outperformed each other in the other metrics (i.e., porosity and wind speed reductions), we conclude that the decisions regarding which treatment to use must take into consideration other priorities. If a more static environment is desired with minimal erosion, the Tree Fences may be the better choice. If restoration is of higher priority, the Scattered Trees would most likely perform better, given that the ideal porosity provides better chances of natural recruitment occurring. Finally, the Tree Fences are the least expensive choice of the two, but it is important to note that the price difference is only $250 more for the implementation of the Scattered Trees (Table 2).

Objectives

This experiment seeks to aid land managers in choosing the best fallowing practices for controlling dust emissions and erosion in a desert environment, thereby maintaining air quality and promoting the restoration of degraded farmland. Borrego Springs is a community of about 2,700 people located in an arid environment where high levels of groundwater extraction for crop irrigation is no longer sustainable (US Census Bureau 2023). California's 2014 Groundwater Sustainability Management Act dictates that each basin or subbasin in the state that is considered overdrafted must have sustainability goals in place. Extensive farmland must be permanently fallowed in the region to achieve this goal. The minimum fallowing standards include removing trees and stabilizing the ground with mulch or ash (Borrego Valley Groundwater Sustainability Agency, 2019). Landowners typically utilize the plant material they have onsite to create mulch, which requires the use of a wood chipper. This process is costly and produces large amounts of carbon emissions, both for the processing of the wood and the transportation of excess mulch offsite (Stolarski et al. 2023). Mulch is known to prevent erosion, but its effects on natural recruitment in the Sonoran desert have not been studied (Prosdocimi et al. 2016). Without erosion control, there is a higher risk of dust emissions which lead to respiratory health hazards and visual blight, which can be detrimental to the general public and the tourism-dominated economy of Borrego Springs (Sing & Sing 2010; Rader 2019). With the results from this study, we can better inform farmers and land managers how they can more effectively retire their land to encourage passive ecological restoration through erosion control. This is crucial not just for farmland in the Borrego Springs area but potentially for other regions where sustainable groundwater management mandates may continue to be implemented across the state.

In this study, we tested more cost-effective alternatives to mulch and ash (the standard practices) for erosion prevention. Overall, the four treatments tested were Mulch Rows, Scattered Trees, Tree Fences, and Sand Fences in two different blocks. Since these fallowing techniques are passive after initial treatment setup, it is important to understand the sites' initial state in terms of its restoration potential. We measured the salinity and determined the seed bank composition of the soils at each site to gather insights on the trajectory of ecological recovery and assess the need for intervention.

Soil seed bank results guide whether future restoration at the experimental site should include the reintroduction of native species and/or control of non-native exotics. The soil salinity findings aid in the selection of proper plant palettes for each site (i.e., choosing species that can tolerate higher salinity for highly saline sites). To determine a suitable plant palette, we also launched a pilot seeding study. The goal of the pilot seeding study is to determine which erosion control treatment is most favorable for allowing native plants to grow and establish, and to determine which species may be appropriate for the conditions of fallowed farmland in this region. The results of these studies can help inform stakeholders who may desire a more active approach in accelerating restoration by directly seeding native species.

Research Questions

This study's main goal was to compare the effectiveness of four erosion control methods to determine which is most conducive to the restoration of the landscape. We addressed the following questions:

1. Is there a more cost-effective alternative to mulching?
2. Which treatment produces the least amount of airborne dust emissions, has the

most ideal porosity, and results in the least erosion?

3. What are the baseline site conditions of the soil seed bank and salinity that could limit restoration potential?
4. Can retired desert farmland support the growth of native species? If so, which treatment provides the most ideal conditions?

Significance

The results of this project are intended to guide adaptive management practices for future retired farmlands in Borrego Springs. The soil seed bank study evaluated the need for the active restoration of native plants versus passive reestablishment at these specific sites, which could inform similar sites. Pilot seeding and salinity testing helped to refine the plant palette for active restoration, which may be necessary given the results of the soil seed bank study. Drone imaging, fence porosity, wind reduction, and erosion assessments were used to determine the most effective dust control treatment for both maintaining public health and promoting restoration. The overall goal was to help inform how the remaining farmland in Borrego Springs will be permanently fallowed using the insights of our study. Since the novel tree-based methods were found to be more effective than mulching alone, faster ecosystem restoration at a lower cost and reduced carbon emissions could be achieved in future farm retirement.

Literature Review

The project is located in the northern part of the Borrego Springs Subbasin. This basin is in an arid desert, receiving an average yearly rainfall of 5.83 inches across 30 years (US Climate Data). The northern region of the subbasin has historically been and is currently dominated by agricultural operations. This part of the Subbasin has seen the most rapid decline in groundwater levels at an average rate of 1.95 feet per year from 1958 to 2017 (Borrego Water District 2019). In retired agricultural fields, salts often become concentrated in the topsoil due to consistent irrigation followed by evapotranspiration (Ibrahimi et al. 2022). High salinity may limit native plant establishment (Fiore et al. 2024; Blanchard et al. 2023).

Most of the agricultural lands found in the Subbasin contain the soil type Rositas fine sand (RoA), which is one of the most susceptible to wind erosion (LandIQ & UCI, 2023). Drylands such as this one are major sources of dust storms, which contribute to many health complications such as pathogenic and fungal infections (valley fever), pneumoconiosis, asthma, and chronic obstructive pulmonary disease (Schweitzer et al. 2018). Although there have been prior studies on erosion control and soil amendments, little is known about retiring farmland in desert regions specifically (Bainbridge 1995; Rader 2019; Webb et al. 2019). Existing literature about retiring farmland in more humid climates states that improperly retired farmland may harbor and spread invasive species, emit dust, and lower the landscape's aesthetic value (Land IQ 2024). Compared to other ecosystems, deserts are more susceptible to erosion. Further, erosion is known to interfere with vegetation succession by affecting seed availability, dispersal, germination, and establishment (Jiao et al., 2009). In a similar desert ecosystem within Arizona, it was found that without erosion prevention of degraded sites, revegetation of saltbush and creosote bush occurred in a period of 20-40 years given ideal conditions, and potentially 300-400 years for other native plants (Gelt 1993).

To prevent erosion, vegetation such as shrubs can help capture airborne sediments and nutrients, and as a result, provide a safe zone for new seedlings to establish (Okin et al. 2001). When shrubs are not available, shrub-like structures can serve similar functions, such as the Scattered Tree treatment in our study. Structures that have been proven effective at reducing wind erosion and trapping sediment include commercially available sand fences and natural fences made from logs or brush (Li and Sherman 2015, Bainbridge 1995). Within a desert environment specifically, natural fences (also known as "vertical mulching") have been effective at reducing erosion with minimal input (Rader 2019). Although all three treatments—Scattered Trees, Tree fences, and Sand Fences—are known to be effective, this study aims to compare their relative performance in achieving dust and erosion control, specifically in a sandy retired desert farmland context using the available tree material onsite.

Knowing the typical porosity of each structure type is key to seeing whether our structures can serve the same erosion-prevention functions as natural vegetation. Porosity refers to the ratio between open space and blockages within the structure, and its influence on air permeability and dust capture. Ideally, a balance is reached between both aspects. Barriers with a 30% to 50% porosity are typically the most effective at achieving this balance (Li & Sherman 2015; Lee et al. 2023). This range is also ideal for minimizing structural stress, which helps to maintain the barrier's stability and durability. If the porosity is too low, wind flow may be fully obstructed, creating strong turbulence and encouraging wind tunneling around the barrier. In time, this can result in scouring and erosion of the surrounding soil (Li & Sherman, 2015). Low-porosity barriers may also obstruct water, seeds, and soil deposition. In contrast, if the porosity is too high, airflow may not be restricted enough, and deposition may be less likely, as airborne material will flow through too easily (Lee et al. 2023). One caveat in the existing literature is that flat fences were used in these studies, whereas two of our fence treatments are made with whole trees with complex 3-dimensional shapes. Our other metrics for measuring soil surface erosion and dust control will help inform whether the porosity of these structures affects their capacity to control erosion similarly.

Methods

Plot Design

This study took place in two separate blocks of retired citrus orchards (i.e., BWD block and T2 block—named for the land owners, Borrego Water District and T2 Borrego LLC). All treatment material (excluding the Sand Fences) was sourced from the felled trees on-site. The Mulch Row treatment had coarsely processed wood laid into rows covering the ground surface. The Scattered Trees consisted of single whole trees or brush piles in a scattered formation, mimicking the layout of a naturally occurring desert shrubland. The Tree Fences also used entire felled trees, but were arranged into contiguous rows to form fences. The Sand Fences are commercially available stakes of wood held together by wire, often used in the restoration of beach dunes. All four erosion control treatments were initially planned to be constructed in rows of 10 (Figure 1). The Scattered Trees in the BWD block deviated from this with a total of 13 rows instead. The Tree Fences in T2 also resulted in 11 rows instead of 10. The rest of the treatments had 10 rows. In cases where we had planned to take wind measurements in row 10 (the originally intended last row), we instead measured from whichever was the last row in that treatment. All treatment plots were oriented perpendicular to the predominant wind direction at

315° (northwest) to best reduce wind speeds (Figure 2).

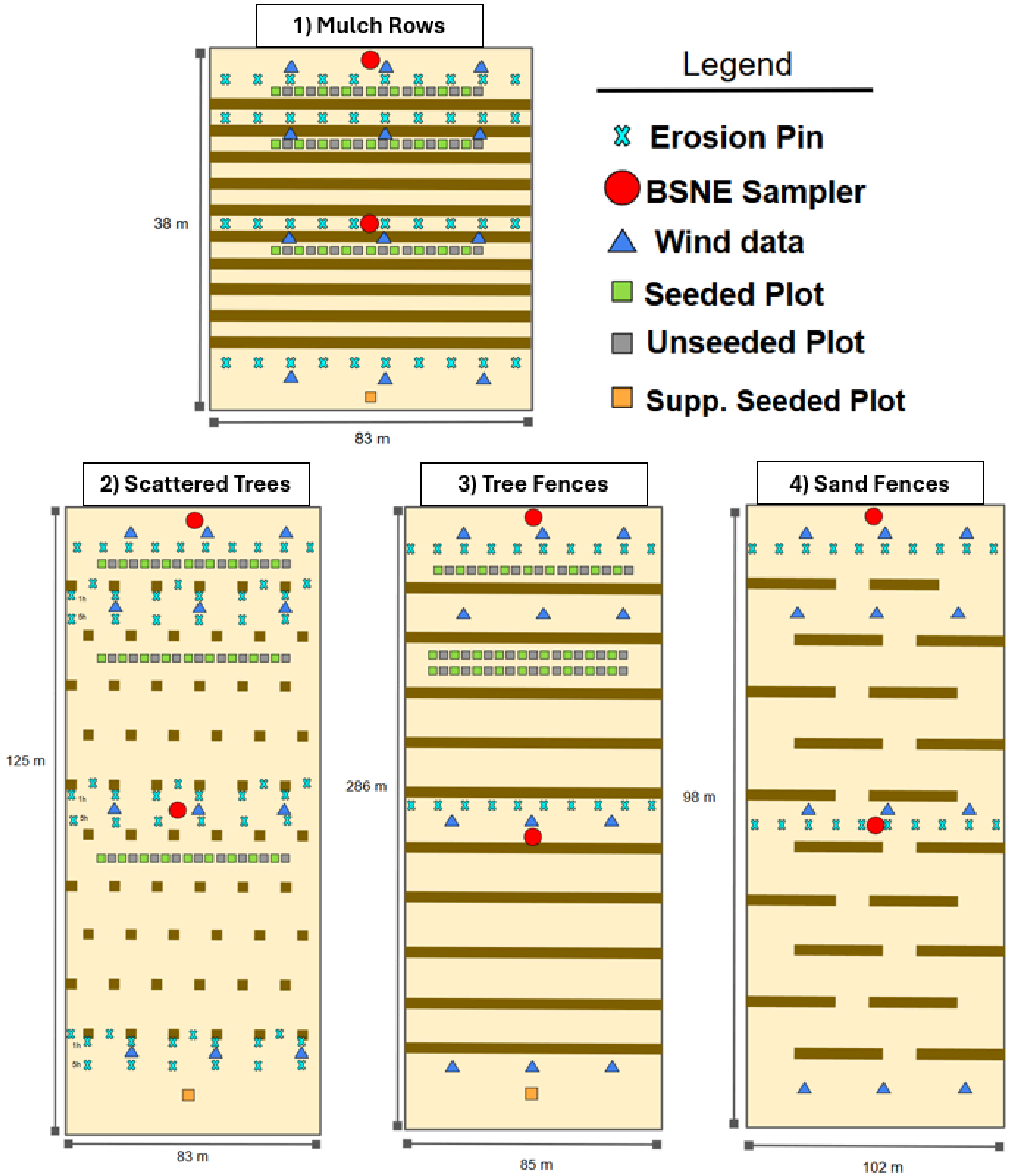

Figure 1. General layout of each treatment with respective placement of all measurable variables. Note diagrams are not to scale. Actual row number variations are explained in the Methods section.

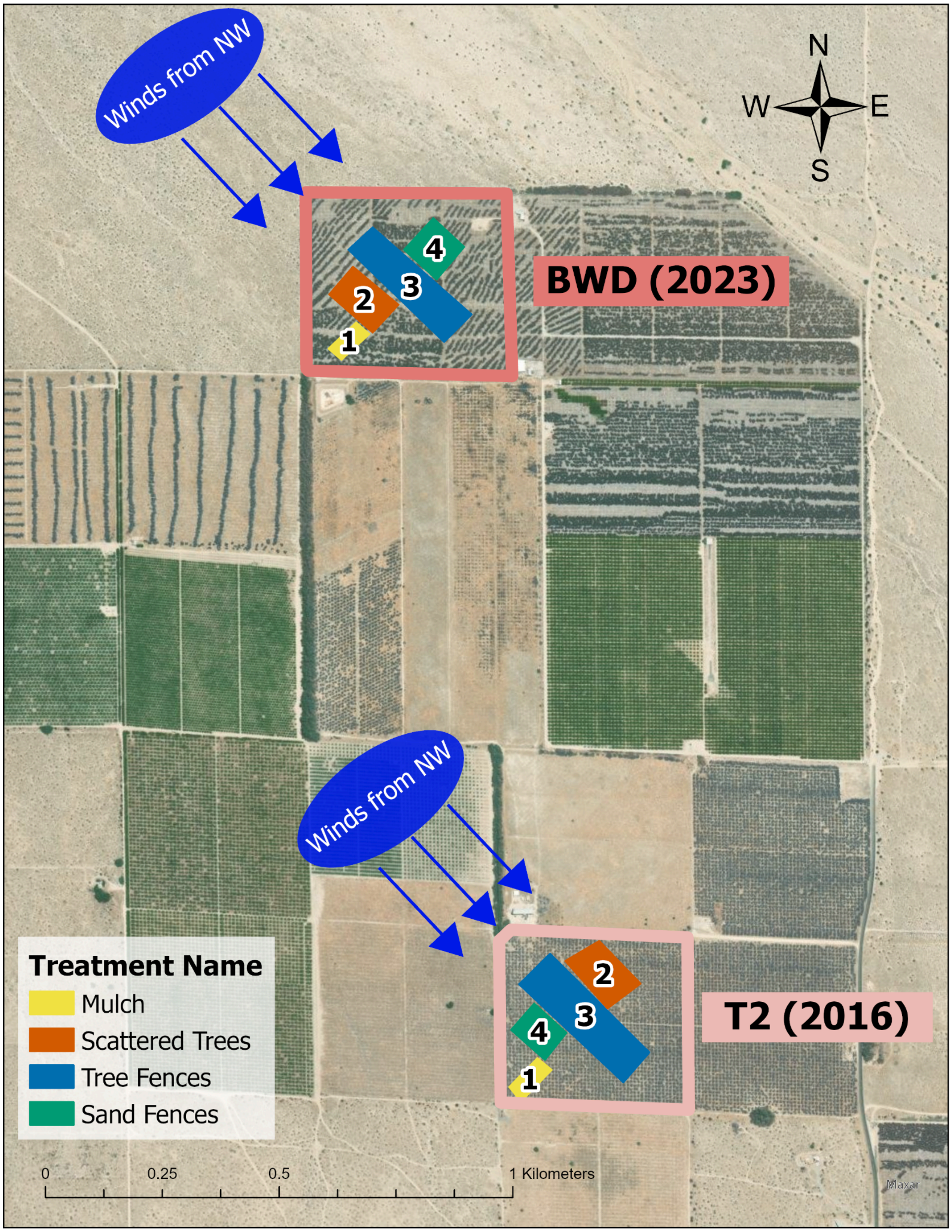

Figure 2. Overview of the two blocks, BWD & T2, with the four treatments: (1) Mulch Rows, (2) Scattered Trees, (3) Tree Fences, and (4) Sand Fences.

Dust Emissions

To understand how the different treatments impact dust emissions, we installed Big Spring Number Eight (BSNE) dust particle collectors (Fryrear, 1986), sourced from Soil Erosion Products (soilerosionproducts.com, Midland, Texas, USA). Dust particle collectors are a widely used tool for measuring wind-blown dust transport. Dust is collected in trays that can swivel 360° on a mounting pole, allowing dust to be collected from any wind direction. We collected wind-blown dust at two heights (20 cm and 50 cm) to capture variation in dust transport given the distance from the ground surface. For our initial three dust collections, two dust particle collectors were located approximately 9 meters upwind of the Tree Fences to act as controls. Additional dust collectors were placed at the midpoint between Rows 5 and 6, and behind Row 10 for the Mulch Rows and Scattered Tree treatments, and the midpoint between Rows 2 and 3 for the Tree Fences. For our fourth and final collection, when all treatments were present, we placed the dust particle collectors so that each treatment contained dust particle collectors in the upwind direction (Row 0) as controls and at the midpoint of Row 5 and 6.

To measure dust transport, we deployed the dust particle collectors for a set period, then collected and weighed the dust collected in each tray. The dust particle collectors were initially set up in October 2024, and trays were collected on three separate occasions through February 2025 for some of the treatments in the BWD block. Upon full treatment installation and completion at both blocks, dust was collected for all treatments in April 2025. For a full breakdown of the timeline, refer to Table 3.

Table 3. Dust particle collection timeline and the treatments & blocks from which collections were taken.

Collection Period	**Blocks**	**Treatments**	**Dust Collection Duration**
October 17, 2024 – December 4, 2024	BWD	Mulch Rows, Scattered Trees	48 days
December 4, 2024 – January 24, 2025	BWD	Mulch Rows, Scattered Trees	51 days
January 24, 2025 – February 27, 2025	BWD	Mulch Rows, Scattered Trees, Tree Fences	34 days
February 27, 2025 – April 10, 2025	BWD & T2	Mulch Rows, Scattered Trees, Tree Fences, Sand Fences	42 days

We measured dust control effectiveness using a general efficiency equation:

$$((dust_{upwind} - dust_{downwind}) / dust_{upwind})* 100 \%$$

For the first three collections, the upwind dust values were calculated by taking the average weight of dust collected for each height (20 cm and 50 cm) of the two dust particle collectors installed upwind of the Tree Fence treatment at BWD. Upon moving the dust collectors for the final collection period (February 27, 2025 – April 10, 2025), the upwind values were instead taken from the dust collected upwind of each treatment. The downwind dust values refer to the weight of each dust collection for the respective height inside the different treatments (Rows 5 and/or 10). We then took the average of the dust control effectiveness found for both heights to compare downwind values across treatments (Rows 5 and 10 for initial 3 collections; Row 5 for final collection).

Wind Speed

Handheld anemometers (Kestrel 1000, Kestrel Instruments, USA; WM-4, Ambient Weather, USA) were used to measure treatment impacts on wind speeds, since wind speeds directly relate to dust emissions. Each anemometer has a small fan that records maximum and average wind speeds over a desired period (in our case, 2 minutes). Four technicians measured wind speed 50 cm above the ground surface simultaneously in Rows 0, 1, 5, and 10 within each treatment. Rows 8 (for Tree Fence treatments in both blocks) and 9 (for the Sand Fence treatment at BWD) were collected as Row 10 had not yet been constructed. Row 11 was collected for the T2 Tree Fence measurements on 4/1/2025 and 4/2/2025. Wind speed data collections took place on four days during the study (2/27/2025, 2/28/2025, 4/1/2025, and 4/2/2025). Currently, wind data is present for 8 of the 8 proposed treatment sites (Table 5).

We used the adjusted wind speed (mean-centered) for our comparisons across the four treatments. Mean-centering allows for standardized comparison between treatments; it compares deviation from average speeds rather than raw wind speeds. This method removes group-level offsets and highlights within-group variability so that the treatment effects are more apparent. A measurement of zero represents no deviation from the average at the sampling time, while a negative value indicates a lower wind speed in comparison to the average of all four rows sampled. Analyzing the data this way was possible since all four rows in a treatment were surveyed simultaneously.

Adjusted wind speed was calculated with the following formula:

$$(2\ minute\ Average\ Speed\ for\ Individual\ Row\ at\ time\ x) - (Average\ Speed\ of\ all\ rows\ at\ time\ x)$$

Fence Porosity

To measure the porosity of each fence structure, 12 unique photos were taken for each treatment (excluding Mulch Rows) at a head-on angle and a distance of 4 meters to minimize distortion and show clear contrast to the background. All photos were taken using the same camera (Samsung Galaxy S22+ Rear Camera at 1x zoom) for resolution uniformity. The direction was consistently from each treatment's upwind side (northwest), facing downwind (southeast). The photos were then cropped appropriately to exclude open sky, single twigs, or ground, and analyzed using a script in MATLAB software to calculate the ratio of fence coverage to visible background as a proxy for porosity (Figure 3). Knowing how the porosity of tree-based fences differs from commercial sand fences will inform future design, construction, and usage.

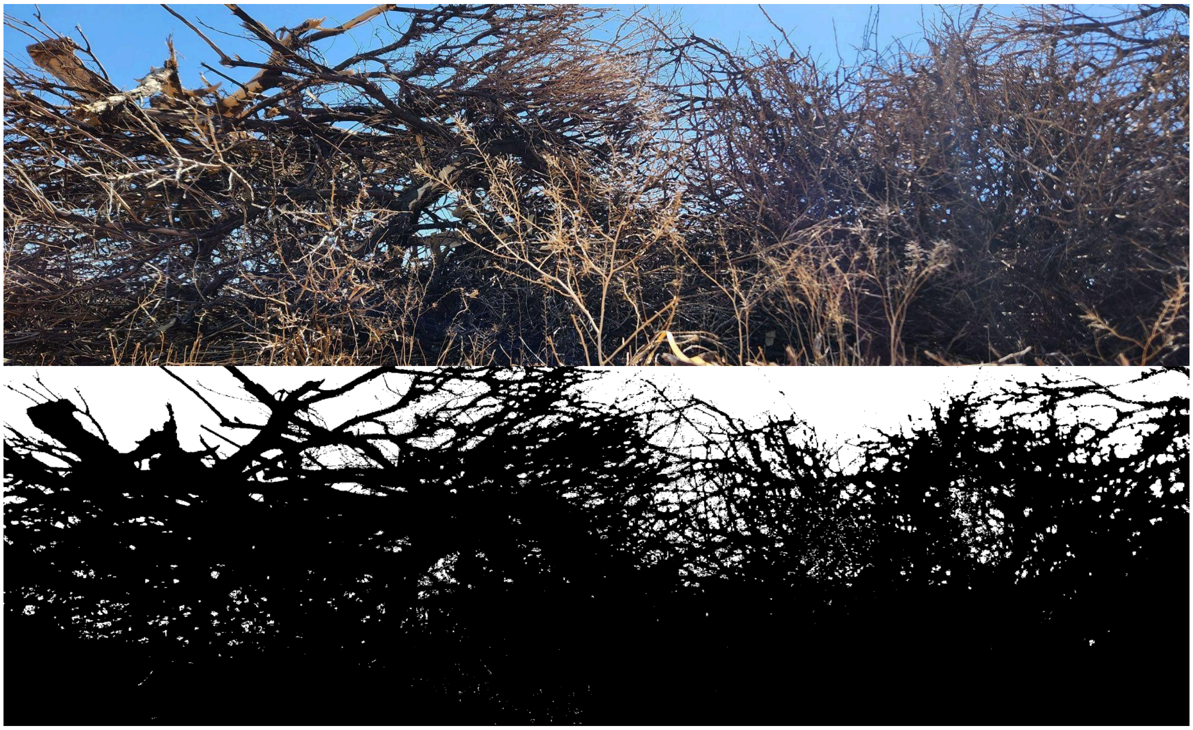

Figure 3. Example porosity imagery used in the analysis. The top photo shows a Tree Fence image before conversion to binary, and the bottom shows after. The ratio of white to black pixels is a proxy for porosity.

Erosion

To monitor erosion in the treatments, we utilized erosion pins that were hammered approximately eight inches into the ground. The exact baseline measurement for each pin was recorded after all treatments were installed on February 28, 2025. Ongoing surveying of the distance between the ground and the top of each pin will reveal whether erosion or deposition is taking place. The pins were placed 10 meters upwind of each treatment, along with placement of two lines in Rows 1, 5, and 10 using the height of the fences (1H) and midpoint of each row as a guide for installation (for layout, see Figure 1). Due to delays in the project timeline, measurable differences are not yet available. UCI Nature will continue to measure erosion pin heights periodically at intervals they deem fit.

Furthermore, drone footage was taken in March 2025, creating Digital Terrain Models (DTMs) and Digital Surface Models (DSMs) of the sites. Similar drone surveys in the future will help us determine the differences in surface elevations of the sites through time, which can help us definitively determine where soil is eroding or being deposited. Despite the lack of data for these two metrics, dust emissions, wind speeds, and porosity analyses can still help us infer the treatment that best controls erosion.

Salinity

To collect soil for salinity testing, 36 evenly spaced samples were taken across the two experimental blocks (72 total). Litter or plant material was cleared from the soil surface. A trowel was used to scoop out the top 15 cm of the soil (in ~ 4 x 4 inches), and the soil was stored in a labeled plastic bag. The samples were tested using the EC 1:5 method (Corwin, Yemoto 2017). A YSI QuadPro Multimeter was used to measure the specific conductance of a 50 g sample immersed in 250 mL of deionized water, which was shaken for 3 minutes. The specific conductance was then converted to ECe using standard conversion factors for the sample soil texture (Gibbs 2000). Resulting values were then associated with their respective locations on points in ArcGIS Pro where we used the IDW (Spatial Analyst) tool to interpolate a raster surface for each block.

Soil Seed Bank

To assess the composition of the soil seed bank at the project sites, soil samples were taken from both blocks. To test soil with minimal disturbance, samples were collected at each corner of the block and one sample 10 meters downwind of each erosion treatment (8 sample points per block). At each point, a 2-meter quadrat was oriented to the cardinal directions, and a sample of the top 5 cm of soil was taken at each corner. The samples were homogenized per treatment, and large debris was removed by hand. These samples were then grown in a greenhouse germination study using established methods (Gross 1990; Lee et al. 2024). Processed soil was spread thinly (<0.5 cm) onto trays containing a mixture of one bag of potting soil (*Sunshine Professional Growing Mix 6 Cubic feet All-purpose Potting soil mix*) and one bag of sand (*QUIKRETE 0.5-cu ft 50-lb Sand*). Trays remained in a greenhouse for the duration of the study, where they were checked and watered every 2 to 4 days to maintain adequate moisture levels for germination and the continued survival of the seedlings. As seedlings emerged, they were marked with a colored toothpick. Once a seedling developed enough to be identified to at least the genus level, it was counted and removed. We transplanted some seedlings to 4-inch pots for further identification as necessary. The germination trial period ended 2-3 weeks after no new seedlings emerged, but seedlings continued to be grown out for identification.

Seeding Pilot Study

To learn about the potential for reintroducing native plant species into retired farmlands in Borrego Springs, we designed a seeding study in which plant species native to the area were seeded in 1 m^2 plots. We established seeding plots in the different dust control treatments to learn if the treatments affected germination and growth. Species for the study were selected based on community composition of nearby sites and seed availability from suppliers. As soil in the retired farmlands was hypothesized to be more saline than the surrounding landscape, we chose species with a range of salinity tolerances (Table 4). Seeding rates were based on recommendations from various sources for each species (*Larrea tridentata*: Hall et al., 2016; *Abronia villosa, Ambrosia dumosa, Ambrosia salsola, Atriplex canescens, Atriplex polycarpa*: Laushman et al., 2021; *Croton californicus*: Southern California Edison, 2019) as well as the published rates for mitigation and restoration projects in the deserts of the Southwest (Mike et al., 2022; U.S. Department of the Interior, Bureau of Land Management, 2022) and were adjusted according to the availability of seed at our disposal (Table 4).

Note that we were not able to find seeding rates for *Geraea canescens* and the two supplemental species. For *Geraea canescens,* we took the average of the two other forbs in the seed mix (*Abronia villosa & Croton californicus*) along with the lightest seed species (*Atriplex polycarpa*) and again adjusted for our availability of seed. For the supplemental species, since viability tests indicated that the seed lots were <1% viable, we decided to evenly distribute the amount of seed at our disposal (7 grams each) across the four supplemental plots.

Table 4. Subplot plant palette. Salinity tolerances are from Calflora, which infers tolerance from existing soil and plant occurrence data (Calflora 2025).

Main Subplots			
Species	**Life Form**	**Salinity Tolerance (mS/m)**	**Seeding Rate (seeds/m^2)**
Abronia villosa	Forb (annual)	1070	27
Ambrosia dumosa	Shrub (perennial)	1010	21
Ambrosia salsola var. salsola	Shrub (perennial)	360	100
Atriplex canescens	Shrub (perennial)	1310	90
Atriplex polycarpa	Shrub (perennial)	1540	113
Croton californicus	Forb (perennial)	790	56
Geraea canescens	Forb (annual)	740	70
Larrea tridentata	Shrub (perennial)	1210	113
Supplemental Subplots			
Dicoria canescens	Forb (annual)	310	1.75 g/m^2
Psorothamnus emoryi	Subshrub (perennial)	690	1.75 g/m^2

The seeding study consisted of 18 1-m^2 subplots upwind (as a control), behind Row 2, and behind Row 6 across the Mulch Rows and Scattered Tree plots at the BWD site. The Tree Fence treatment consisted of 18 1-m^2 subplots upwind, in Row 2 at a distance equal to the average height of the Tree Fences (Row 2-1H), and midway between Rows 2 and 3 (Row 2-MID) at both blocks (see Appendix Table 3 for subplot distances from treatment rows). The total number of subplots was 216 including the T2 Tree Fences. Seeding was limited to these treatments because they were the only treatments available at the time of seeding. The Tree Fence plots were seeded with a different design also due to the availability of the rows built in this treatment at the time of seeding and to test if the cover provided by the Tree Fences led to increased herbivory (Holl, 2002).

Of the 18 subplots in each row, half were paired control subplots in which no seeding was done, and the other half were experimental subplots in which the plant palette was evenly sown. More specifically, each row consisted of 9 seeded (experimental) subplots and 9 unseeded (control) subplots separated by a width of 1 meter , alternating between experimental and control subplots. Subplots were outlined by placing nails into the ground at each of the four corners of a 1-meter square, tying jute twine around the corners, and affixing a uniquely numbered tree tag to the nail in the top left corner. Downwind of each of the treatment plots we seeded, we also planted one supplementary subplot consisting of seeds that were not available in large enough quantities to use in the main plots, totaling four additional subplots (Table 4).

Before seeding, the seeds were weighed out for each plot according to the calculated seeding rates. Small envelopes were used to store the weighed out seed, such that each envelope contained the prescribed amount of seeds (of all species) for one of the seeded plots. Seeds were sown on December 20, 2024 before any rain events occurred for the 2024-2025 growing season.

To ensure even distribution, once in the field we used 8-ounce cups to scoop soil *in situ* into a 1-gallon bag into which we also emptied one seeding envelope, and homogenized the contents by hand. The contents of the bag (soil and seeds) were scattered evenly within the bounds of the subplots. Foam paddles were then used to tamp the seeds into the soil to secure them against being easily blown away by the wind.

Analyses

To analyze differences in wind speed mitigation, fence porosity, and soil salinity results between the four treatments, we ran ANOVA tests (function 'ANOVA', package Car; Fox et al. 2019). Since dust particle collector, soil seed bank composition, native seedling germination, and soil textural data are limited, statistical analyses were not conducted; results will be qualitative.

To evaluate treatment effects on vegetation recruitment in seeded subplots, we conducted two separate generalized linear mixed models (GLMMs) using a negative binomial distribution with the glmmTMB function (Brooks et al., 2017). In both models, the response variable was total vegetation count per subplot, including both native and non-native species. Seeded and unseeded plots showed no significant difference, so seeding status was excluded from the models.

In the first model, we restricted the dataset to Rows 0 and 2 only—rows shared by all three treatments (Mulch Rows, Scattered Trees, and Tree Fences). We recoded "2-MID" as Row 2 and excluded subplots from Row 2-1H and Row 6 to ensure consistency across treatments. The fixed effects included Treatment, Row, and their interaction.

In the second model, we expanded the analysis to include Row 6 and focused on only the

Mulch Rows and Scattered Tree treatments to examine treatment differences more thoroughly across all three shared rows (Rows 0, 2, and 6). The Tree Fence treatment was excluded in this model. As with the previous model, the fixed effects included Treatment, Row, and their interaction.

Post hoc pairwise comparisons were performed using the emmeans package (Lenth, 2023), with Tukey adjustments applied for multiple comparisons. Results are reported on the log (count) scale. All analyses were performed in R (R Core Team, 2024; v. 4.3.3).

Results

Dust Emissions

Due to the limited data for dust particle collections, analysis for this treatment is qualitative. Preliminary results show fairly similar dust control efficiency values for the Scattered Trees and Tree Fences, with a mean of 93% and 94% across both blocks, respectively (Table 5, Figure 4). On average, Sand Fences control dust with a 58% efficiency. The Mulch Rows displayed the lowest dust control efficiency with a negative average of -165%. Except for one single measurement (T2, Tree Fences, Row 5), more dust was consistently collected at the lower height of 20 cm versus 50 cm by the dust particle collectors. Note that these results are only reflective of the final dust collection on (February 27, 2025 – April 10, 2025) when the wind was predominantly blowing from the northwest.

Table 5. Average dust control efficiency for each treatment across both blocks.

Final Dust Collection (April 10, 2025)			
Treatment	**Block**	**Average Dust Control Efficiency %**	**Average Efficiency % per Treatment**
Mulch Rows	BWD	-359	-165
	T2	29	
Scattered Trees	BWD	91	93
	T2	94	
Tree Fences	BWD	89	94
	T2	99	
Sand Fences	BWD	43	58
	T2	73	

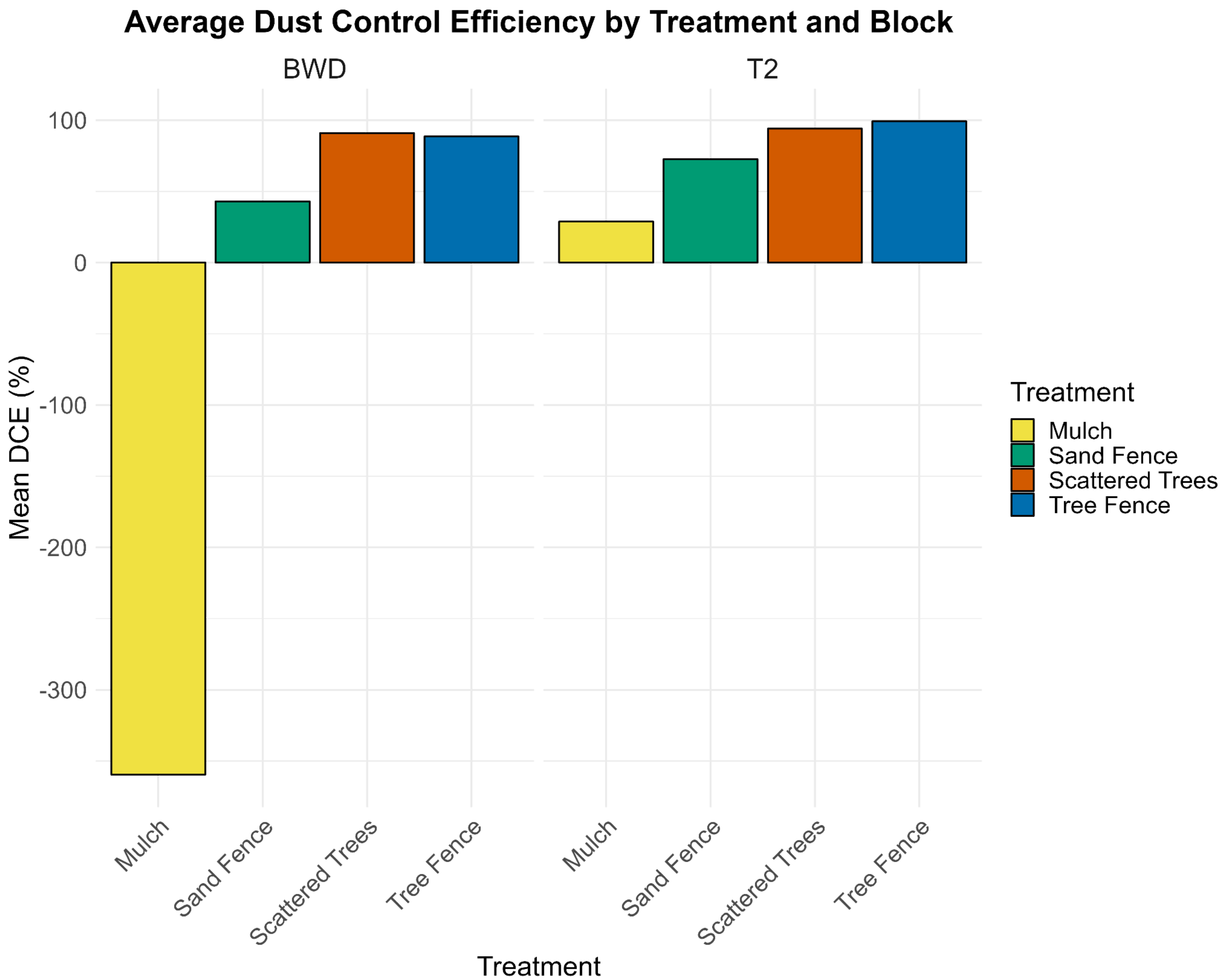

Figure 4. Dust control efficiency (DCE) for all four treatments in Row 5 from last collection for the period of February 27, 2025 – April 10, 2025. Positive values indicate deposition is taking place while negative values indicate erosion.

Wind Speed

We found a significant interaction between treatment type and row number and a main effect of row number on adjusted average wind speeds (Table 6). A post-hoc Tukey test indicated significant differences in mean-centered average wind speeds taken upwind (Row 0) compared to those taken downwind (Rows 1, 5, 10, and 11) for the Sand Fence, Tree Fence, and Scattered Tree treatments (Table 7). The post-hoc Tukey test did not indicate significant differences in time-adjusted average wind speeds taken upwind (Row 0) compared to wind speeds taken downwind (Rows 1, 5, and 10) for the Mulch Row treatment. The post-hoc Tukey test did indicate near significant differences between mean-centered average wind speeds taken in Row 1 and Row 10 for the Tree Fence treatment, but not other treatments. Figure 5 reflects these trends. The standard deviation was highest for the Scattered Tree treatment, while the other three treatments showed similar variance (Table 8).

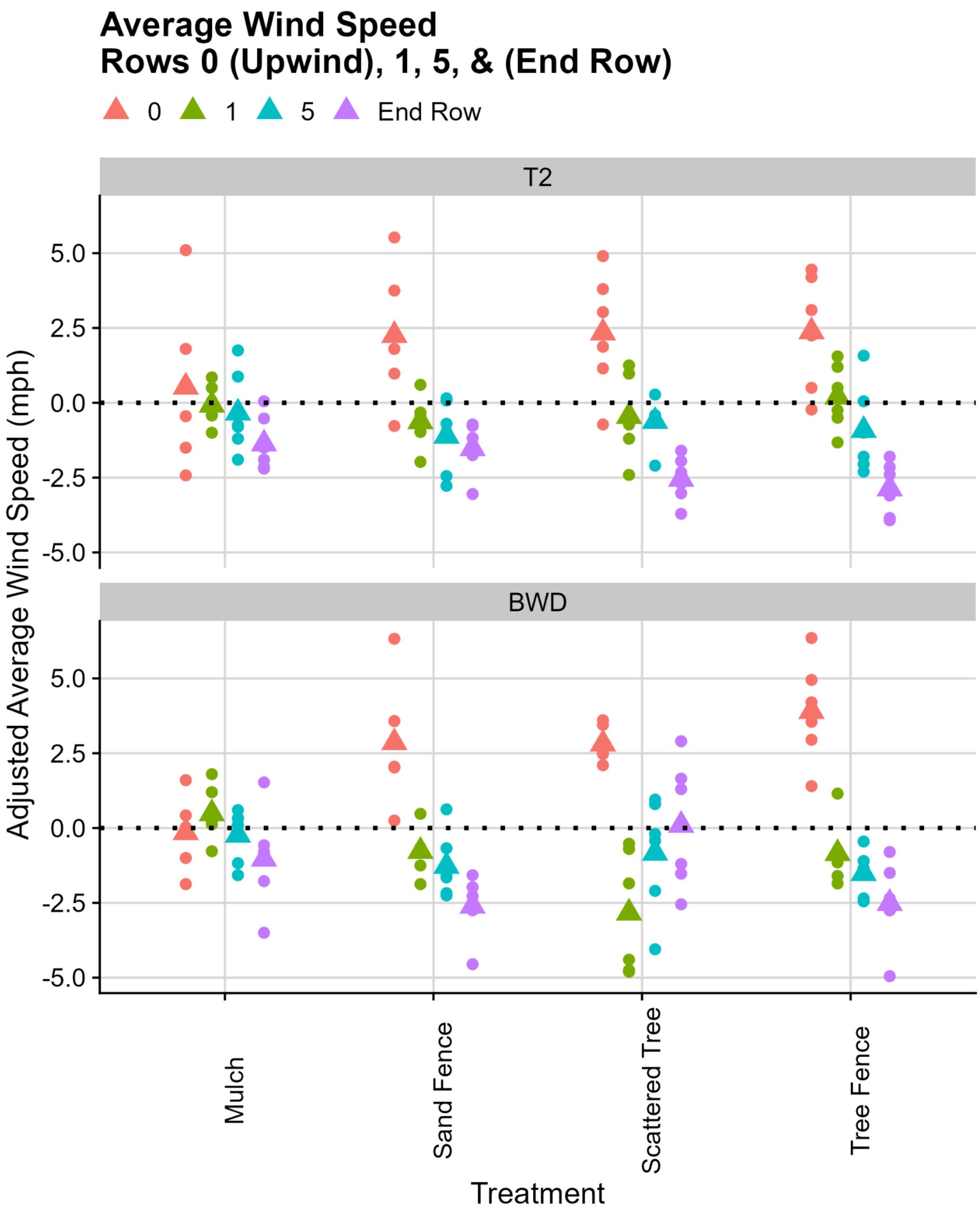

Figure 5. Mean-centered average wind speeds at Rows 0, 1, 5, and End Row (i.e. Rows 10, 11, or 13) across Mulch Row, Sand Fence, Scattered Tree, and Tree Fence treatments by block (BWD and T2).

Table 6. Significant results from analysis of variance (ANOVA) test for mean centered average wind speeds at both T2 and BWD blocks across four treatments. Statistical significance ($P<0.05$) is indicated with * symbol.

Interaction	**F-statistic**	**Degrees of Freedom**	**p-value**
Block	5.30 e-3	1	0.94
Row	47.9	3	2.30e-16*
Row:Treatment	4.29	9	2.1e-4*

Table 7. Post hoc Tukey pairwise comparison test between rows for mean-centered average wind speeds at both T2 and BWD blocks within Sand Fence, Scattered Trees, Tree Fence, and Much Row treatments. Statistical significance ($P<0.05$) is indicated with * symbol. Near significant result indicated with *n.

Treatment	**pairwise comparison**	**Standard Error**	**p-value**
Sand Fences	Row 0 - Row 1	0.687	1.2e0-3 *
	Row 0 - Row 5	0.687	1.00e-4 *
	Row 0 - Row 10/11	0.687	<1.00e-4 *
Scattered Tree	Row 0 - Row 1	0.687	<1.00e-4 *
	Row 0 - Row 5	0.687	1.0e-3 *
	Row 0 - Row 10/11	0.687	1.00e-4 *
Tree Fence	Row 0 - Row 1	0.687	4.00e-4 *
	Row 0 - Row 5	0.687	<1.00e-4 *
	Row 0 - Row 10/11	0.687	<1.00e-4 *
	Row 1 - Row 10	0.687	0.069 *n
Mulch Rows	Row 0 - Row 1	0.687	1.00
	Row 0 - Row 5	0.687	0.90
	Row 0 - Row 10/11	0.687	0.89

Table 8. Standard deviation of mean-centered average wind speed for Mulch Row, Sand Fence, Tree Fence, and Scattered Tree treatments. BWD and T2 site results combined.

Treatment	Standard Deviation (mean-centered average wind speed)
Mulch Rows	1.31
Sand Fences	1.25
Tree Fences	1.35
Scattered Trees	1.74

Fence Porosity

Image analysis revealed that the Scattered Trees had a mean porosity of 28.1% and a maximum porosity of 38.2% between both sites, falling closest to the ideal porosity range of 30% to 50% (Table 9, Figure 6) (Li & Sherman 2015; Lee et al. 2023). The Tree Fences exhibited the lowest mean porosities (18.7% at BWD; 21.6% at T2), suggesting a denser structure that may restrict airflow and seed influx. As expected, the Sand Fences had little porosity variance between photos. Sand Fence means (56.7% at BWD; 55.9% at T2) were close to the ideal porosity, but fell just above the target range. The Mulch Row treatment is stated to have a porosity of 100% since it does not obstruct wind flow but relies solely on soil coverage for dust control.

Table 9. Porosity Metrics for Each Treatment

Treatment	Minimum Porosity (%)	Maximum Porosity (%)	Mean Porosity (%)
Borrego Water District Block			
Mulch Rows	100%	100%	100%
Scattered Trees	18.2%	37.4%	28.3%
Tree Fences	11.5%	31.0%	18.7%
Sand Fences	52.7%	59.0%	56.7%
T2 Block			
Mulch Rows	100%	100%	100%
Scattered Trees	15.5%	39.0%	27.9%
Tree Fences	14.0%	28.8%	21.6%
Sand Fences	50.1%	59.8%	55.9%

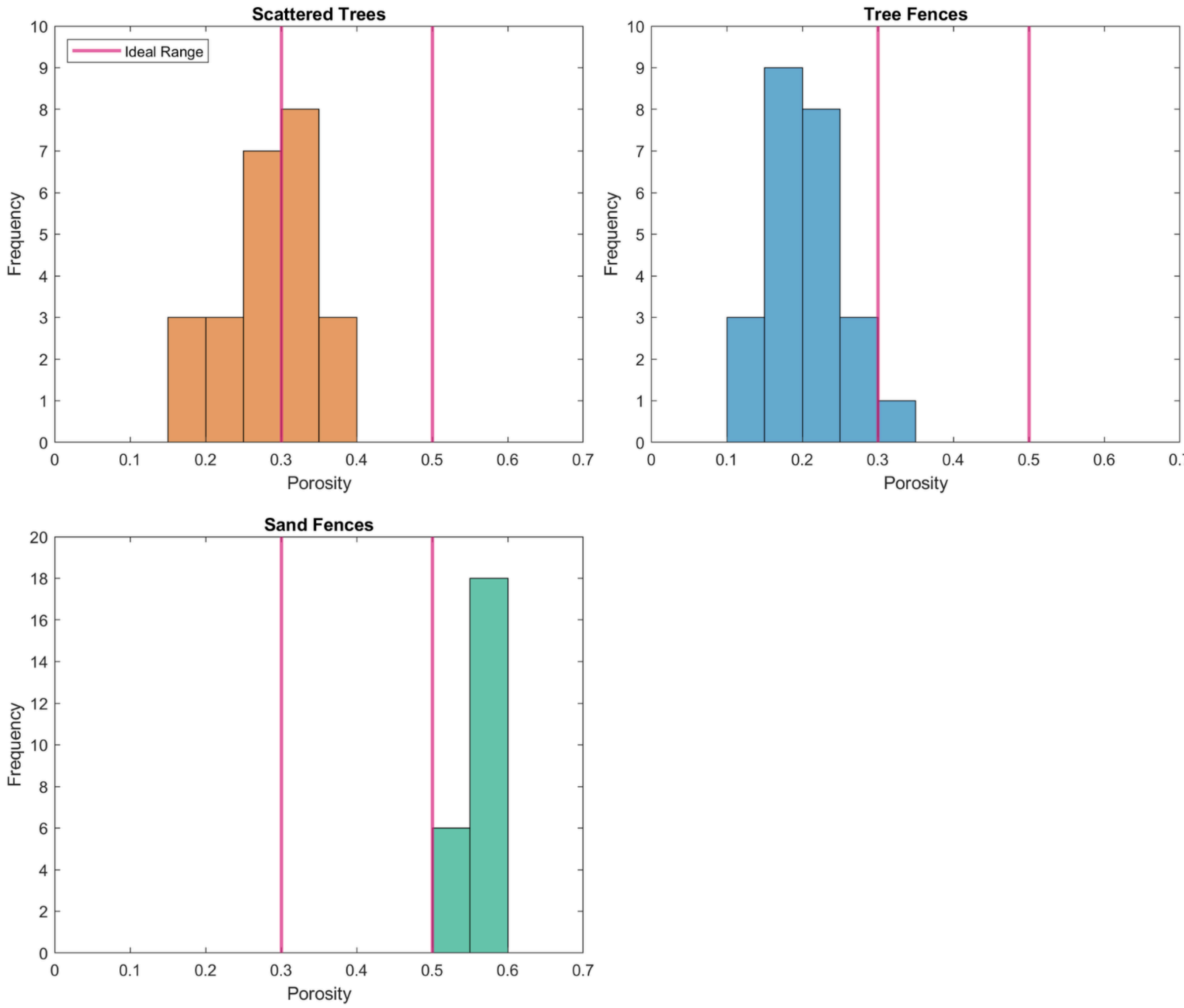

Figure 6. The distribution of porosity across the Scattered Trees (top left), Tree Fences (top right), and Sand Fences (bottom). Frequency refers to the number of photos falling within the respective range. Scattered Trees fell in the ideal range of 0.3 (30%) to 0.5 (50%) most often, while Tree Fences and Sand Fences were mostly outside of the ideal range (30-50%; Li & Sherman 2015; Lee et al. 2023).

Salinity

Interpolation results from salinity mapping show that there are differences in the soil salinity levels across both blocks . The BWD block appears to be more saline than the T2 block with the majority of the land cover falling in the slightly saline and moderately saline ranges for BWD and non-saline and slightly saline for the T2 block (Figures 8 & 9). On the contrary, ANOVA analysis between the two blocks does not indicate significant differences in soil salinity as seen by the similar mean soil salinity at both blocks (Table 10).

Table 10. Average Salinity and Standard Deviation at each Block

Block	Mean ECe (mS/m)	Standard Deviation	Salinity Class
BWD	479.5	378.8	Slightly saline
T2	410.1	589.9	Moderately saline

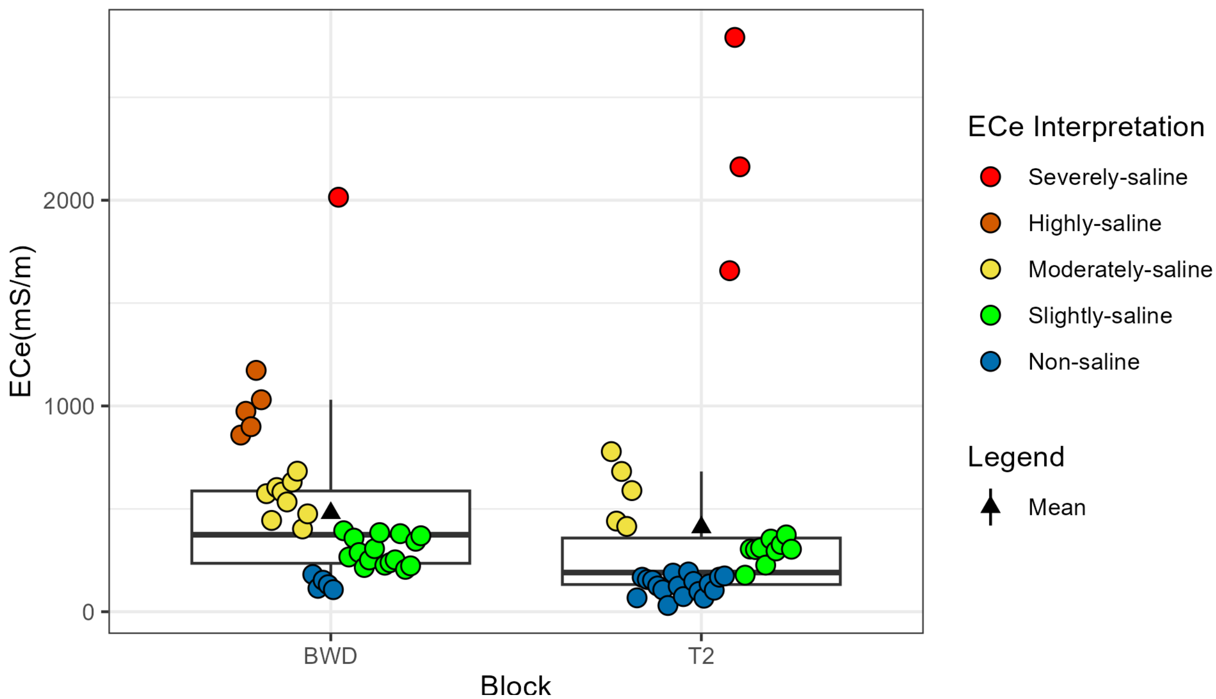

Figure 7. Box plots showing the quartiles for salinity at each site. Raw values of soil salinity samples are colored by their salinity category.

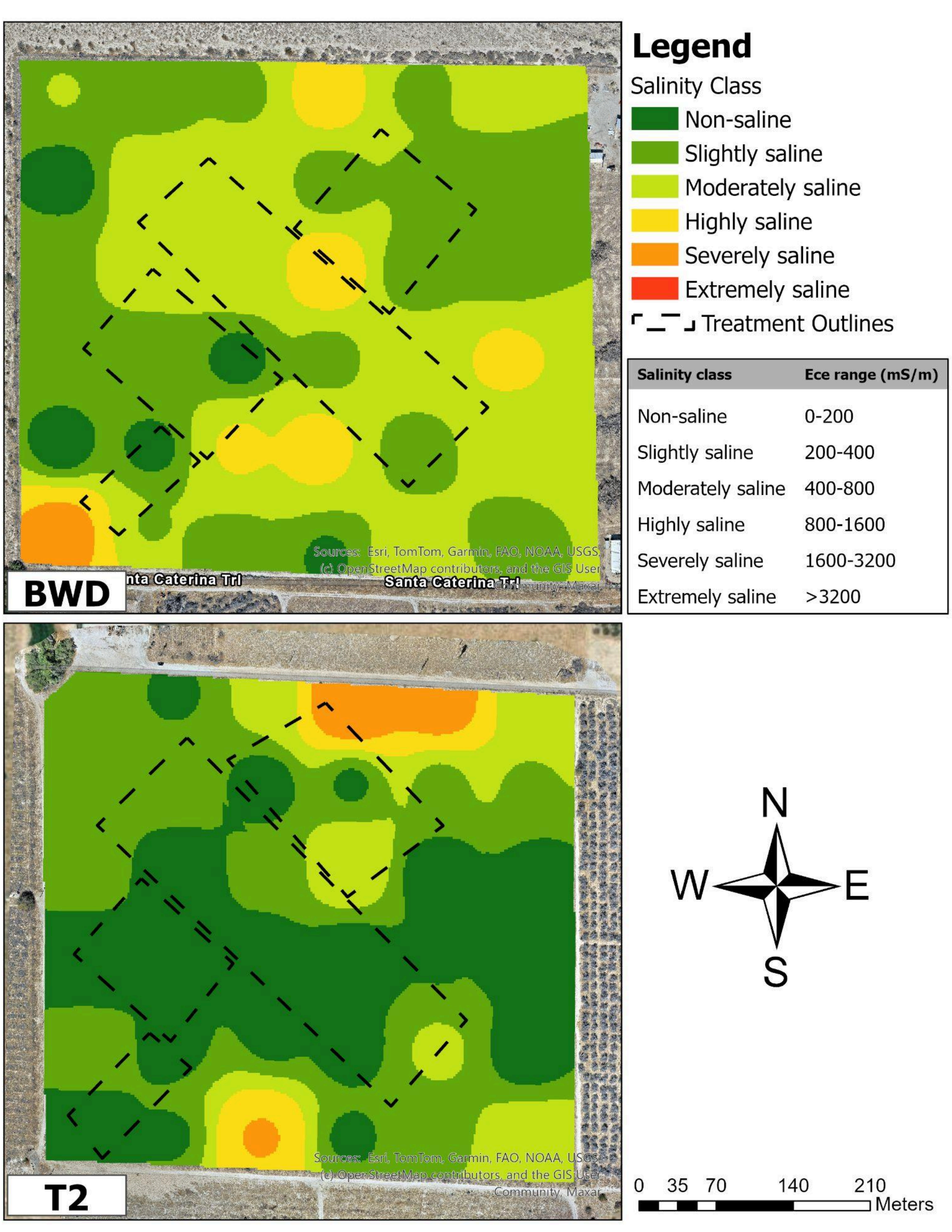

Figure 8. Map of soil salinity based on interpolation of soil samples taken from each site.

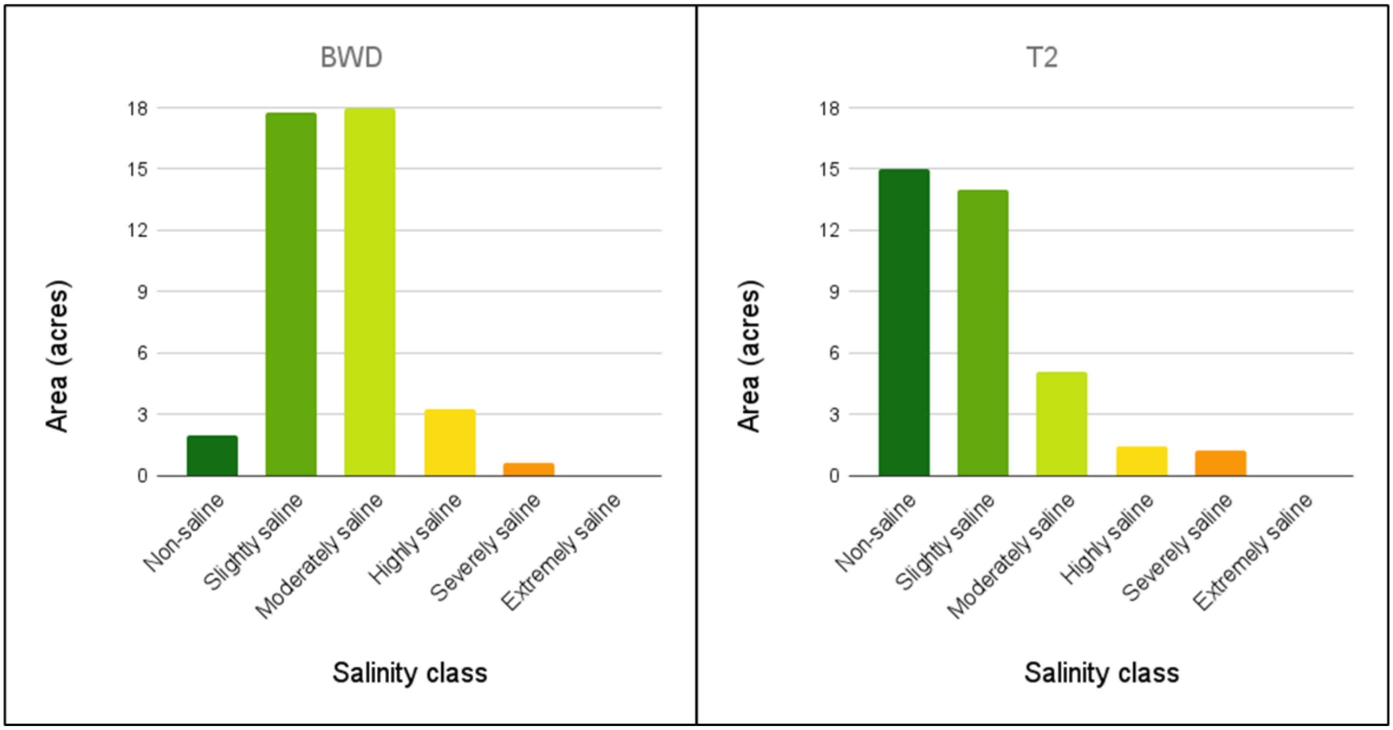

Figure 9. Charts depicting the area of each salinity class across each block.

Soil Seed Bank

The BWD and T2 blocks had dramatically different soil seed bank densities and compositions (Figure 10). Overall, T2 had a much more substantial soil seed bank that skewed more towards the invasive grass *Schismus barbatus* (a monocot), while BWD had fewer germinants overall and was dominated by dicots. After having grown out seedlings in the greenhouse, we identified the majority of our dicot seedlings at both sites as *Sisymbrium irio* (London rocket). Fewer than ten of the seedlings across all collections were Sahara mustard (*Brassica tournefortii*) which was surprising given its local abundance. From T2, we found some native plants: one instance of desert dandelion (*Malacothrix glabrata*), a few seedlings belonging to the family Onagraceae (the evening primrose family), and two seedlings that are popcorn flowers (Cryptantha s.l.) that have yet to be identified to species level. There were also seedlings of either *Chylisma* sp. or *Eulobus californicus* present in some of our BWD samples, but the seedlings died before our final seedling count and before they could be identified to species level. All of our monocot seedlings have been identified as *Schismus barbatus*.

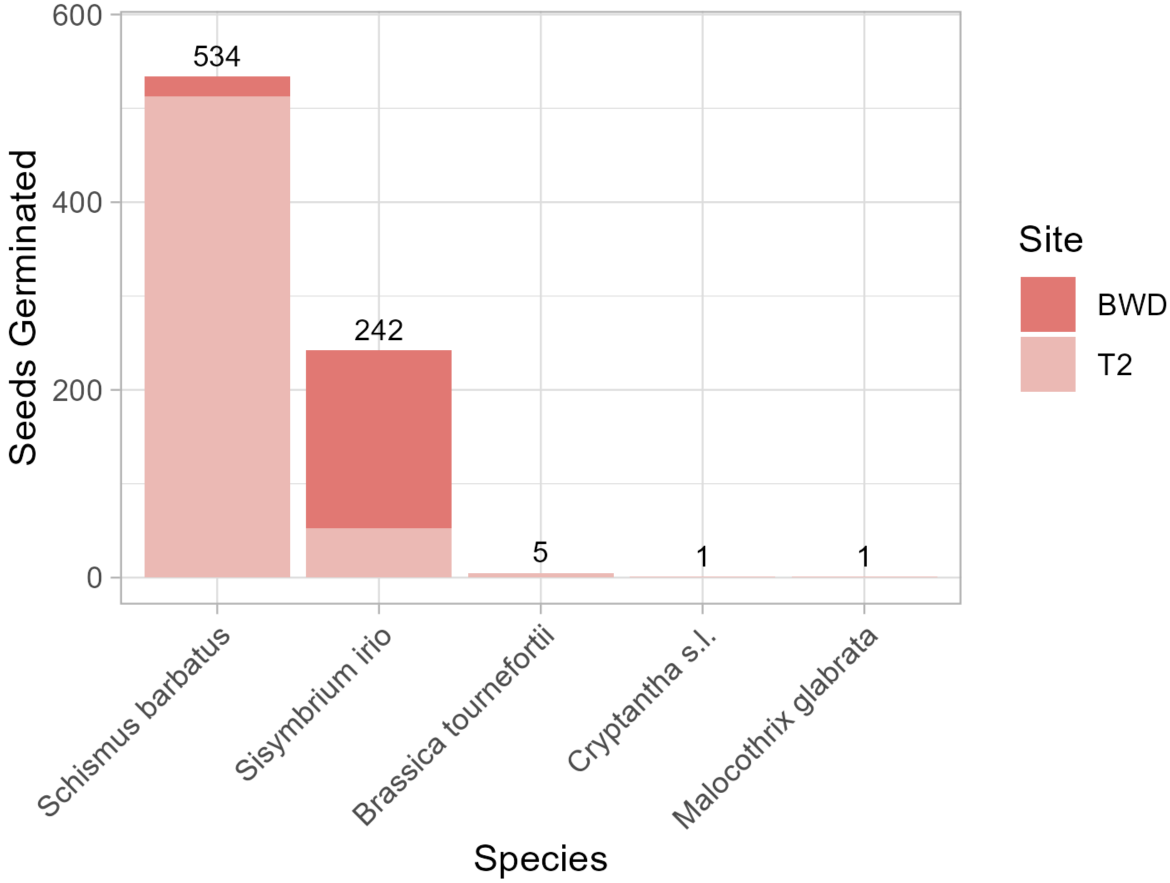

Figure 10. Abundance-diversity plot of all individuals by species found in the soil seed bank grow-out study. Bars are colored according to the site from which individuals were located.

Seeding Pilot Study

We saw relatively little germination within the seeded subplots with most subplots being bare. Even so, we counted 19 *Atriplex sp.*, 4 *Ambrosia sp.*, and 2 *Gerea canescens* native seedlings growing within the subplots at both blocks. For non-natives, numerous *Schismus sp.* (1,558), several *Brassia tournefortii* (5), and some resprouting citrus shoots (29) were also observed within both seeded and unseeded subplots.

In the first GLMM model examining Rows 0 and 2, total vegetation counts (natives and non-natives combined) were significantly influenced by both Treatment ($\chi^2 = 15.51$, $p < 0.001$) and Row ($\chi^2 = 15.41$, $p < 0.001$) (Table 11). The interaction between Treatment and Row was not statistically significant ($p = 0.135$). Post hoc tests showed that Mulch Row subplots supported significantly more vegetation than Tree Fence subplots ($p = 0.0006$), and Scattered Trees also had more vegetation than Tree Fences ($p = 0.0302$). Mulch Rows and Scattered Trees did not significantly differ from one another ($p = 0.47$). Additionally, Row 0 had significantly more vegetation than Row 2 across all treatments ($p = 0.0008$).

In the second GLMM model (Rows 0, 2, and 6; Mulch Rows and Scattered Trees only), row position was a strong predictor of vegetation count ($\chi^2 = 25.90$, $p < 0.001$), while treatment ($p = 0.16$) and the treatment-by-row interaction ($p = 0.33$) were not statistically significant (Table 12). Pairwise contrasts showed a marginally significant trend toward higher germination in Mulch Rows compared to Scattered Trees ($p = 0.075$), with log-scale means of 0.087 and -0.858, respectively. Vegetation counts were again highest in Row 0, with significantly lower counts observed in both Row 2 ($p = 0.0001$) and Row 6 ($p < 0.0001$). There was no significant difference between Row 2 and Row 6 ($p = 0.88$), indicating that the decrease in vegetation from Row 0 plateaus by Row 2 and persists through Row 6 for these two treatments.

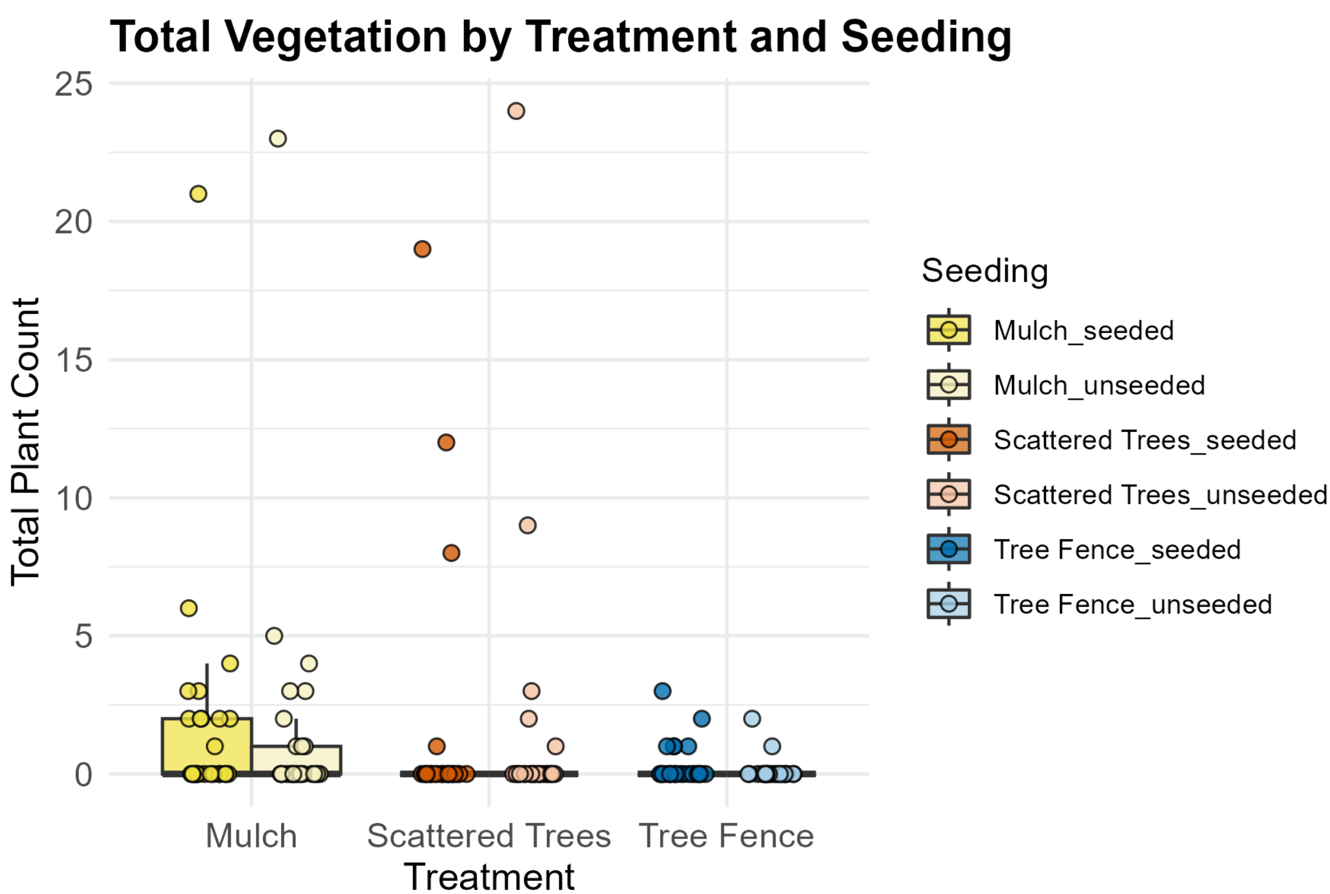

Figure 11. Boxplots with overlaid jittered points showing total vegetation count per subplot by treatment and seeding status in the BWD block. Seeded plots are shown in darker shades, and unseeded plots in lighter shades. The boxes represent the interquartile range, with horizontal lines indicating medians; points represent individual subplot observations. Vegetation counts were generally highest in seeded Mulch Row plots and lowest in Tree Fence treatments across both seeding conditions.

Table 11. Results of GLMM on Vegetation Counts for Mulch Rows, Scattered Trees, and Tree Fence Treatments (Rows 0 and 2 only). Statistical significance ($P<0.05$) is indicated with * symbol.

Effect	**Chi-Square (χ^2)**	**Degrees of Freedom**	**p-value**
Treatment	15.51	2	<0.001 *
Row	15.41	1	<0.001 *
Treatment:Row	4.01	2	0.135
Post hoc Pairwise Comparisons			
Contrast	**Estimate (log scale)**	**Standard Error**	**p-value**
Mulch Rows - Scattered Trees	0.665	0.568	0.471
Mulch Rows - Tree Fences	2.471	0.667	0.0006*
Scattered Trees - Tree Fences	1.805	0.712	0.0302*
Row 0 - Row 2	1.790	0.532	0.0008*

Table 12. Results of GLMM on Vegetation Counts Comparing Mulch Rows and Scattered Trees (Rows, 0, 2, amd 6). Statistical significance ($P<0.05$) is indicated with * symbol. Near significant result indicated with *n.

Effect	**Chi-Square (χ^2)**	**Degrees of Freedom**	**p-value**
Treatment	1.97	1	0.161
Row	25.90	2	<0.001 *
Treatment:Row	2.20	2	0.333
Post hoc Pairwise Comparisons			
Contrast	**Estimate (log scale)**	**Standard Error**	**p-value**
Mulch Rows - Scattered Trees	0.945	0.531	0.0751*n
Row 0 - Row 2	2.485	0.598	0.0001*
Row 0 - Row 6	2.831	0.638	<0.0001 *
Row 2 - Row 6	0.347	0.710	0.877

Discussion

This study evaluated the effectiveness of four dust and erosion control treatments (Mulch Rows, Scattered Trees, Tree Fences, and Sand Fences) across multiple ecological and physical parameters. Tree-based treatments, particularly Scattered Trees and Tree Fences, were the most effective in reducing wind speed and capturing airborne dust, with dust control efficiencies exceeding 90%. In contrast, Mulch Rows performed poorly in both dust mitigation and wind reduction. Porosity measurements revealed that Scattered Trees had values closest to the ideal range (30–50%), potentially explaining their superior performance. Salinity comparisons across the sites suggest a downward trend over time, indicating that salinity will not be a big determining factor for seeding success. Although overall subplot germination was low due to limited precipitation, the Mulch Rows supported slightly greater native seedling emergence than tree-based treatments, though not at a statistically conclusive level. Recruitment within treatments seems to be poor based on upwind germination comparisons to downwind rows. While the species composition of the soil seed banks differed between the two blocks, both were shown to have a high proportion of invasive species, suggesting that an active restoration approach may be required to achieve desirable ecological outcomes.

Erosion and Dust Control Effectiveness

The high dust control efficiency values of 93% and 94% for Scattered Trees and Tree Fences, respectively, suggest that both these structures are exceptionally effective at controlling dust emissions within treatment zones. These findings align with previous research suggesting that woody or shrub-like vegetation is more effective at dust capture than herbaceous or bare ground patches (Field et al. 2012). The Scattered Trees' mean porosity (28.1%) was also the treatment closest to the ideal porosity range (30-50%), further supporting their effectiveness in disrupting wind flow while minimizing soil scouring (Li & Sherman 2015; Lee et al. 2023). Tree Fences were much denser, and although effective at dust capture, future monitoring of the surrounding erosion pins is recommended to assess whether their density may contribute to soil scouring.

Sand fences had a mean porosity slightly above the ideal range, which likely contributed to their lower dust control efficiency of 58%. The Mulch Row treatment showed a negative average dust control efficiency (-165%), indicating that more dust accumulated within the middle rows (e.g. Row 5) than at the upwind edge (Row 0). This effect was more pronounced in the BWD block (-359%) than T2 (29%), possibly due to prevailing westerly winds (Figure 12) and differing surrounding environments; the open western exposure of BWD may have increased dust influx compared to the more agriculturally buffered T2 (Figure 13).

Although not all treatments were present during the initial three dust collections, consistent negative dust efficiency values for the Mulch Rows were observed in Rows 5 and 10, while Scattered Trees exhibited some dust control in Row 5 but negative values in Row 10 (Appendix Figure 1). This pattern is explained by wind direction variability (for wind directions during the first three collections, refer to Appendix Figures 2 - 4). During the initial three collection periods, wind frequently originated from the southwest in addition to the anticipated northwest, essentially reversing the upwind and downwind zones. Consequently, the middle rows (e.g. Row 5) functioned as the most protected zones since the last “downwind” row (e.g. Row 10) will sometimes act as the “upwind” row. This insight was further supported by the final dust collection with an extra dust collector that was deployed at Row 10 of the Scattered Tree treatment in BWD, which rendered a 44% dust control efficiency compared to 91% in Row 5 of the same treatment. These findings suggest that the safest zones for vegetation establishment are the interior rows, and restoration practitioners should prioritize these areas when allocating resources for native seed planting.

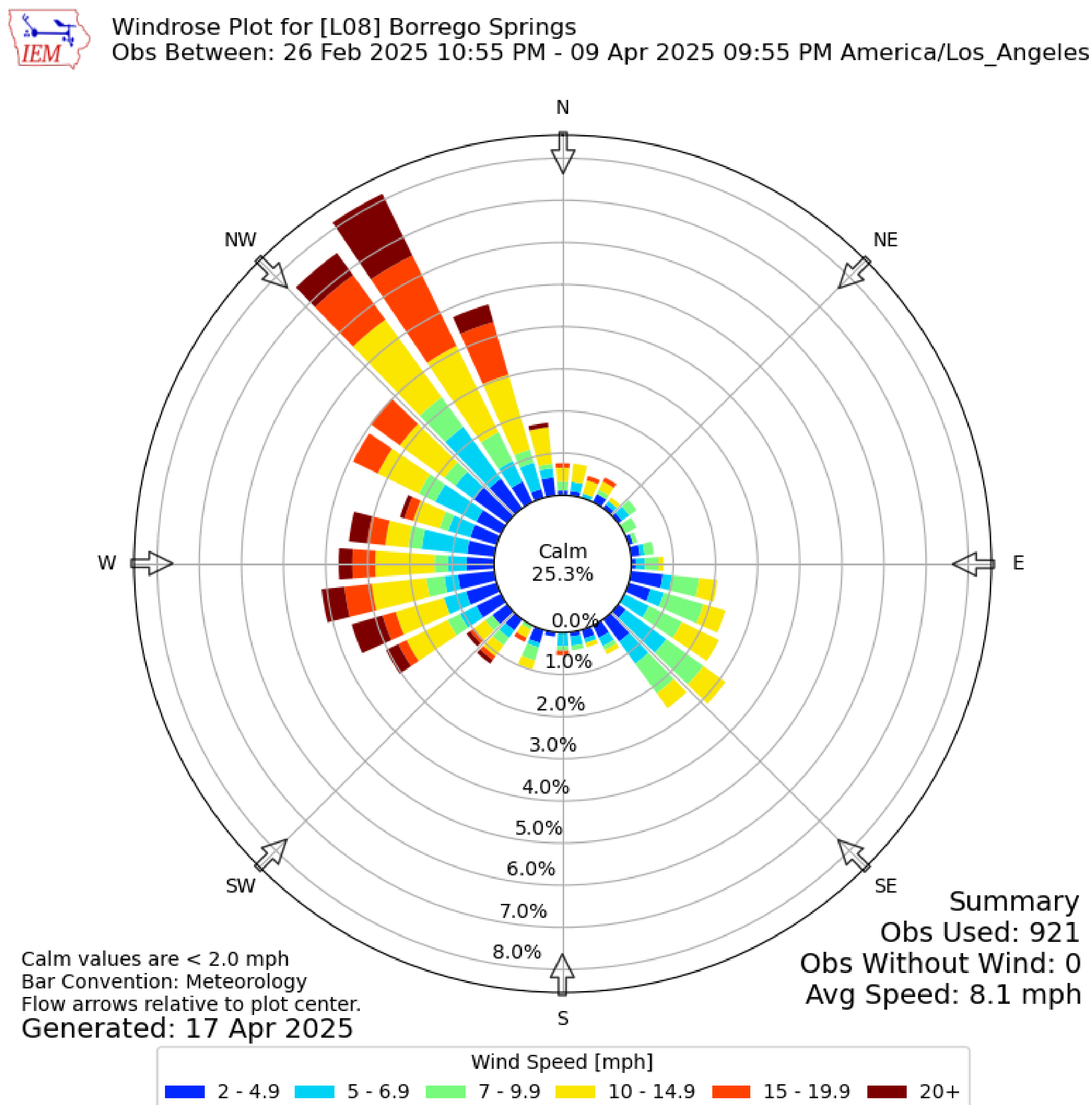

Figure 12. Wind speeds and direction for duration of last dust particle collection for the period of February 27, 2025 – April 10, 2025.

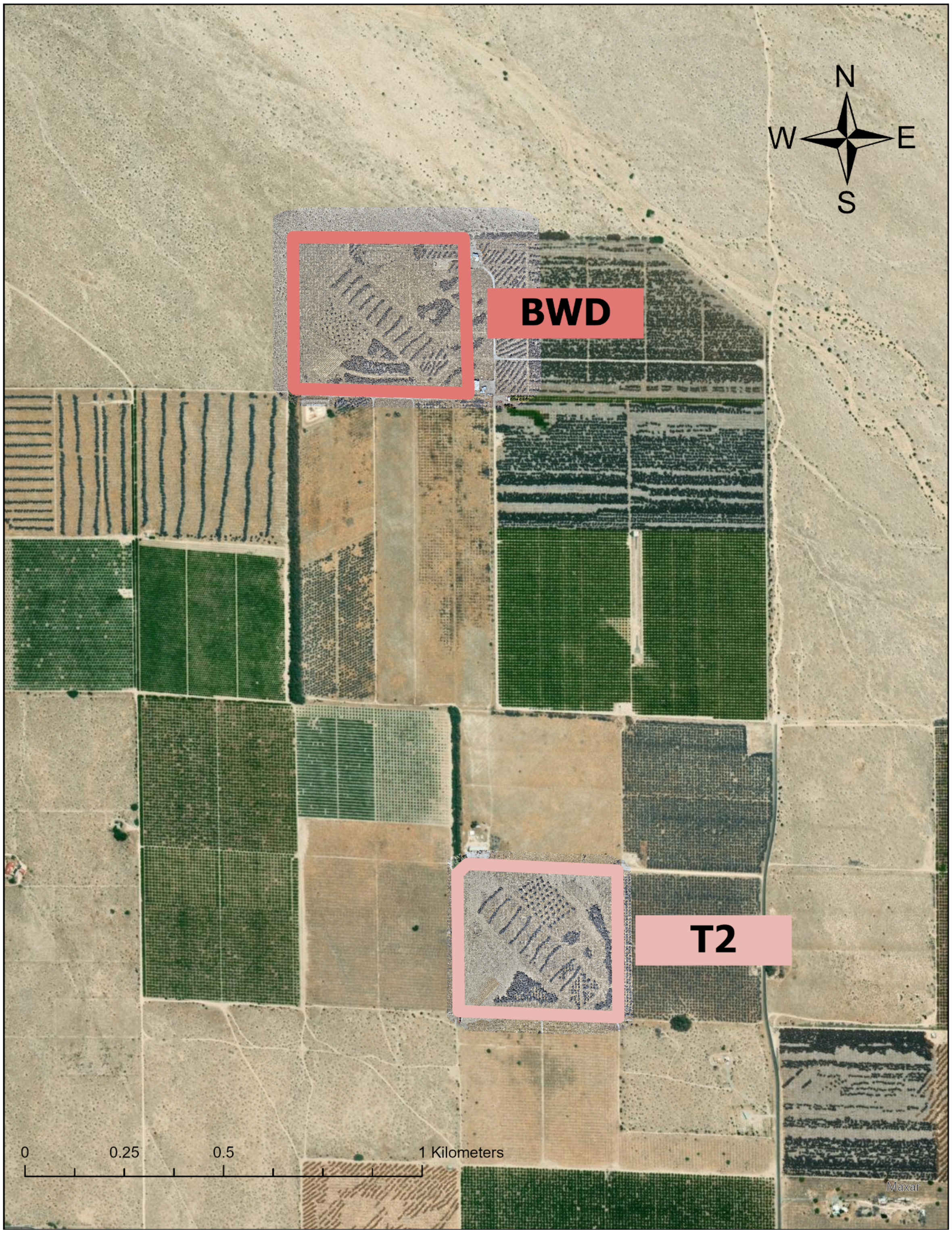

Figure 13. Map of the two blocks and their immediate surroundings.

Wind Speed Reduction

Wind speed analyses demonstrated that Tree Fences, Sand Fences, and Scattered Trees effectively reduced wind speeds, whereas Mulch Rows did not. These results were expected for Sand Fence and Tree Fence treatments since previous studies found them effective at wind velocity reduction (Li and Sherman 2015; National Academies of Science 2020; Ludwig and Tongway 1996). However a direct comparison between these types of fences has not been documented. The Scattered Trees had the greatest variation when compared to the other two effective treatments, suggesting this treatment is less consistent than all the other treatments. This may potentially lead to better plant recruitment within the Scattered Tree treatment over the long-term.

Wind results were similar between the two blocks. Differences were only indicated for Row and Row:Treatment interactions, thus ruling out block effects. Nearly significant results were seen between Rows 1 and 10 in the Tree Fence treatment; this was not seen in any other treatment. This suggests a cumulative effect and a strong ability for the Tree Fence treatment to reduce wind speeds compared to the other treatments. The results of this study show that the Tree Fence treatment is both more consistent and is the most effective at reducing wind speeds which imply better dust and erosion control for these sandy environments.

Initial Site Conditions

Seedbank studies are common in restoration and inform vegetation management such as active seeding or spontaneous vegetation restoration in disturbed sites (Wang et al. 2021). Soil seed bank analysis revealed a predominance of non-native species, with only seven native seedlings identified among over 800 germinants.While this could be partly attributable to greenhouse conditions favoring the germination of non-native seeds, the subplot seeding palette of native species grown for comparison in the same greenhouse showed the that majority of seeded natives sprouted with the exception of two species (*Abronia villosa* and *Dicoria canescens*). This suggests that greenhouse conditions were likely not a hindrance in native species germination, which leads to the conclusion that there are more non-native than native seeds in the soil seed bank. Our seeding pilot study revealed a similar proportion of non-native seedlings *in situ*, so the implications for future management are the same. Non-native species will, if not managed, likely dominate retired farmland in the Borrego Valley Subbasin and pose an increased fire risk as seen in the Mojave desert (Matthew L. Brooks, 1999).

Of note, the soil sample collected in the northeast corner of BWD had a much larger seed bank than the rest of the block (Appendix Figure 5). This may be attributable to a lack of trees historically present at the location, leading to decreased disturbance from agricultural activity. The difference between BWD and T2 could be attributed to the time since fallowing, or the blocks' positions relative to other farm parcels and wildlands (Figure 13). T2, fallowedin 2016, may have had more time to accumulate a soil seed bank that is skewed towards Schismus, given that the surrounding parcels are all agricultural. On the other hand, BWD is immediately adjacent to a relatively undisturbed desert habitat and was fallowed much more recently (in 2023) than T2. Also worth noting is that despite the large amount of *Sysimbrium irio* seen in our soil seed bank samples, there were no suspected *S. irio* seedlings seen in our seeded subplots. This suggests that large amounts of water, such as the conditions present when these farming plots were irrigated (or in this case, with regular watering in a greenhouse), are needed for *S. irio* to germinate in the desert. This means that despite its lower numbers, *Brassica tournefortii* is the greater management concern.

Soil Salinity Patterns

Mapping spatial variability in salinity is valuable for guiding restoration planting palettes. This mirrors previous studies which promote a saline tolerant plant palette for restoration on retired farmlands (Blanchard et al. 2023). Moderately to highly saline soils were expected, as continuous irrigation often leads to soil degradation and increases in soil salinity (Herrero & Pérez-Coveta, 2005). The two sites had high spatial variability in salinity but similar overall average salinity. From the salinity interpolation map, the longer fallowed site (T2) appears to have less saline soils when compared to the newly fallowed site (BWD) which suggests a promising trend towards equilibrium for future retired farmland. Future monitoring of the blocks is recommended to confirm this trend.

If confirmed, the rate of decreasing soil salinity levels may suggest that salinity will not be of concern when choosing a plant palette as is suggested by the T2 site that had mostly non-saline and slightly-saline soils. Even more promising is the fact that 2 out of the 2 (moderately-saline tolerant) *Geraea canescens* that sprouted in our subplots were found at BWD which had a majority of slightly-saline to moderately-saline soils (Table 13). This indicates that more saline tolerant plants should not have a problem establishing on newly fallowed sites as is confirmed by the 18 out of 19 (highly-saline tolerant) *Atriplex spp.* also found at BWD. It is important to note that even though *Atriplex spp.* were the most abundant species onsite, this may just be due to the prolific nature of the species as backed by the germination trial that took place in the greenhouse where *Atriplex spp.* also dominated the subplot despite not having saline soils in greenhouse conditions (Table 14).

Table 13. Seeded subplot species classified by salinity class with seedling count results across both blocks. Note *Ambrosia* and *Atriplex* species could only be identified to the genus level at the time of monitoring.

Species	Salinity class	Seedling count
Croton californicus	Moderately Saline	0
Geraea canescens	Moderately Saline	2
Ambrosia spp.	Slightly-Highly saline	4
Abronia villosa.	Highly Saline	0
Atriplex spp.	Highly Saline	19
Larrea tridentata	Highly Saline	0

Table 14. Species counts for duplicate seed mix of subplots grown in the greenhouse.

Species	Count
Atriplex spp.	109
Ambrosia salsola var. salsola	57
Ambrosia dumosa	12
Geraea canescens	5
Larrea tridentata	1

Seeding Pilot Study

This water year, Anza-Borrego Desert State Park received 1.11 inches of rain (National Weather Service, 2025) making this a relatively dry year compared to the average yearly rainfall of 5.83 inches. Despite this, a qualitative comparison of the seeded subplots in BWD showed that the Mulch Rows germinated 18 native seedlings (mostly *Atriplex spp.*), followed by 5 seedlings in Tree Fences, and 1 in Scattered Trees. This suggests that Mulch Rows may contain the most conducive conditions for native species germination.

For germination across different rows within the same treatment, Row 0 contained less native seedlings compared to Rows 2 & 6 for Mulch Rows (Appendix Figure 9). The same trend is true for the Tree Fences when comparing Row 0 and 2-1H, however, we saw the same number of seedlings for Row 0 and 2-MID (Appendix Figure 9). Since the Scattered Trees only had one native seedling, results for this treatment are inconclusive. Because seedling counts were so low across all the treatments, future monitoring is recommended to take place in a wetter year to find statistically significant differences between native species germination specifically.

Germination count comparisons for both native and non-native seedlings between treatments did reveal that Mulch Rows outperformed the Tree Fences significantly and the Scattered Trees marginally significantly (Appendix Figure 10). Previous research has shown that mulch retains higher soil moisture compared to barren ground (Le et al., 2024) and decreases the soil temperature (Machado et al., 2024). Although our plots were seeded on the barren soil between mulch rows, it is possible that the mulch may have been retaining enough moisture to create a microclimate throughout the whole treatment plot that promoted more germination. One caveat to mulch's effectiveness specific to our sites in Anza-Borrego is that these conducive conditions may not be sustainable long-term if the Mulch Rows continue to be buried by deposition as we observed started happening in T2 (Figure 14). Scattered Trees and Tree Fences were also significantly different, however, this difference most likely mainly stems from the differences in the upwind rows, which would only be an indicator of the original seed bank present, and not a comparison of treatment effectiveness (Appendix Figure 10).

Figure 14. Drone imagery depicting the burial of the Mulch Rows in the T2 block over the span of 3 months.

Comparing total vegetation (natives and non-natives) at BWD allowed us to better see significant differences in germination across the different rows within each treatment. In the Mulch Rows and Scattered Trees we saw a significant reduction in vegetation from Row 0 to the downwind rows (Rows 2 & 6; Appendix Figure 10). For both treatments, there was no significant difference between Rows 2 and 6 indicating that there may be no cumulative effects on recruitment after Row 2. Since the majority of vegetation in this analysis were non-native species, our findings may imply that invasive species removal within the treatments may not be necessary. Given that these findings provide a clue regarding the treatments' ability to recruit plants, this may also have implications for potential native species recruits that would also have trouble finding their way into the treatments. This would mean that seeding may be vital to initiate the ecological restoration of these sites. Fortunately, competition from invasives would not be a great concern if overall recruitment is poor. Future monitoring of the subplots is necessary to find out whether these differences are truly due to diminished recruitment abilities within the treatments or if the seed bank within treatments may have been dramatically altered upon installation of each treatment with heavy equipment.

Study Limitations

A major setback in gathering overall data for this project were delays in treatment setup by our contractor. Treatments were expected to be completed by late September 2024, but were not finished until February 2025. This led to only being able to use two days worth of wind data and one dust collection period where the wind was predominantly blowing in from the northwest in both instances. This limited the power of our statistical analysis and therefore further monitoring is recommended to draw more concrete conclusions for both of these variables.

Delays also impacted our seeding pilot study design. In order to get seeds in the ground before any major precipitation was anticipated to occur, we decided to work with the treatments available to us at the time, that being the Mulch Rows, Scattered Trees, and partial Tree Fence (Rows 0 - 3) treatments set up at the BWD block.

This study's timeframe limited the ability to detect measurable soil erosion using erosion pins, which typically require multi-year monitoring. Future long-term monitoring by UCI Nature or subsequent MCRS cohorts will be essential to validate the relationships between fence porosity, wind, dust control, and erosion outcomes. Previous studies of fence porosity used flat fences, while the tree structures analyzed have complex 3-dimensional shapes. It is uncertain how much influence this kind of shape has on wind speeds, dust control, and recruitment when comparing porosity values alone.

The seeding pilot study was constrained by below-average precipitation during the peak growth season (February–March), limiting germination success. Although the seeding pilot study model did find significant reductions in seedling counts from Row 0 to Row 2 in all the treatments, it is important to note that the raw numbers indicate that Row 2-1h had more seedlings than Row 0 for the Tree Fences. This may point to limitations in the model that was based on data with a substantial amount of zeros for subplot counts. Wind monitoring also faced limitations due to variability in wind direction and strength; notably, during initial wind data collections, wind blew in from the west and southeast, thereby making that data unusable.

Conclusion

An active management approach for these sites is likely necessary for long-term ecological restoration and habitat improvement. Both the Scattered Tree and Tree Fence treatments are likely good choices for controlling erosion and reducing dust emissions. The Tree Fences are ideal for wind reduction, but the Scattered Trees show more promise for restoration given their more ideal porosity. Cost comparisons and availability of fallowed plant material may be the deciding factors for landowners when choosing between these two best treatments with Scattered Trees requiring less brush than Tree Fences. Based on dust control efficiency results, seeding should be done in the center rows of the treatments since erosion was minimal in the middle of the treatments. Further work is needed to collect data on the erosion pins and run another Digital Terrain Model to confirm our inferences on erosion control. Since the Tree Fences had low porosity on average, it would be worth further studying any scouring effects occurring around the structures to get a better idea of this treatment's effect on erosion despite reductions in wind speeds.

The site had an abundance of non-native species based on the soil seed bank analysis. Invasive management should be focused on the northeast corner of the BWD site since it had the highest abundance of non-native seeds, but all areas sampled had invasive species present. Species of concern include both *Brassica tournefortii* and *Schismus barbatus.* Since the only monocot identified in the soil seed bank was *Schismus barbatus,* a monocot-specific herbicide such as Fusilade can be used without concern of impacting native vegetation. Follow-up monitoring is recommended on the seeding pilot study during a wetter year to determine which treatment fosters the best environment for native plant growth. A more robust study is also recommended to confirm treatment effects on recruitment so that seeding may be recommended or deemed unnecessary.

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Appendix

Appendix Table 1. Dust Control Efficiency Results for Rows 5 & 2 in BWD Block. Note: Since upwind served as the control, it was used to calculate the dust control efficiency of the treatments at Rows 5 & 2.

BWD Block							
Date	Treatment	Row	Sampler ID	Height (cm)	Sand weight (g)	Dust Control Efficiency %	Average Efficiency % per Row
December 2024	Upwind	0	204	20	0.8926	NA	NA
				50	0.3032	NA	
	Upwind	0	208	20	1.5281	NA	NA
				50	0.544	NA	
	Mulch Rows	5	501	20	2.9559	-144	-175
				50	1.2903	-205	
	Scattered Trees	5	574	20	0.6930	43	54
				50	0.1502	65	
January 2025	Upwind	0	204	20	5.4464	NA	NA
				50	2.3392	NA	
	Upwind	0	208	20	3.2954	NA	NA
				50	2.6665	NA	
	Mulch Rows	5	501	20	13.5561	-234	-127
				50	3.3803	-20	
	Scattered Trees	5	574	20	4.3424	-7	17
				50	1.6714	41	
February 2025	Upwind	0	204	20	17.6585	NA	NA
				50	2.7298	NA	
	Upwind	0	208	20	9.0227	NA	NA
				50	2.1872	NA	
	Mulch Rows	5	501	20	1.6361	-30	-24
				50	0.5714	-18	
	Scattered Trees	5	574	20	0.5928	53	61
				50	0.1467	70	

BWD Block							
Date	Treatment	Row	Sampler ID	Height (cm)	Sand weight (g)	Dust Control Efficiency %	Average Efficiency % per Row
	Tree Fences	2	431	20	0.9612	24	56
	Tree Fences	2	431	50	0.0583	88	56
April 2025	Mulch Rows	0	575	20	2.4341	NA	NA
April 2025	Mulch Rows	0	575	50	0.5991	NA	NA
April 2025	Mulch Rows	5	501	20	9.5831	-294	-359
April 2025	Mulch Rows	5	501	50	3.1466	-425	-359
April 2025	Scattered Trees	0	208	20	19.3073	NA	NA
April 2025	Scattered Trees	0	208	50	2.2747	NA	NA
April 2025	Scattered Trees	5	574	20	1.0682	94	91
April 2025	Scattered Trees	5	574	50	0.2859	87	91
April 2025	Tree Fences	0	204	20	2.3484	NA	NA
April 2025	Tree Fences	0	204	50	1.6653	NA	NA
April 2025	Tree Fences	5	431	20	0.3948	83	89
April 2025	Tree Fences	5	431	50	0.1007	94	89
April 2025	Sand Fences	0	624	20	22.7232	NA	NA
April 2025	Sand Fences	0	624	50	4.1939	NA	NA
April 2025	Sand Fences	5	623	20	5.7673	75	43
April 2025	Sand Fences	5	623	50	3.7205	11	43

Appendix Table 2. Dust Control Efficiency Results for T2 block.

T2 Block							
Date	Treatment	Row	Sampler ID	Height (cm)	Sand weight (g)	Dust Control Efficiency %	Average Efficiency % per Row
April 2025	Mulch Rows	0	304	20	407.625	NA	NA
				50	56.1705	NA	
		5	438	20	263.0935	35	29
				50	43.7356	22	
	Scattered Trees	0	577	20	18.4416	NA	NA
				50	5.8561	NA	
		5	576	20	0.5647	97	94
				50	0.5117	91	
	Tree Fences	0	306	20	104.4366	NA	NA
				50	25.0511	NA	
		5	625	20	0.1851	100	99
				50	0.341	99	
	Sand Fences	0	303	20	68.2881	NA	NA
				50	15.9559	NA	
		5	578	20	12.6472	81	73
				50	5.7882	64	

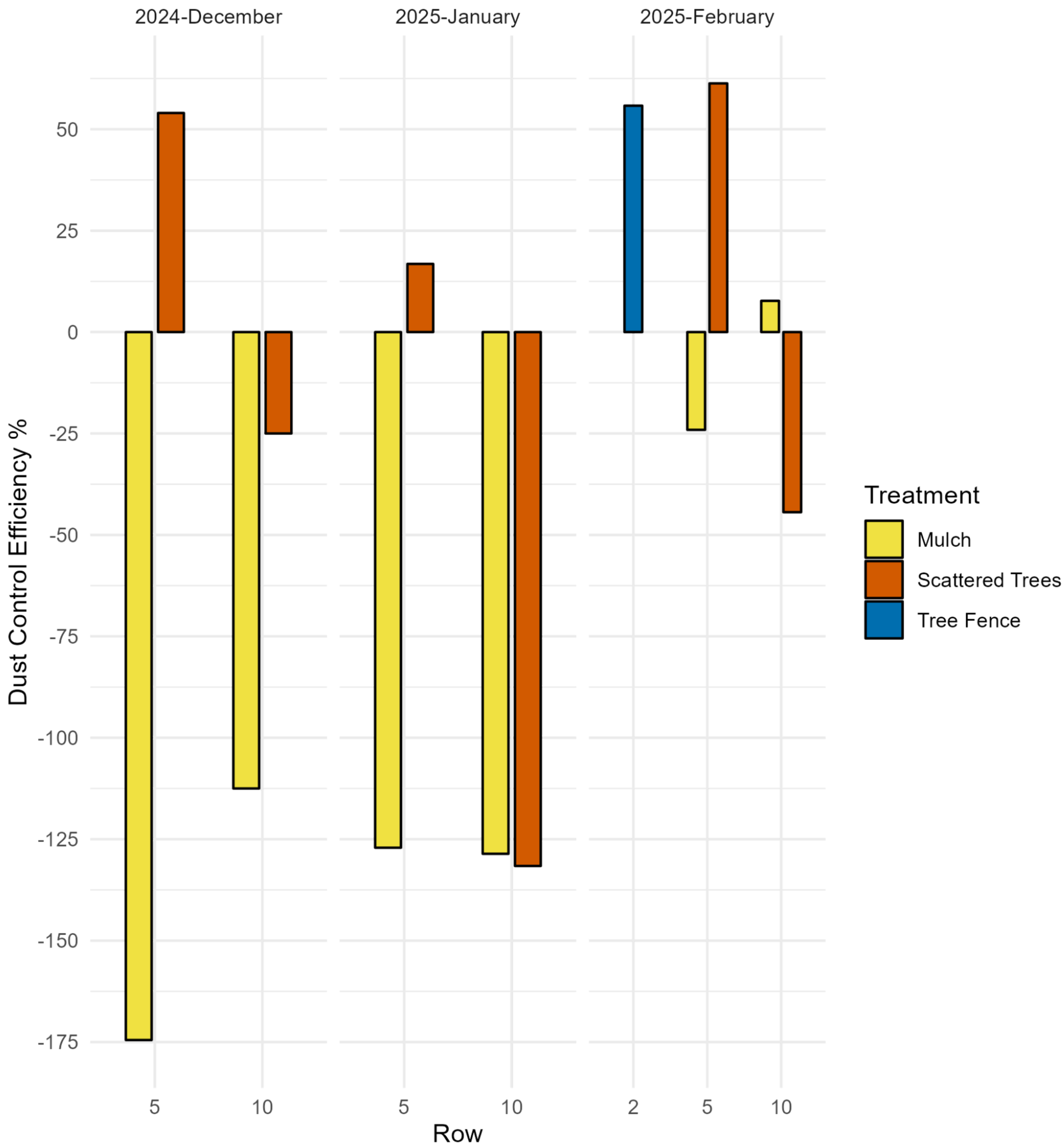
Appendix Table 3. Location of seeded subplots relative to the rows in which they were set for each treatment.

Block	Treatment	Row	Average distance from row to center of subplot (m)
BWD	Mulch Rows	upwind	5.00
		2	1.10
		6	1.03
	Scattered Trees	upwind	5.00
		2	3.70
		6	2.85
	Tree Fences	upwind	6.00
		2-1H	4.08
		2-MID	8.50
T2	Tree Fences	upwind	5.50
		2-1H	4.13
		2-MID	18.13

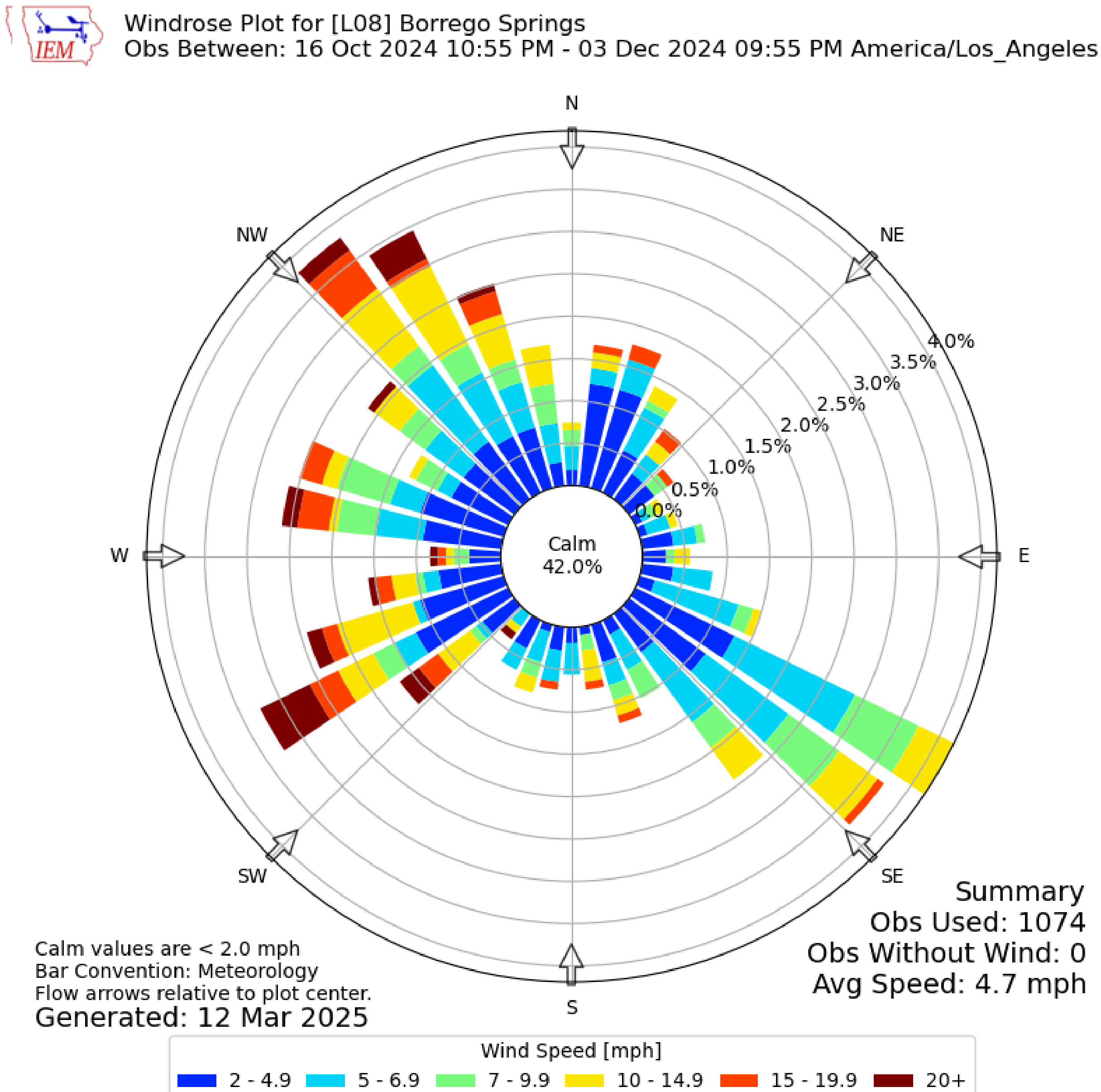
Appendix Table 4. Mean-centered wind speed data for all treatments.

Block	Treatment	Row	Mean-centered wind speed
T2	Mulch Rows	0	0.52916667
T2		1	-0.07083333
T2		5	-0.3375
T2		End Row	-1.37083333
T2	Sand Fences	0	2.25416667
T2		1	-0.62916667
T2		5	-1.1125
T2		End Row	-1.52916667
T2	Scattered Trees	0	2.33833333
T2		1	-0.45166667
T2		5	-0.61833333
T2		End Row	-2.55166667
T2	Tree Fences	0	2.37916667
T2		1	0.19583333
T2		5	-0.92083333
T2		End Row	-2.87083333
BWD	Mulch Rows	0	-0.15
BWD		1	0.48333333
BWD		5	-0.23333333
BWD		End Row	-1.03333333
BWD	Sand Fences	0	2.85833333
BWD		1	-0.775
BWD		5	-1.275
BWD		End Row	-2.60833333
BWD	Scattered Tree	0	2.8125
BWD		1	-2.8375

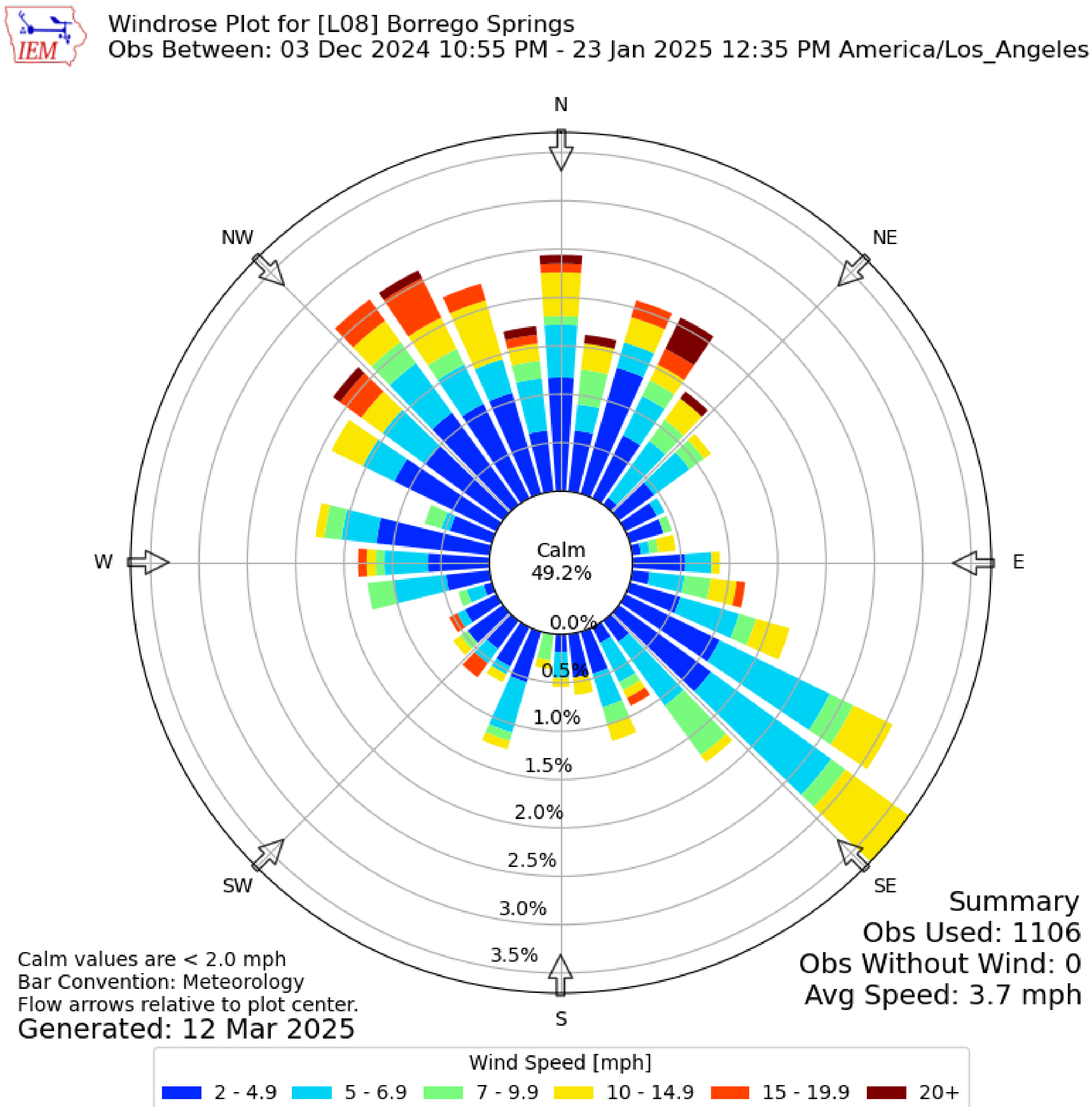
Block	Treatment	Row	Mean-centered wind speed
BWD		5	-0.8375
BWD		End Row	0.09583333
BWD	Tree Fences	0	3.9
BWD		1	-0.85
BWD		5	-1.51666667
BWD		End Row	-2.51666667



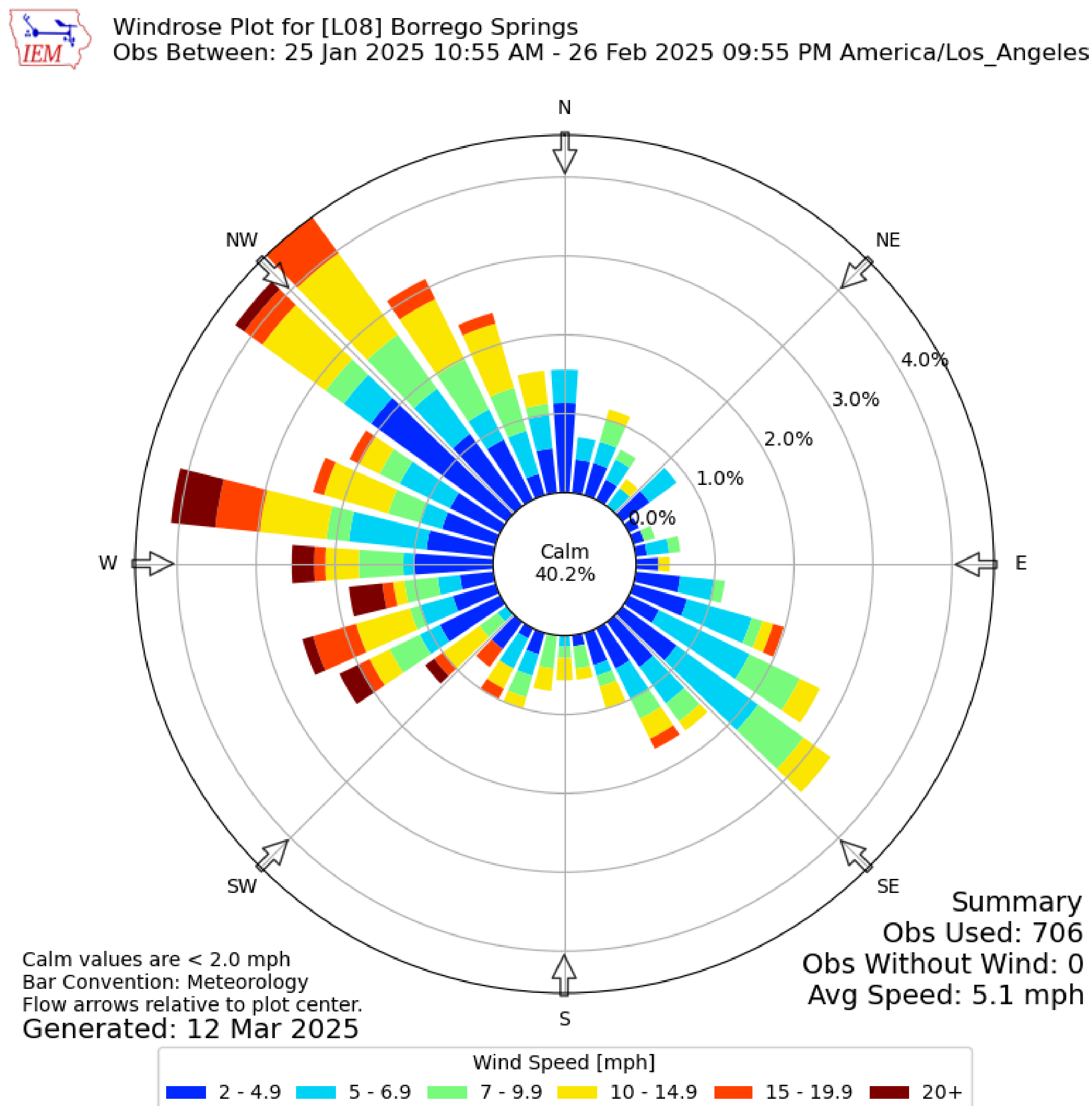
Appendix Figure 1. Preliminary Dust Data Collections. Note the negative values in Row 10 for December and January correlating to wind direction data coming from the southeast.



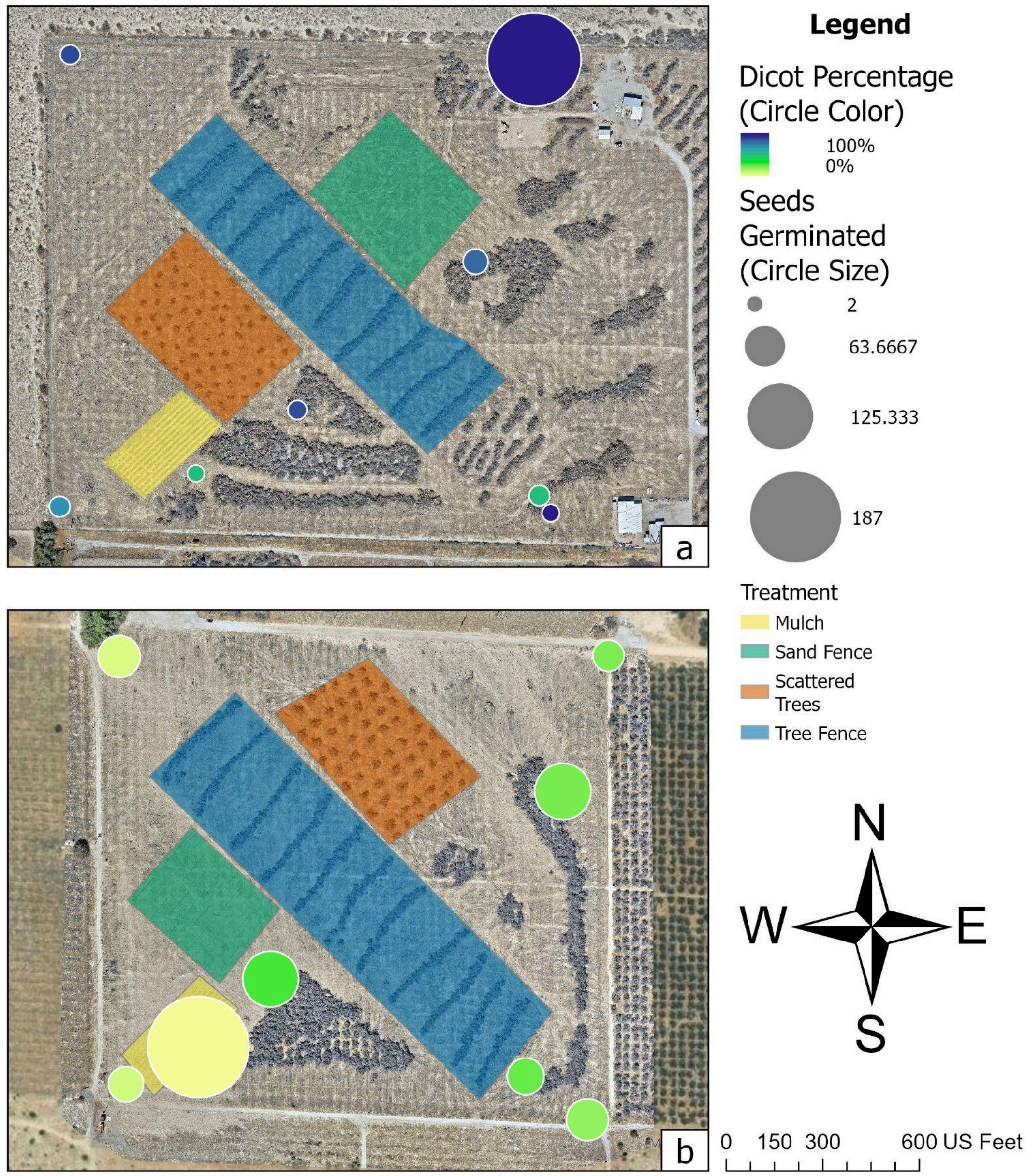
Appendix Figure 2. Windrose generated with data from October 2024 - December 2024 (Iowa State University, 2024).



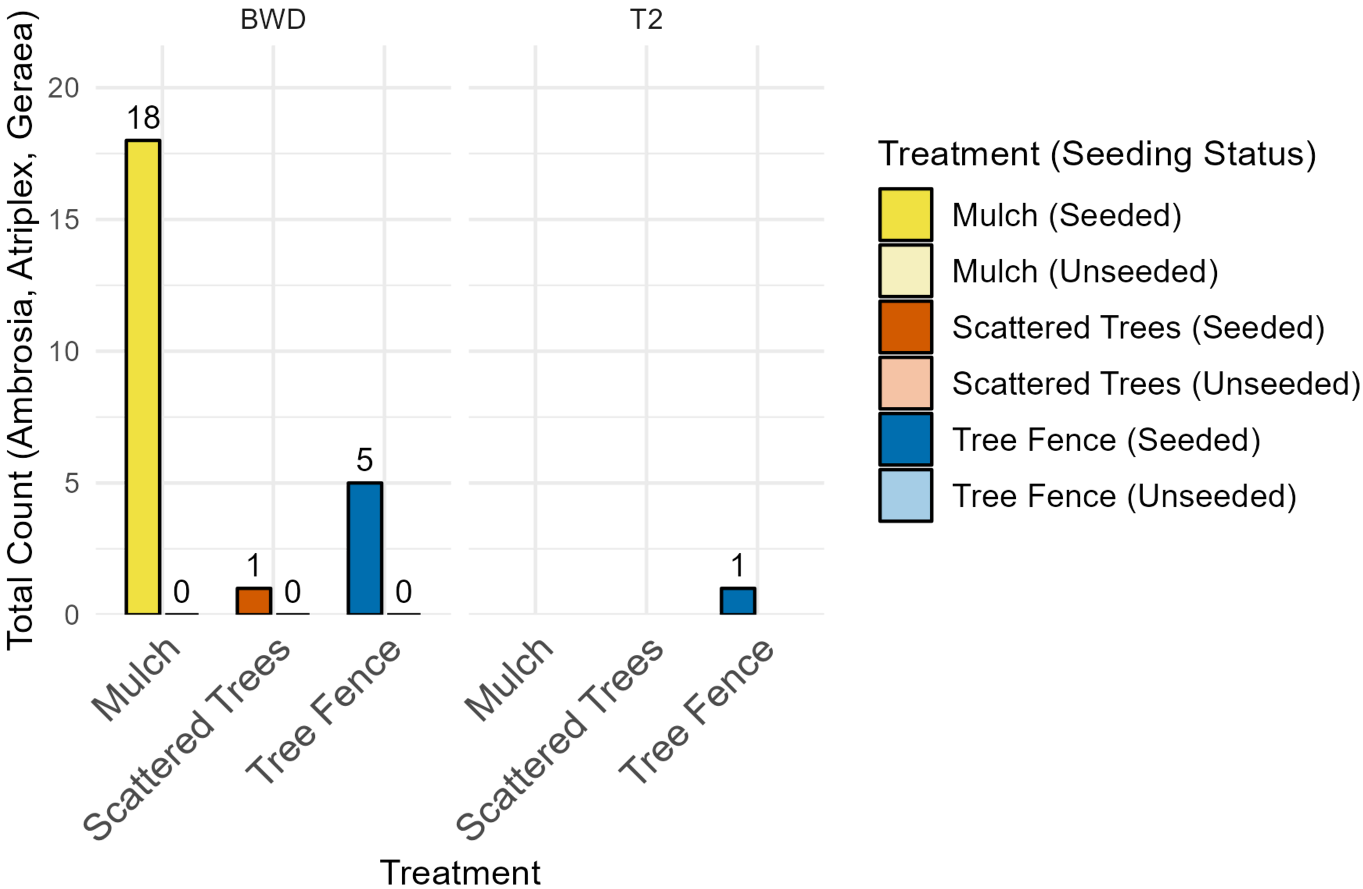
Appendix Figure 3. Windrose generated with data from December 2024 - January 2025 (Iowa State University, 2025).



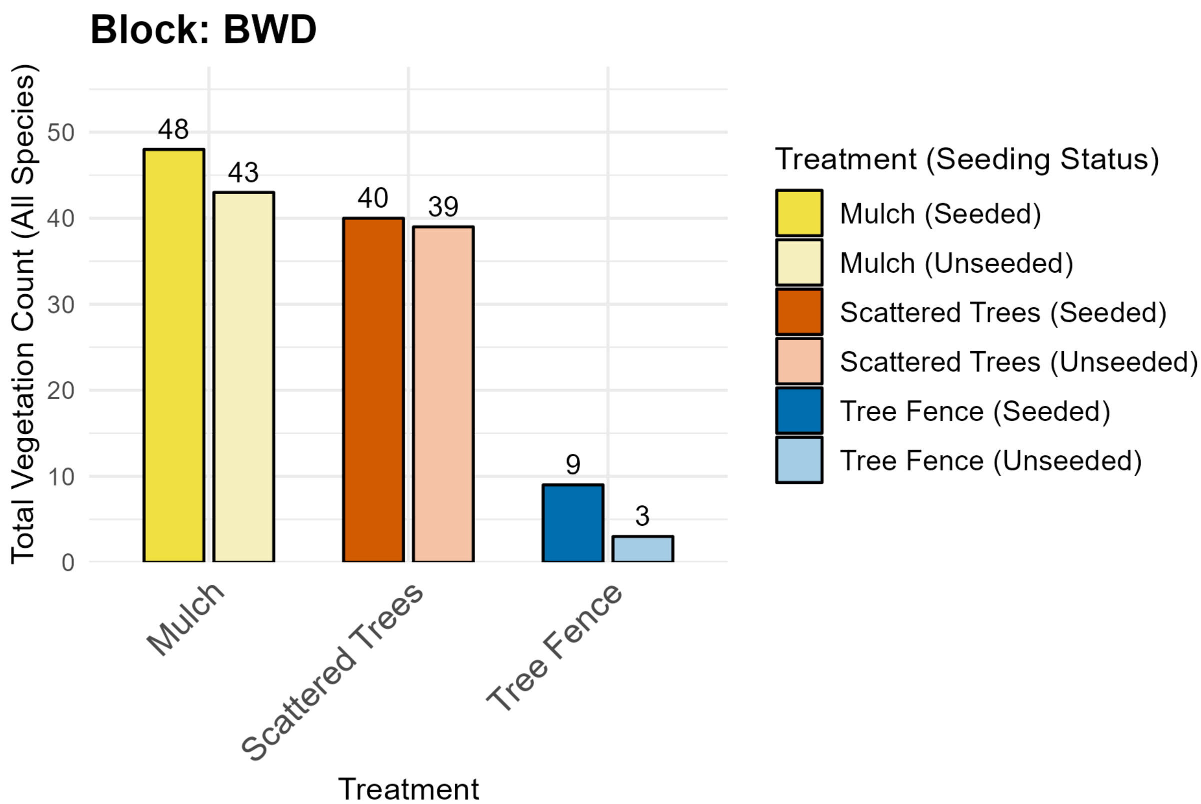
Appendix Figure 4. Windrose generated with data from January 2025 - February 2025 (Iowa State University, 2025).



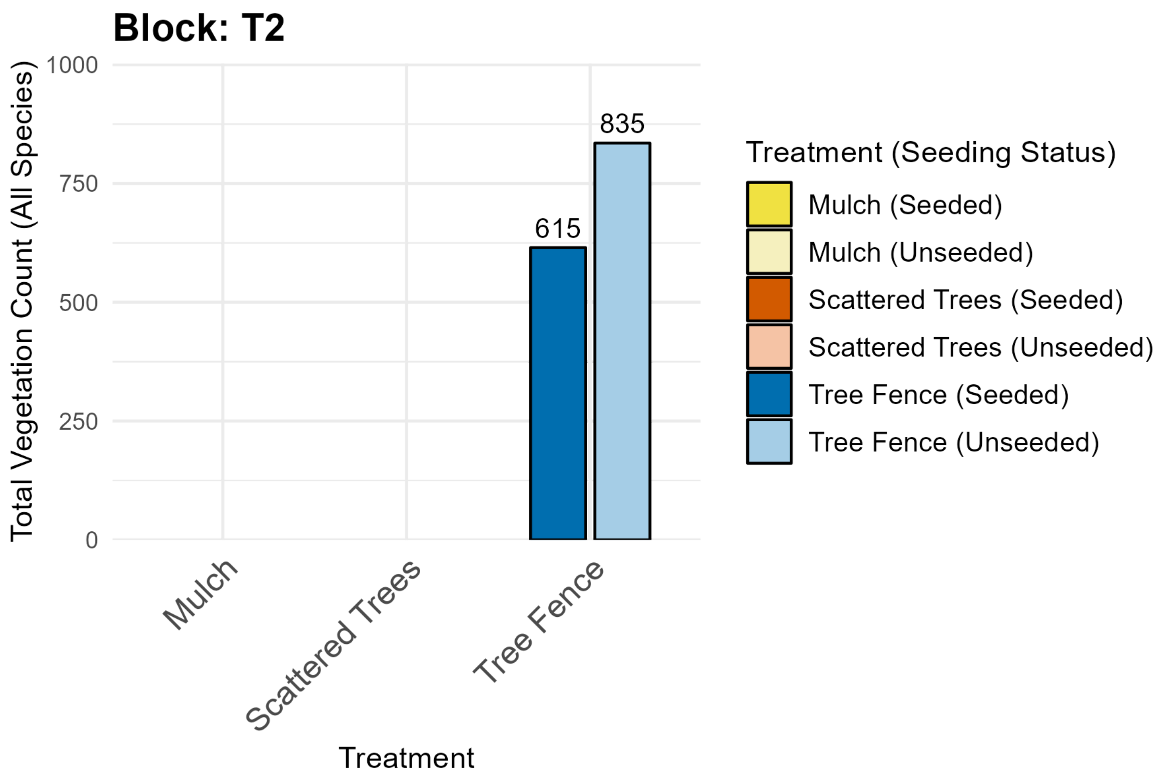
Appendix Figure 5. Maps from the BWD (a) site and T2 (b) site showing soil seed bank collection points where the point color shows the relative dominance of grasses (monocots, yellow) and non-grasses (dicots, blue) and the point size represents the total number of seedlings from that collection.



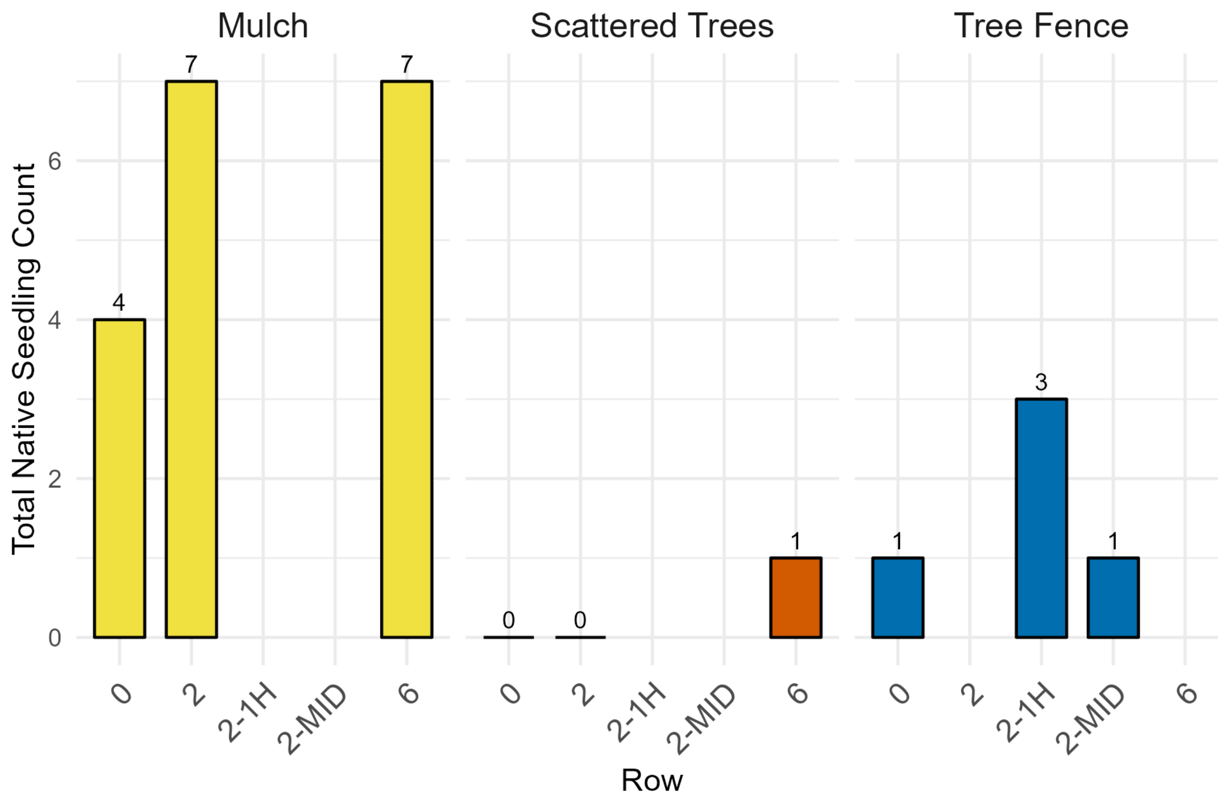
Appendix Figure 6. Bar plot showing counts of native species found throughout the treatments separated by block, treatment, and seeding status. No native species were observed in unseeded plots.



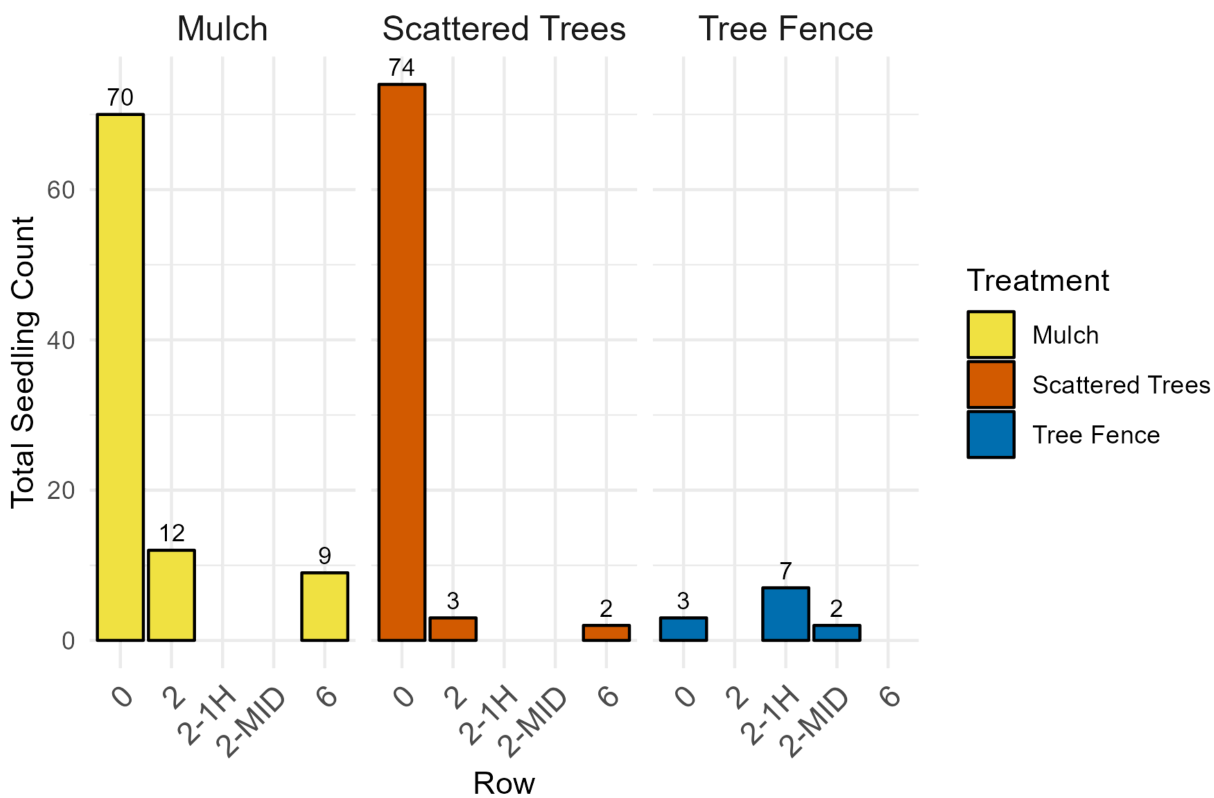
Appendix Figure 7. Bar plot showing counts of all seeded subplot germination (natives and non-natives) found throughout the treatments at BWD separated by seeding status. No significant differences were found between seeding status.



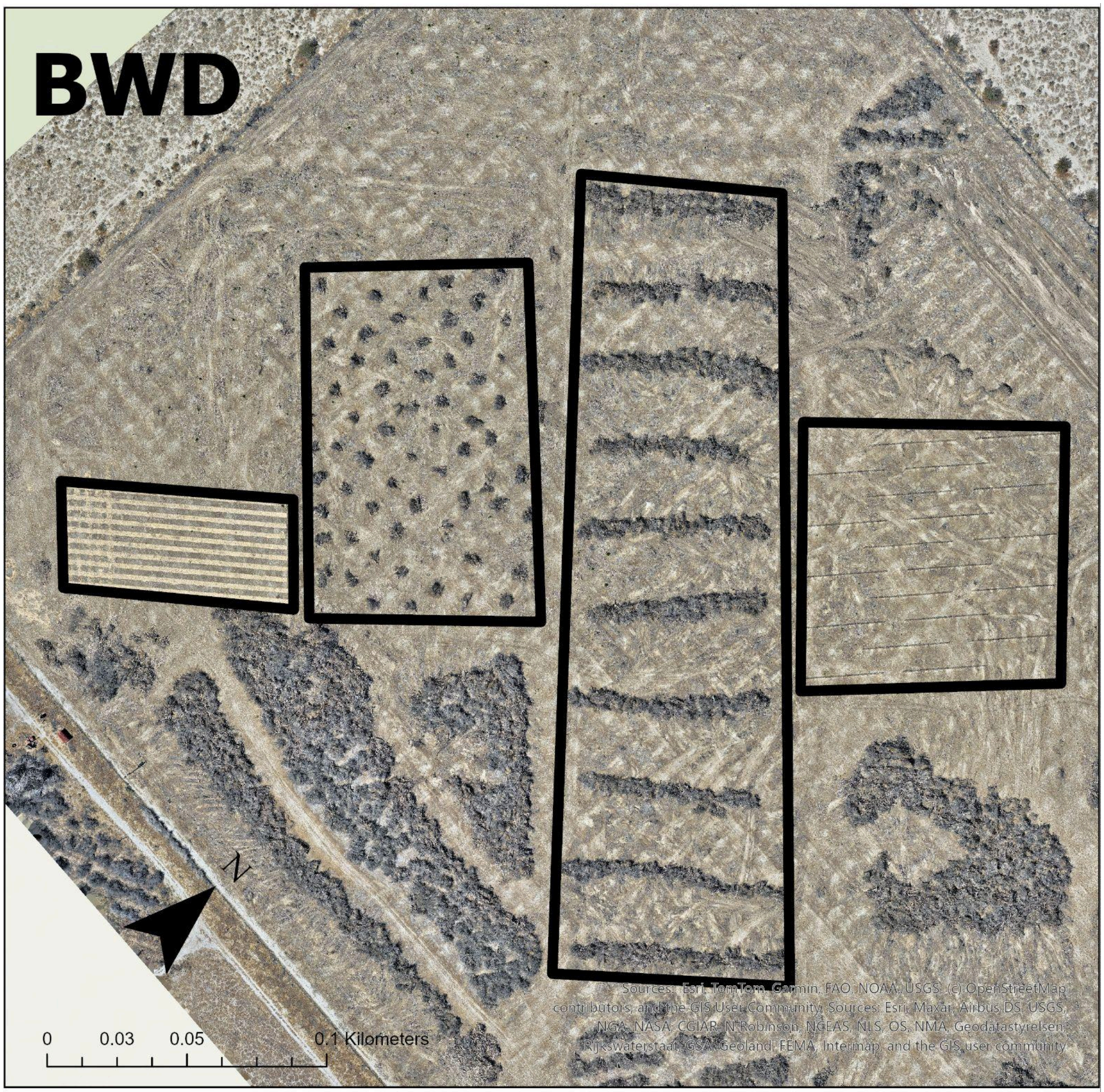
Appendix Figure 8. Bar plot showing counts of all germination found throughout the seeded subplots at T2. Note that the Tree Fences were the only treatment seeded in this block.



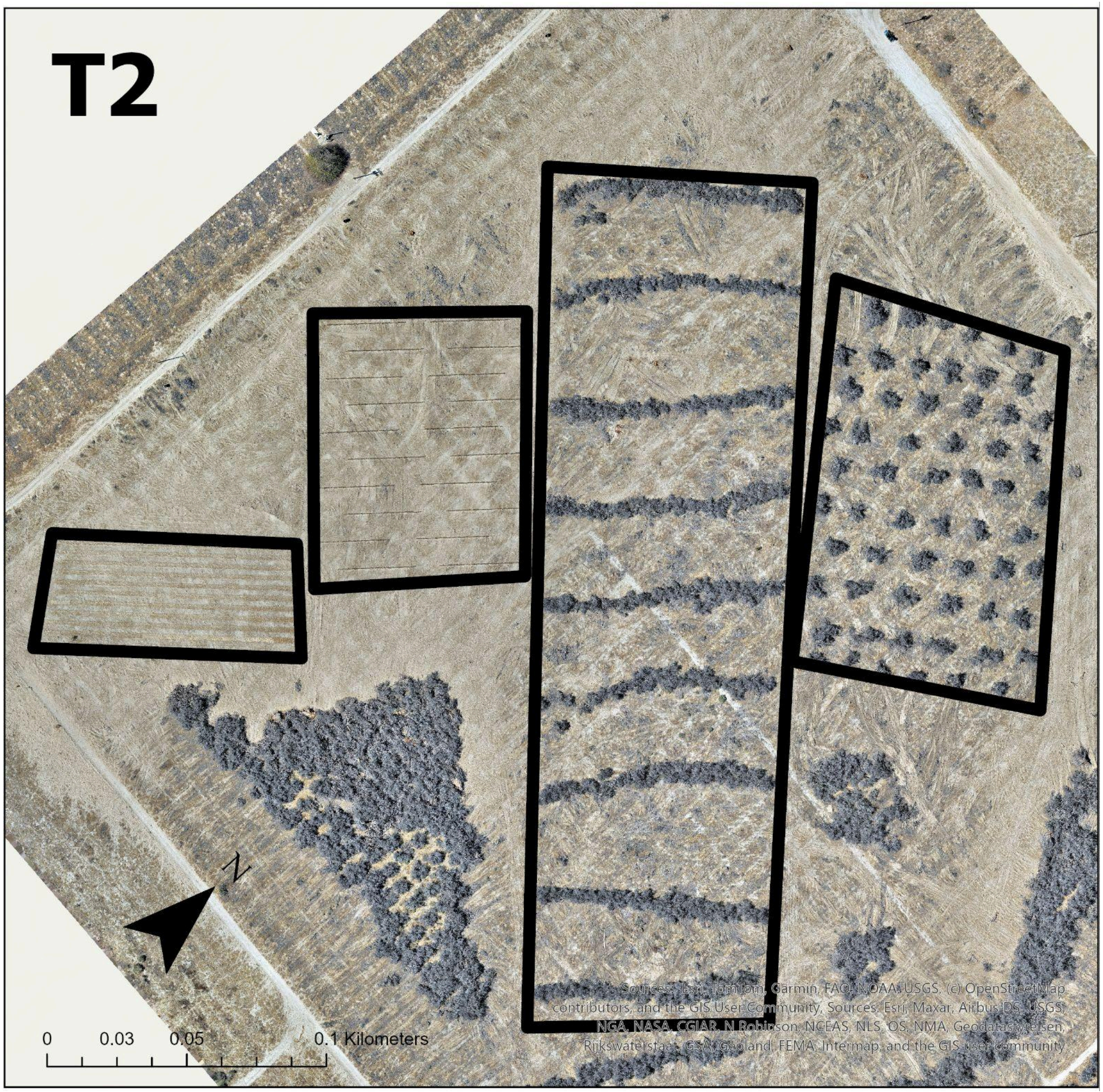
Appendix Figure 9. Bar plot showing counts of native species germination found throughout the seeded subplots at BWD by row.



Appendix Figure 10. Bar plot showing counts of all vegetation (native and non-native) species germination found throughout the seeded subplots at BWD by row.



Appendix Figure 11. Drone image of BWD block taken March 2023. Treatments from left to right: Mulch Rows, Scattered Trees, Tree Fences, and Sand Fences.



Appendix Figure 12. Drone image of T2 block taken March 2023. Treatments from left to right: Mulch Rows, Sand Fences, Tree Fences, and Scattered Trees.