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RESEARCH ARTICLE

Detecting spatiotemporal changes in harvester ant disks in response to fire and rodent competition using small unoccupied aerial systems imagery

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Abstract
Context North American deserts are changing due to expansion and increasing intensity of human activities. Disturbances and landscape change affect harvester ants, a keystone species in dryland ecosystems. Imagery acquired from small Unoccupied Aerial Vehicles (sUAVs) was analyzed to assess aboveground ant responses to change over time in the context of disturbance ecology and biological community interactions.
Objectives We assessed the effectiveness of using sUAV imagery to detect spatiotemporal trends in ant disks over time and evaluated how ant disk density and area changed due to fire and rodent exclusion.
Methods In 2011, we implemented a controlled experiment in Tooele County, Utah, USA, to test the effects of experimental fire and rodent reduction on desert communities. We applied supervised object-based image classification to sUAV images from 2016, 2021, and 2023 and assessed classification accuracy and how fire and rodent removal affected ant disk density and area over time.
Results Mapping accuracy of ant disk detection using sUAV imagery was consistent across all years. Our classification method detected ant disks at a lower density than manual methods. We failed to detect ant disks < 2.5 m in diameter; however, disks above 2.5 m were accurately identified. Burning increased disk density by 2.33 disks per plot, and rodent exclusion increased disk density by 1.73 disks per plot. Ant disk area increased by an average of 5.7 m^2 per plot per year but was not affected by fire or rodents.
Conclusions sUAV imagery can be used to monitor harvester ants' response to disturbances, with limitations. Our remote sensing methods have the potential to assess dryland ecosystem resilience to abiotic and biotic change by evaluating the responsiveness of harvester ant communities using mound and disk characteristics.

Keywords *Pogonomyrmex occidentalis* · Disturbance · Competition · Remote sensing

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Introduction

Human activity and subsequent disturbance often lead to landscape-level changes that decrease ecosystem stability. Small Unoccupied Aerial Vehicles (sUAV) are an emerging remote sensing platform used to monitor changes across landscapes and inform management decisions and conservation priorities. sUAVs are increasingly used in ecological monitoring and have a wide range of applications. For example, they are being used to monitor changes in regenerating vegetation (Sankey et al. 2019; Nuijten et al. 2021), vegetation recovery after disturbance (Pádua et al. 2019; Dashpurev et al. 2021; Luber et al. 2023), and detect invasive grass litter to predict future invasions (Bishop and Errigo 2023). Data collected from sUAVs bridge the gap between microscale field measurements and macroscale satellite imagery (Peterson et al. 2023). Several benefits of using sUAV imagery include (a) relatively cost-effective for local-scale mapping (up to 10 km^2) at centimeter spatial resolution (Manfreda et al. 2018); (b) much higher temporal resolution (i.e., data collection on demand) (Anderson and Gaston 2013); (c) collection of high spatial resolution data as an alternative to labor-intensive manual counting methods (Pérez-Luque et al. 2022), for example, when estimating population size (Hodgson et al. 2018); and d) high level of adaptability that provide data specific and relevant to fine-scale research objectives (Peterson et al. 2023). Some of the limitations of sUAVs include the inability to map large areas due to battery life, flying altitude/distance constraints, disturbance by rain and wind, national and local regulations that prevent sUAV data collection, large data sets and computing limitations, and the analytical expertise to process the data collected (Schill et al. 2024). In summary, sUAVs provide an opportunity to monitor local-level changes more cost-effectively and at finer spatiotemporal scales than ever before.

With a proper understanding of the benefits and limitations, sUAV technology can be an effective tool in answering specific research questions. sUAVs have been used to monitor environmental change by detecting keystone or indicator species and identifying changes over time to assess overall ecosystem health (Zmarz et al. 2015; Kivinen et al. 2020). This research applies sUAV imagery to detect fine-scale changes in ant communities. Ants can be effective indicator species to monitor landscapes because of their sensitivity and fast response to environmental change (Tiede et al. 2017). Western harvester ants (*Pogonomyrmex occidentalis*) are ecosystem engineers that alter desert ecosystems by removing vegetation and dispersing seeds (Rissing 1986; MacMahon et al. 2000; Uhey and Hofstetter 2022). Harvester ants remove vegetation to form large cleared areas called disks that alter soil nutrient and water properties (Sharp and Barr 1960; Carlson and Whitford 1991). Western harvester ant disks are scattered across landscapes with regular spacing at densities that can be up to 100 disks per hectare (Usnick and Hart 2002; Uhey and Hofstetter 2022) and may leave up to 3% of the landscape barren through vegetation clearing (Clark and Comanor 1975). These disks play important ecological roles in desert ecosystems by increasing spatial heterogeneity in plant communities (Gosselin et al. 2016) and by providing resources for grasses after disturbances such as drought (Nicolai et al. 2008), fire (Nicolai 2019), and grazing (Uhey et al. 2024). We explore using sUAV-derived imagery to measure ant disks and how harvester ant disk size and density change over time. sUAVs have been successfully used to detect ant mounds in tundra systems for ants that do not clear disks, providing a proof of concept for our experiment (Monsimet et al. 2024); we expand on this by evaluating the effectiveness of sUAVs in detecting ant mound and disk changes over time and in response to experimental treatments. Remotely sensing ant populations may provide insights into the overall health of their environment and the potential effects of human-induced environmental change.

In the Great Basin Desert, human activities have altered fire regimes, leading to broad-scale changes to native plant communities. The increase in fire size and frequency has allowed invasive annual grasses to become dominant, replacing native sagebrush and perennial grasses (D'Antonio and Vitousek 1992; Maestas et al. 2023). Vegetation state changes typically lead to changes at higher trophic levels. Harvester ants (*Pogonomyrmex occidentalis*) are abundant in the Great Basin Desert and play an essential ecological role in structuring plant and animal communities (Uhey and Hofstetter 2022). However, changes in climate, disturbance regimes, and trophic interactions can alter the effect ants have on dryland ecosystems (Day et al. 2018; Pienaar et al. 2024). Increases in fire and invasive annual grasses have been shown to increase harvester ant disk density (Holbrook et al. 2016; Day et al. 2018). Fire may also affect the interactions between ants and native rodents, with rodents having a stronger negative effect on ants in burned than unburned areas (Pienaar et al. 2024). These taxa are vital to ecosystem function because of their impact on the plant community (St. Clair et al. 2016; Uhey and Hofstetter 2022). Rodents and ants compete for seed and seedling resources, which can lead to reduced population growth in ant communities (Brown et al. 1979; Valone et al. 1994). Fire and cheatgrass invasions have created novel ecosystems for ants and rodents, which may change the nature of their interactions. Monitoring ant disk density and size could provide insight into how disturbance alters trophic cascades, and vegetation state changes that could influence the function and biodiversity of dryland ecosystems. Because of the size of western harvester ant disks, there is an opportunity to explore whether sUAVs can be used to monitor how they respond to ecological change over time. Measurements of ant disk densities in the same experimental plots at different time points showed different responses to rodents between 2016 and 2022; Day et al. (2018) showed that rodents had no significant effect on ant disk density in 2016, but by 2022, rodents had a significant negative impact on ant disk density (Pienaar et al. 2024). By using sUAV imagery to compare across multiple years, we can understand how fire and rodents affected ant disk density over time.

This study addresses two research questions. First, how effective is the classification of sUAV imagery in monitoring changes in ant disk density and size over time? Second, how does fire and rodent activity affect ant disk density and size over time? We predict that fire and rodent exclusion will increase ant disk density and area over time by removing woody vegetation and decreasing rodent competition for limiting resources.

Methods

Study site

Data were collected from a long-term research experiment in the Great Basin Desert in Tooele County, Utah, USA. Wyoming big sagebrush (*Artemisia tridentata wyomingensis*) is the dominant vegetation, but in recent years, invasive species Halogeton (*Halogeton glomeratus*) and cheatgrass (*Bromus tectorum*) have become more prevalent. The experiment was installed in 2011 and used five replicated 60 × 60 m blocks divided into four treatment combinations in a full factorial design. Treatments applied were burning and rodent exclusion, with unburned and rodent access as controls. Fires were started in burned plots using drip torches, and straw was laid to carry the fire across shrub interspaces. Rodent exclusion treatments were applied using 1 m tall, welded wire metal fencing and placing 20 cm of metal flashing along fence tops to prevent rodents from climbing in (Fig. 1). Fences were entrenched to 30 cm below ground to prevent burrowing, with 70 cm remaining above ground. For more details on the experimental design and site, see St. Clair and Bishop (2019). To maintain the treatment effect, rodents were removed from exclusion plots during live trapping events twice yearly. Rodent access plots had 12 × 10 cm holes cut in the wire fence every 4 m.

Data collection

Very high-resolution (1–3 cm) natural color (red, green, blue) stereo imagery was acquired using a multi-rotor sUAV in 2016, 2021, and 2023 (Table 1). Each image dataset was acquired using a different RGB sensor (Table 1) and processed as part of a separate research investigation. Image data from 2016 were collected in October using a Sony ILCE-QX1 20 MP attached to a 3DR Solo, and conditions were mostly sunny with a slight breeze. The data were used to map how invasive grasses are affected by biotic resistance and repeated disturbance, and images were taken right after the reburn (St. Clair and Bishop 2019). Soil reflectance differed between the 2016 images and others mainly due to the burn treatments. 2021 imagery was collected in November using the factory 20MP camera on the DJI Phantom 4 Pro V2, and conditions were mostly clear during the flight. In 2023, imagery was collected in May using the 20 MP Hasselblad L1D-20c camera on the DJI Mavic Pro V2, where conditions were clear but with strong winds that affected the sUAV, which may have caused the difference in resolution between 2021 and 2023 (Table 1). Data from 2021 and 2023 were collected to assess ant disk density across the study site. Image quality between datasets varied by year for several reasons, including inconsistent weather conditions, changing sun angles due to time of day and time of year, and variations in camera parameters from using

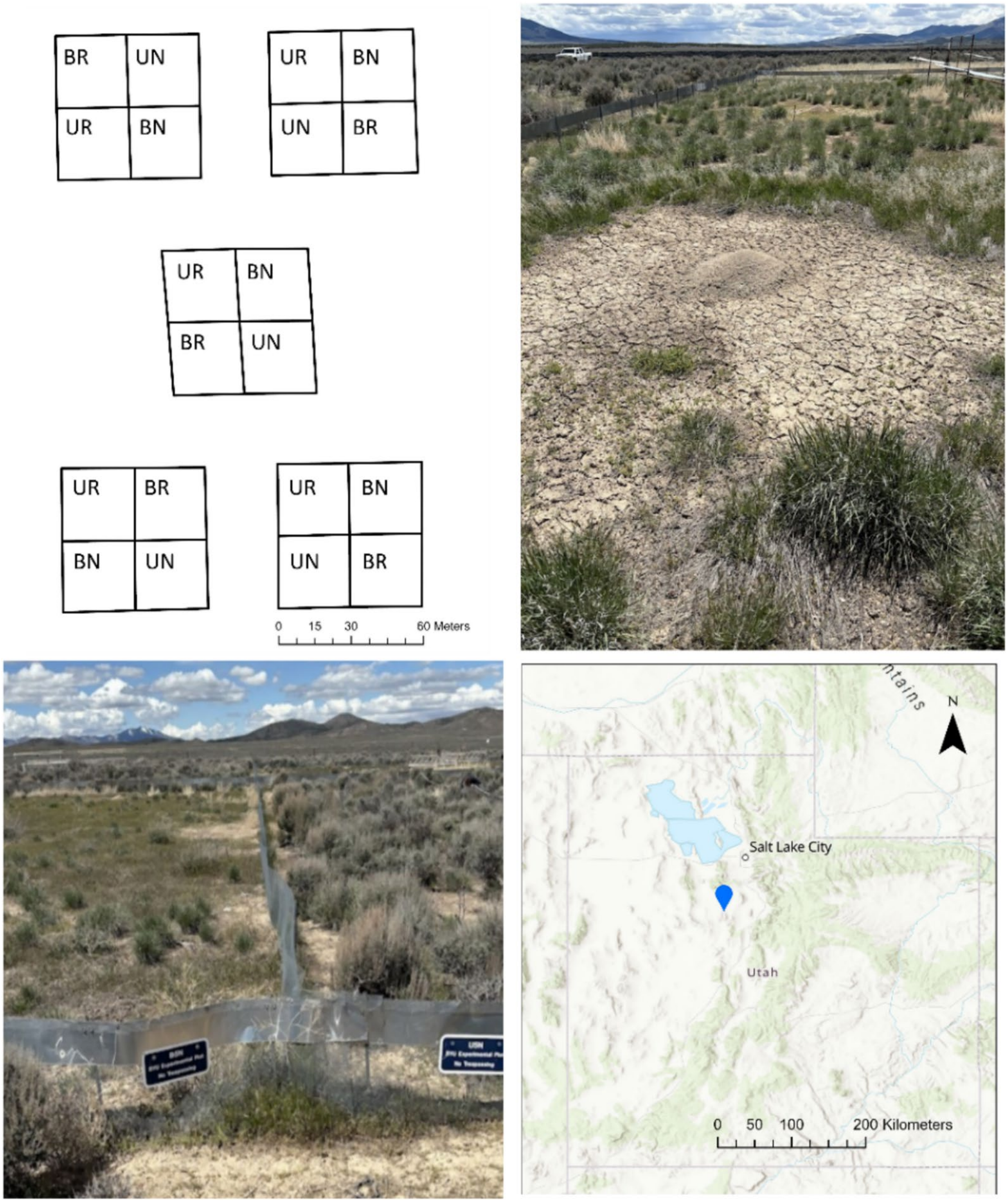

Fig. 1 Top Left: Experimental layout of treatment plots. *BR* Burned-Rodent Access, *BN* Burned-Rodent Exclusion, *UR* Unburned-Rodent Access, and *UN* Unburned-Rodent Exclusion. Top right: an example of a western harvester ant disk within the study plots. Bottom left: Rodent control fencing around the study plots showing a burned and unburned plot. Bottom right: Study location in Rush Valley, Utah, USA

different sensors. Field data collected manually on 17 September 2022 were used to verify the accuracy of our imagery classification. Ant disks were counted in each plot, and disk diameters were recorded. To compare ant disk size, we measured disk diameter; however, since disks are not perfectly circular, we measured the width of the disk through the center of the mound between the two points where the width was greatest.

Table 1 Details of cameras used for each year

Date	Camera	Drone	Image dimensions (cm)	Cell size (cm)	Flight height (m)	ISO	White balance	Overlap	Sidelap
28-Oct-16	Sony ILCE-QX1 20.1 MP	3DR Solo	4000 × 3000	3	60.96	400	Manual	0.85	0.7
11-Nov-21	DJI FC6310s (factory default)	DJI Phantom4 Pro V2	4032 × 3024	1	60.96	800	Manual	0.85	0.7
2-May-23	Hasselblad L1D-20c_10.3_(RGB) (factory default)	DJI Mavic 2 Pro	5472 × 3648	1.5	60.96	100	Auto	0.8	0.8

Orthomosaic classification

Each sUAV image dataset was post-processed using Pix4D Mapper (Pix4D SA, Switzerland) (http://www.pix4d.com) to produce a point cloud, digital surface model (DSM), and resulting orthomosaics for each year. For each image, we used the default parameters in Pix4D for the specific camera used. Spatial resolution varied between 1 and 3 cm. The single-band DSMs and 3-band RGB orthomosaics were loaded into eCognition Developer 10.4.0 software (Trimble Germany GmbH, Munich, Germany) for image segmentation and ant disk feature detection. Objects were created from the multi-layer image stack using the multiresolution segmentation algorithm with a scale parameter of 80 and shape function of 0.05. Image object features included in the supervised classification feature space were red, green, and blue mean spectral values, roundness, compactness, and neighboring class. We then performed a supervised classification to assign classes to objects. We used a K-nearest neighbor classifier ($k = 1$), with each object being assigned to the class with the highest mean value for that object. Objects were classified as ant disks, vegetation, or bare ground. In specific years, field equipment in the imagery was included with the bare ground class. We further refined our classification by manually iteratively excluding objects above certain thresholds for the number of pixels, length-to-width ratio, brightness, compactness, and roundness of the image object. Classification rulesets were developed to classify the treatment plots for each year and performed individually on each block to optimize accuracy (see Fig. 2).

We evaluated the accuracy of our classification by computing error matrices in ArcGIS Pro (Table 2). This was done by generating a stratified random sample of 30 points per class, visually identifying the observed class for each point, and comparing our visual ground truth with the predicted classification output. To further evaluate the accuracy of our classification, we compared the estimated density of ant disks determined by sUAV imagery to the collected manual counts. We compared the mean number of mounds per treatment plot for manual and sUAV classifications.

Statistics

All statistical analyses were run using program R (R CoreTeam 2020). We used ANOVA to compare ant disk density and total mean area per treatment across treatments and detection methods. We specifically compared the drone imagery from 2021 to the manual counts from 2022. We used the square root of the number of disks to meet the assumption of normality for an ANOVA. The explanatory variables included were the collection method (manual or drone) and the treatment plot with their interaction. Generalized linear mixed-effects models (GLMMs) were used to evaluate the treatments' effects on disk densities and area over time. Treatment blocks were included as random effects, with burn treatment, rodent exclusion,

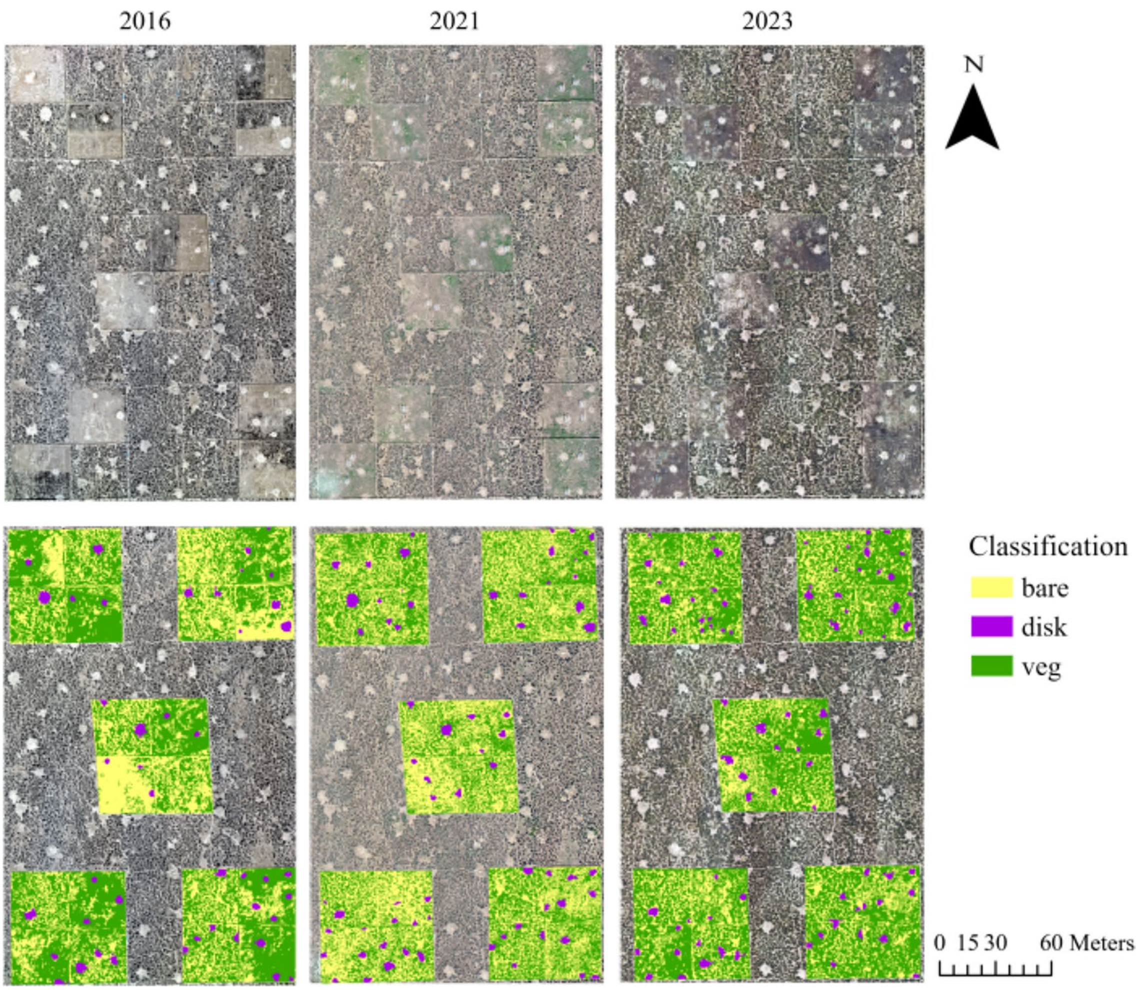

Fig. 2 Orthomosaics and resulting classifications for 2016, 2021, and 2023 show the distribution of ant disks, vegetation, and barren ground

and year designated as fixed effects. To determine if there was a size limit at which drones were not able to detect ant disks, we performed a sensitivity analysis in R by using ANOVA models to assess the difference between drone and manually collected methods. The analysis was repeated using subsets of the data that were manually collected, and disks below a size threshold were removed. We evaluated size cutoffs from 100 to 500 cm at 50 cm increments. We determined that a cutoff of 250 cm resulted in no significant difference in disk densities between manual and sUAV counts.

Results

Effectiveness of remote sensing ant mounds

Classification accuracy was high across the three sampling years: 2016 (kappa = 0.85), 2021 (kappa = 0.78), and 2023 (kappa = 0.83) (Table 2). Our classification objective was to maximize the accuracy of disk detection, not necessarily the overall accuracy of the various classes. Classification accuracy for the disk class was similar across all years. User's accuracy for disk detection was 0.97, 0.83, and 0.93 in 2016, 2021, and 2023 respectively (Table 2). Producer's accuracy for

Table 2 Error matrix of classification accuracy for 2016, 2021, and 2023 small unoccupied aerial vehicle imagery

	2016	Bare	Vegetation	Disk	Total	U Acc
	Reference data					
Classified data	Bare	24	6	0	30	0.8
	Vegetation	1	28	1	30	0.93
	Disk	1	0	29	30	0.97
	Total	26	34	30	90	
	P Acc	0.92	0.82	0.97		0.9
					Kappa	0.85
	2021	Bare	Vegetation	Disk	Total	U Acc
	Reference data					
Classified data	Bare	25	4	1	30	0.83
	Vegetation	3	27	0	30	0.9
	Disk	4	1	25	30	0.83
	Total	32	32	26	90	
	P Acc	0.78	0.84	0.96		0.86
					Kappa	0.78
	2023	Bare	Vegetation	Disk	Total	U Acc
	Reference data					
Classified data	Bare	23	4	3	30	0.77
	Vegetation	1	29	0	30	0.97
	Disk	1	1	28	30	0.93
	Total	25	34	31	90	
	P Acc	0.85	0.92	0.9		0.89
					Kappa	0.83

U Acc User's accuracy, *P Acc* Producers accuracy

disk detection was 0.97, 0.96, and 0.9 in 2016, 2021, and 2023 respectively (Table 2).

Disk density

We compared mound densities collected manually in 2022 to densities calculated using sUAV imagery in 2021. The classified sUAV image counts detected fewer mounds than were manually detected in all treatment plots (see Fig. 3A). There was a significant difference between detection methods in determining the number of mounds ($F = 11.0$, $p = 0.002$). We investigated if there was a size cut-off at which the difference between detection methods became irrelevant by iteratively removing disks below a specific diameter. When we removed all disks that were manually determined to have a diameter of less than 2.5 m, the difference in disk density between the sUAV and manual methods was greatly reduced, and there was no longer a significant effect of the detection method on number of disks counted ($F = 0.61$, $p = 0.44$, see Fig. 3B).

Area

We compared total disk areas per treatment plot between remote sensing and manual methods. Manual methods showed a higher total average disk area per plot across all treatment types ($F = 2.3$, $p = 0.001$, see Fig. 5A). We then made the same size correction by removing all disks with a diameter of less than 2.5 m. However, the difference between manual and remote sensed methods persisted after removing the disks with diameters below the threshold ($F = 7.1$, $p = 0.012$, see Fig. 5B).

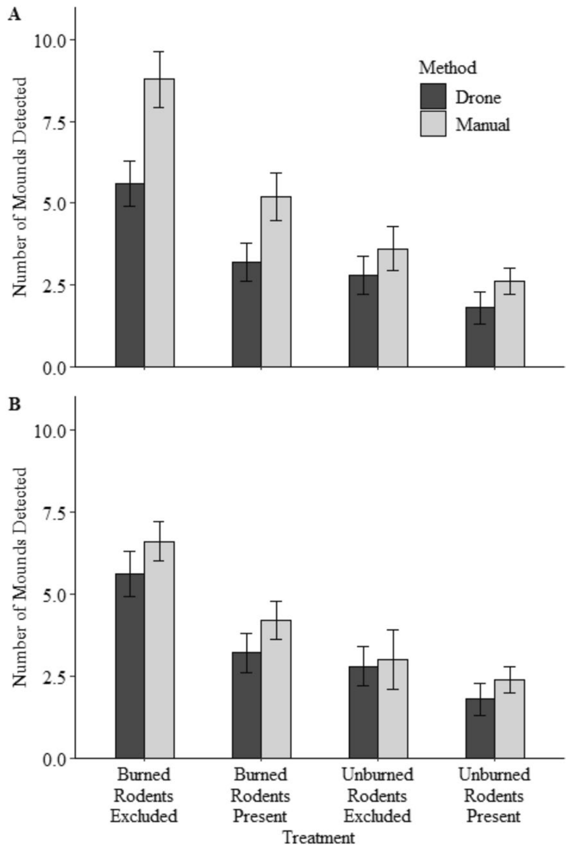

Fig. 3 Disk density comparison between small Unoccupied Aerial Vehicle (2021) and manual counts (2022) across burned or unburned and rodent presence or exclusion treatments. **A** Includes all disks regardless of size. **B** Only includes disks with a diameter greater than 2.5 m

Effects of fire and rodents on ant mound formation over time

Mean disk density per plot increased across all treatment plots from 2016 to 2023, with the number of disks per plot increasing by 0.26 each year (SE ± 0.05, $t = 4.9$, $p < 0.001$). The highest disk density was in burned rodent exclusion plots (6.0 disks per plot in 2023). The lowest density was in unburned rodent presence plots (3.2 disks per plot in 2023) (Fig. 5A). Unburned plots had 2.33 fewer disks than burned plots (SE ± 0.45, $t = -5.2$, $p < 0.001$), and plots with rodents present had 1.73 (SE ± 0.45, $t = -3.9$, $p < 0.001$) fewer disks than plots that excluded rodents. Fire and rodent exclusion treatments also showed an interactive effect where the positive effect of rodent exclusion on disk density was greater in burned plots than in unburned plots ($t = 2.0$, $p = 0.051$).

The average total disk area per plot increased over time across all treatments. The average total disk area per 30 m × 30 m plot increased by 5.6 m^2 per year (SE ± 2.18, $t = 2.6$, $p = 0.012$). Fire and rodent exclusion did not significantly affect total ant disk area ($t = -1.3$, $p = 0.21$ and $t = -0.96$, $p = 0.34$ for fire-by-rodent interaction, respectively) (Fig. 5B).

Discussion

We explored the use of sUAV technology to assess spatiotemporal patterns of ant disks in response to fire and rodent exclusion. Our first research question asked how effective the classification of sUAV imagery is for monitoring changes in ant disk density and area over time. We demonstrated that sUAV imagery can effectively detect ant disks in the Great Basin Desert with some limitations (Table 2). Detecting ant disks using remotely sensed imagery depends on the spectral, spatial, and temporal resolutions of the collected data (Peña et al. 2015). When conducting change detection using remote sensing, it is important to keep collection and classification parameters consistent between years to minimize differences between classification periods. Differences in conditions (wind) and equipment (camera) used for our three data collection flights resulted in pixel sizes ranging from 1 to 3 cm that could impact classification accuracy. The 2016 imagery was collected with an external camera attached to the drone, which made focusing the camera difficult. However, despite having the coarsest resolution, the 2016 classification had the highest accuracy score. Thus, better resolution does not necessarily mean better accuracy. The resulting classification accuracy should also stay consistent across all years to compare change over time. Our results showed similar accuracy scores for disk detection between the 3 years, sufficient to compare disk size and density. However, it should be noted that when different sensors are used and flights occur at various times of day and year, there may be differences in the quality of each image produced due to inconsistent lighting (Olson and Anderson 2021) and because of phenological variability between years and seasons

(Bradley and Mustard 2008; Jackson et al. 2020). This variability can create challenges in running classification algorithms and achieving acceptable levels of accuracy. Future change detections can be improved by repeating flights at the same time of day and using the same sensor in the same configuration each time. The image classification technique with the highest accuracy can also vary between flights. Thus, a decision needs to be made whether to classify with consistency of technique across all images or maximize accuracy by using a different technique for each dataset (Jackson et al. 2020).

When comparing our remotely sensed results to our manually collected data, we saw differences in disk density and area (Figs. 2 and 3). We tested if the difference between remotely sensed and manual methods could be due to the inability to detect the smallest disks in the imagery (Zhou et al. 2022). When we removed all disks with a diameter < 2.5 m, there were a similar number of disks detected for each treatment between the two methods (Fig. 3). Thus, our remote sensed methods were effective at detecting ant disk density when the disks had a diameter greater than 2.5 m. Higher spatial resolution could improve the detection of ant mounds, and as sUAV sensor technologies improve, the size cut-off at which we can remotely detect ant disks will decrease (Vogt 2004). Improved radiometric resolution can also improve the detection of smaller disks as there will be greater contrast between pixels, improving the machine learning classification accuracy (Verde et al. 2018). The 2.5 m size cut-offs did not have the same effect on disk area (Fig. 4). Our manual methods likely overestimated disk area because areas were calculated as circles, with the diameter being measured at the widest part of the disk for ease of data collection and consistency between observers. Because disks are not perfectly circular, each disk's area will always be overestimated. Thus, we do not believe the differences between our manually measured and remote sensed areas confound our results.

Remote sensing methods are sufficient for determining harvester ant disk density when monitoring landscape response to ecological changes such as disturbance and variation in competition. Manual methods detect more ant disks; however, disks missed by the classification of sUAV imagery were the smallest and likely to have a lower biological impact (Cole et al. 2022). Harvester ant's effects on plant communities are related to disk size, as disk perimeters have enhanced plant regeneration post-disturbance (Nicolai 2019). Larger disks result in a greater total area experiencing enhanced regeneration. sUAV image classification is also more accurate than manual methods in determining disk area because of how difficult it is to determine the area of an irregular shape in the field, and so we have the added benefit of not needing to rely on proxies (such as width) to monitor habitat quality (Stephens et al. 2015). Although remote sensing techniques detect disks with lower accuracy, they can cover large areas more cost-effectively than manual methods, especially when integrated with high-resolution satellite imagery. Thus, there is a trade-off between manual and remote sensed methods in terms of accuracy and size of an

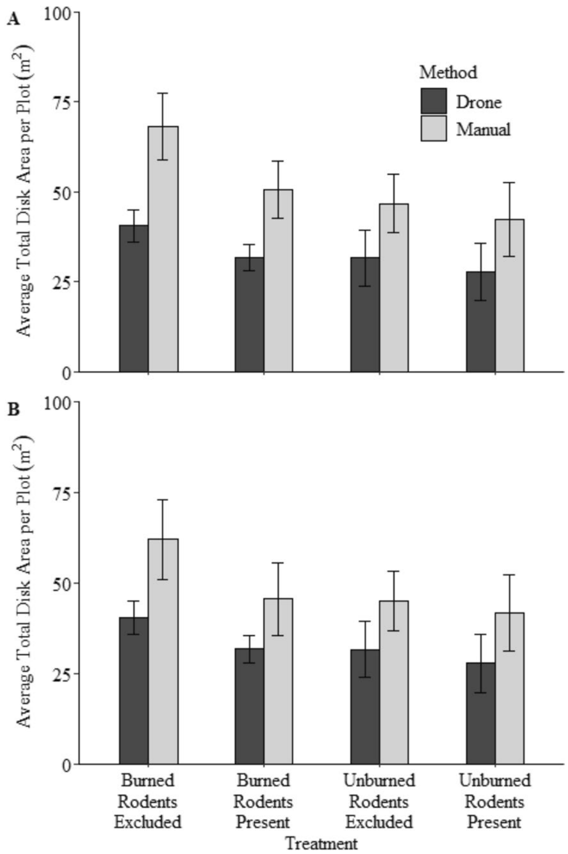

Fig. 4 Disk area comparison between small Unoccupied Aerial Vehicle (2021) and manual counts (2022) across burned or unburned and rodent access or rodent exclusion treatments. **A** All disks of all sizes. **B** Only disks with a diameter greater than 2.5 m are included

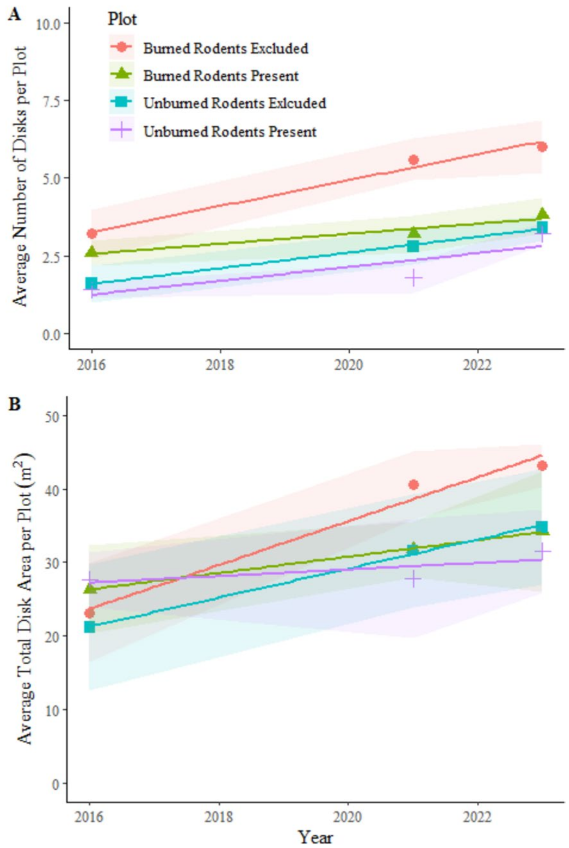

Fig. 5 **A** Mean number of disks per plot over time calculated using sUAV imagery (± SE). **B** Average total disk area (m^2) per plot over time (± SE)

area, and the technique used should depend on the research question.

Burned areas showed higher ant disk density than unburned areas across all years. This finding is in agreement with past studies that show that fire increases ant disk density (Holbrook et al. 2016; Day et al. 2018; Pienaar et al. 2024). Fire in the western United States can and has dramatically changed plant community composition through the removal of native sagebrush and the facilitation of invasive annual grasses (D'Antonio and Vitousek 1992; Gill et al. 2018; Fusco et al. 2022). Invasive annual grass abundance is positively correlated with harvester ant disk density (Holbrook et al. 2016). Fire or rodents did not significantly affect the total disk area per plot. Previous research showed that ant disks tend to be smaller in burned areas but occur at higher densities (Day et al. 2018). In burned areas, ants may be able to establish disks more easily because there is less woody vegetation to remove (Pienaar et al. 2024). This would increase disk density without increasing the total disk area per plot because of the development of smaller disks. Harvester ants appear to be resilient to the state transitions caused by fire and invasive grasses that negatively affect many other native species (Mack 1981; Fletcher et al. 2019).

Rodent exclusion led to higher ant disk densities across all years (Fig. 5). Exclusion of either rodents or ants can result in increases in the other due to competition release (Brown et al. 1979). Previous studies have presented varied results on the effects of rodent exclusion on ant disk density; rodent exclusion had no significant effect on *Pogonomyrmex desertorum* disk density in the Chihuahuan Desert (Valone et al. 1994). In the Great Basin Desert, rodents had no effect on *P. occidentalis* after 5 years (Day et al. 2018) but reduced ant disk density compared to rodent exclusion plots after ten years (Pienaar et al. 2024). In the Sonoran Desert, rodent exclusion initially increased *Pogonomyrmex rugosus* density (Brown et al. 1979), but over time, density decreased (Davidson et al. 1984). An argument proposed for why rodent exclusion does not affect ants is that as time passes since rodents have been removed, the abundance of preferred ant forage decreases due to herbivory and granivory, which prevents the exponential growth of ant populations (Davidson et al. 1984). However, we show continued increases in ant density over the study period. Hence, changes in forage abundance are either not negatively affecting ants in the Great Basin Desert, or the positive effects of fire are still outweighing the potential negative effects. The positive effects of rodent exclusion on ant disk density could be direct through a decrease in physical attacks by rodents on ant mounds (Wiernasz et al. 2014). Rodent exclusion may also benefit ants indirectly by increasing cheatgrass density (St. Clair et al. 2016), which has been positively correlated with ant disk density (Ostoja 2008; Holbrook et al. 2016; Pienaar et al. 2024).

Conclusion

Our results provided some important ecological insights and suggest that sUAVs can be an effective tool for monitoring harvester ant disks in desert ecosystems with some limitations (Fig. 4). Harvester ants are an ecologically important species in desert ecosystems, and their resilience to fire may provide community-level resilience to change by facilitating regrowth after disturbance (Uhey and Hofstetter 2022). We demonstrate that sUAVs can be used to measure the effects of fire and rodent competition on harvester ants. Remote sensing methods, including sUAV and satellite data collection, may allow for more efficient monitoring of ecosystems vulnerable to human-induced change. Our results demonstrate that harvester ants exhibit resilience to fire and the consequent invasion of cheatgrass species due to burning (Fig. 5). Ants' resilience to these changes may have positive effects on ecosystem productivity and biodiversity that decrease due to invasion (Vale 1975; Uhey and Hofstetter 2022).

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Author contributions The study was conceived and designed by RP, SBS, and TB. Data collection was performed by RP, SBS, and TB. Image classification was performed by RP, TB, and SRS. RP: wrote the first draft of the manuscript, and all authors commented on versions of the manuscript.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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