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Fire Ecology

FIELD NOTE

The impact of UAS aerial ignition on prescribed fire: a case study in multiple ecoregions of Texas and Louisiana

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Abstract

Background Small Unmanned Aerial System (UAS) technologies and their applications have expanded in recent years, to include aerial ignition support in prescribed fire and wildland fire settings. In 2019, we incorporated the use of UAS aerial ignition into our existing prescribed fire program of over 20 years. To assess its impact, comparisons of UAS and non-UAS burns were performed on burn data from 2012 to 2021, with 58 total UAS burns conducted from 2019 to 2021. A subset of these burns conducted at Cook's Branch Conservancy in Montgomery County, TX, included post-burn assessment data, which we used to compare UAS and non-UAS fire effects.

Results Non-parametric significance tests were used to analyze and compare non-UAS burning before (2012–2018) and after (2019–2021) the incorporation of the UAS, and UAS burning from 2019 to 2021. Response variables included ha day^{-1} burned and six different post-burn assessment metrics. Principal findings were that from 2019 to 2021, UAS burns were 61 ha day^{-1} or 129% more efficient than non-UAS burning and required one extra staff member to pilot the UAS on average. This increase enabled a previously unachievable efficiency in terms of hectares burned each year vs days burned each year when using the UAS. While fire effects were less severe for most post-burn assessment metrics during UAS burning, burn results still met fuel management goals when compared to non-UAS burning.

Conclusions A large increase in ha day^{-1} was previously unachievable, making the UAS a viable tool for accomplishing safer and more effective prescribed burn operations in the limited number of suitable days available. When managed responsibly, UAS aerial ignition is poised to have a positive impact on the safe and effective application of prescribed fire, resulting in more achievable conservation and fuel management goals.

Keywords IGNIS, UAS, Aerial ignition, Prescribed fire, Interior ignition, Fire management

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Resumen

Antecedentes Las tecnologías de los Sistemas de Pequeños Vehículos Aéreos no Tripulados (UAS en idioma inglés) y sus aplicaciones, se han expandido en años recientes, incluyéndolos como soporte en la ignición de quemas prescriptas y otras aplicaciones en incendios de vegetación. En 2019 incorporamos el uso de igniciones aéreas mediante UAS en nuestro programa de quemas prescriptas de más de 20 años. Para determinar su impacto, comparamos datos entre quemas mediante UAS y no UAS (tradicionales) que fueron realizadas entre 2012 a 2021, con un total de 58 quemas usando UAS y conducidas entre 2019 y 2021. Un subconjunto de esas quemas conducidas en el Cook's Branch Conservancy en el condado de Montgomery, Texas, incluyó la determinación de datos post-quema, que fueron usados para comparar los efectos del fuego entre UAS y no UAS.

Resultados La significancia de pruebas no paramétricas fue usada para analizar y comparar las quemas no UAS (tradicionales) entre 2012 y 2018, y luego de la incorporación de las quemas mediante UAS desde 2019 y hasta 2021. Las variables respuesta incluyeron las ha . día^{-1} quemadas, y la determinación de seis diferentes mediciones post quemas. Los principales resultados mostraron que desde 2019 y hasta 2021, las quemas mediante UAS fueron de 61 ha . dia^{-1}, o un 129% más eficientes que las técnicas no UAS, y requirieron en promedio de un miembro más del staff para pilotar el UAS. Este incremento permitió obtener la eficiencia no lograda con anterioridad en términos de ha quemadas por año versus días de quema por año cuando el UAS fue usado. Aunque los efectos del fuego fueron menos severos en la mayoría de las mediciones durante las quemas mediante UAS, los resultados de estas quemas alcanzaron las metas requeridas en cuanto a manejo de combustible cuando se compararon con las quemas tradicionales (no UAS).

Conclusiones Un gran incremento de ha . día^{-1}, que fuera previamente inalcanzable, fue lograda ahora con el uso del UAS, una herramienta para cumplir de manera más segura y efectiva las operaciones de quemas prescriptas en un período limitado de días disponibles para poder efectuarlas. Si se manejan con responsabilidad, la ignición realizada desde los UAS está preparada para tener un impacto positivo en una aplicación segura y efectiva de quemas prescriptas, resultando en metas más alcanzables de conservación y manejo de combustibles.

Introduction

In this study, we examine and analyze our multi-year, programmatic use of UAS aerial ignition during prescribed fire operations and follow with a discussion on how it has impacted our application of fire. We relate this discussion to the larger issues encountered by fire managers and aim to contribute to the argument that UAS aerial ignition can serve as a technological tool for managing the uncertainty and risk inherent in all fire operations (Borchers 2005). To date, UAS technologies have been used for wildfire and prescribed fire support in numerous ways. Examples include fire severity estimation and post-burn evaluation (Carvajal-Ramírez et al. 2019; Hillman et al. 2021; Fernández-Guisuraga et al. 2022), fire behavior analysis such as rate-of-spread (Moran et al. 2019), and even conceptual uses for suppression (Aydin et al. 2019). In 2017, the development of mission planning and aerial ignition using UAS technologies began to see significant progress (Beachly et al. 2017a, 2018). This included an example of successful deployment of UAS aerial ignition support on a prescribed fire (Beachly et al. 2017b). These developments highlight the potential of UAS innovations to displace manned aerial ignition, keep fire personnel safer, and reduce the operational costs of fire (Beachly et al. 2017b).

The use of prescribed fire has and continues to be a critical management tool for reducing wildfire hazards, while also restoring and maintaining fire-adapted ecosystems (McKelvey et al. 1996; Stephens et al. 2009; Waldrop and Goodrick 2012). A history of human-influenced fire suppression, dating back to early nineteenth century, has contributed to increases in woody vegetation in previously herbaceous fuel-type ecosystems (Parsons and DeBenedetti 1979; Baker 1992; Backer et al. 2004). Despite the well-documented benefits of prescribed fire, its application is becoming increasingly more difficult because of factors such as climate change (Hennessy et al. 2005; Bowman et al. 2013; Hurteau et al. 2014; Mitchell et al. 2014; Kupfer et al. 2020), increased wildland-urban interface (WUI) (Cohen 2008; Mell et al. 2010), and public perception of prescribed fire (Kreuter et al. 2008, 2019). We provide background on some of these challenges so we can share how UAS aerial ignition helped to mitigate them in our case study.

Meaningful and safe application of prescribed fire is heavily dependent on specific weather and fuel conditions (Schroeder and Buck 1970; Platt et al. 2015; Yurkonis et al. 2019). Appropriate timing is further complicated by factors such as regulating agencies, nearby hazards and communities, resource availability, and smoke management (Collins et al. 2010; Melvin and McIntyre 2018; Miller et al. 2019; Schultz et al. 2019). Increasing global temperatures from anthropogenic activities are narrowing these windows and making them less frequently available, thereby exacerbating these challenges (Kupfer et al. 2020). It is therefore critical that weather windows are taken advantage of as often as possible, and to their fullest extent.

Recent evidence suggests that less traditional seasons for prescribed burning are underutilized and could serve as opportunities to counteract the gradual loss of suitable burn days (Baijnath-Rodino et al. 2022). Particularly the spring months and, to a lesser extent, the winter months might provide windows to expand on currently prescribed fire scheduling. Despite these opportunities, they are counteracted by the fact that most fire personnel are hired and available during a lengthening summer wildfire season (Striplin et al. 2020). Furthermore, this new evidence coincides with prominent United States Forest Service staff recently alerting legislators to a shortage of wildland firefighters to support an already demanding wildfire season (Castronuovo 2021). These issues highlight the need for creative solutions to staffing challenges confronted in current fire operations, with UAS technologies and their efficiencies providing a potential means for alleviating these problems.

Other issues fire managers are encountering regularly include WUI and public perception of fire. These challenges are increasingly ubiquitous abroad and frequently present within our geographic range of burning. Texas in particular has experienced large population growth (United States Census Bureau 2020), urbanization, and land-use changes, all of which have contributed to prescribed fire becoming an increasingly difficult management tool to use. The WUI problem, where urban sprawl encroaches near or adjacent to natural areas, is increasingly present as Texas's major metropolitan areas and surrounding counties experience significant growth (Radeloff et al. 2005; Schuett et al. 2007; Monroe et al. 2012). Proximate to these areas, both private burn vendors and government agencies regularly manage prescribed fire operations (Wall et al. 2019; Texas Parks and Wildlife Division n.d.-an.d.-b). This requires an ongoing adaptation to the developing WUI problem, both in Texas and elsewhere.

With 93% of land ownership in Texas being private, WUI and wildfire hazard reduction challenges extend past applying prescribed fire on public lands (Texas Parks and Wildlife Division n.d.-a). This necessitates relationship building with private landowners and consideration of their perception of prescribed fire's use (Rideout 2003; Kreuter et al. 2008, 2019). A common theme amongst landowner concerns is the legal liability of prescribed fire (Toledo et al. 2014). For example, escaped fires are amongst the largest legal concern for private landowners (Weir et al. 2019). Ways to assuage these fears become challenging in light of recent incidents, including two escaped prescribed fires in New Mexico, whose convergence led to the largest wildfire in the state's history (Heller and Sobczky 2022). Recent fires in Texas and Florida serve as more examples of how prescribed fire incidents can lead to distrust from communities towards land managers (Clark 2021; DeGuzman et al. 2022). These incidents and their ramifications intensify the need for efforts that mitigate legal concerns and risks surrounding prescribed fire. We use this study as an opportunity to introduce some examples of how UAS aerial ignition has assisted our operations regarding these interrelated issues, with some discussion of specific examples.

In 2018, Drone Amplified of Lincoln, NE, released the first example of a commercially available UAS aerial ignition platform named "IGNIS" to the open market. We incorporated the IGNIS platform into our existing burn program of 20 years and used it extensively between 2019 and 2021. This study uses a data-driven approach to assess how UAS aerial ignition has impacted unit size and fire effects, and uses those results to support a larger discussion of the technology's role and impact on our fire program. We tested the hypothesis that burn unit size and fire effects were equal for populations of non-UAS burning before (2012–2018) and after (2019–2021) the incorporation of the UAS, and UAS burning from 2019 to 2021. Using our results, we discuss how those impacts relate to the issues prescribed burn practitioners are facing, with a focus on those benefits from a prescribed fire manager's perspective.

Methods

Study area

Our geographic range of prescribed burning includes numerous regions of both Texas and Louisiana. Between 2012 and 2021, primary regions of burning include mixed loblolly pine (*Pinus taeda*) and shortleaf pine (*Pinus echinata*) forest in Walker, San Jacinto, Trinity, and Montgomery counties of East Texas; mixed loblolly pine and longleaf pine (*Pinus palustris*) forest in Newton and Jasper counties of deep East Texas; and forest ranging from loblolly pine plantation to mature longleaf pine forest in Beauregard, Vernon, and Bienville parishes in Central and West Louisiana. Additionally, Gulf Coast Prairie in both Harris and Waller County, TX, and numerous counties across the Edwards Plateau, Cross Timbers, Blackland Prairies, and East Central Texas Plains ecoregions of Texas are also included in the areas burned during this time frame (Fig. 1).

Fig. 1 Various aerial perspectives during UAS aerial ignition. **a** Looking straight down, with the IGNIS in view, at a longleaf pine forest burn in Vernon Parish, LA. **b** A recently ignited area at Cook's Branch Conservancy in Montgomery County, TX, with the two front M600 prop arms in view. **c** A recently ignited area along the Colorado River in Burnett County, TX. **d** An example of ignition drop points beginning to radiate outward during a Coastal Prairie Burn in Waller County, TX

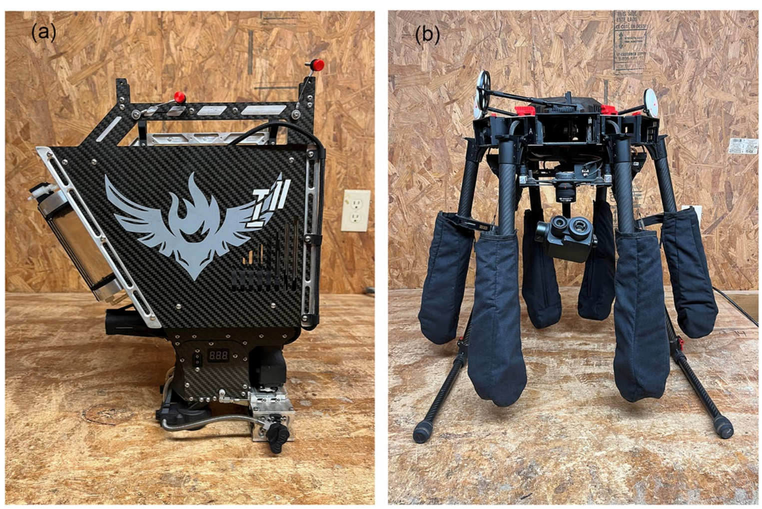

Fig. 2 **a** A side view of the IGNIS unit. The upper hopper portion makes up most of the unit, and the milled aluminum dropper can be seen on the lower, right of the unit. **b** The DJI Matrice 600 Pro UAS, with prop arms folded, propeller socks installed, and GPS receivers folded down

We used post-burn assessment results collected on Cook's Branch Conservancy (CBC) in Montgomery County, TX, when assessing UAS vs non-UAS burning fire effects. CBC represents one of our most comprehensively managed conservation areas, with a long history of prescribed fire starting in 2000. Forest type is predominantly loblolly pine and shortleaf pine, with varying levels of intermixed hardwood like southern red oak (*Quercus falcata*), sand post oak (*Quercus margarettiae*), water oak (*Quercus nigra*), black tupelo (*Nyssa sylvatica*), and winged elm (*Ulmus ulata*) being some common species.

UAS aerial ignition

Equipment used

The UAS aerial ignition unit is comprised of two primary pieces of hardware, the UAS vehicle and IGNIS platform (Drone Amplified; Lincoln, NE, USA). The first is a DJI Matrice 600 Pro (M600) hexacopter UAS (DJI; Shenzhen, Guangdong, China), weighing 10 kg without payload and capable of 40 min of flight time, or 18 min when carrying a maximum payload capacity of 5.5 kg (Fig. 2). The second, the IGNIS platform, weighs 2 kg unloaded or 4 kg with a full hopper of approximately 450 ignition spheres and mounts to the payload rails beneath the lower hood of the M600. The IGNIS is made up of two primary components: the upper hopper portion that contains the ignition spheres, and the lower dropper portion where they are injected before being released. A maximum drop rate of 120 spheres per minute is available to an operator and can be adjusted so that spheres are consistently dispensed at a designated spacing, regardless of whether the M600's horizontal speed is changing.

Necessary accessories for the flight included six M600 TB48S intelligent batteries, an IGNIS battery, A3 Pro flight controller, an Android-based tablet or phone with the IGNIS app downloaded, USB-C cable, and a launch pad. Extra batteries and a generator were also included with day-of burn equipment to extend operating time. During the early stages of operation, four sets of M600 batteries were available, but proved to be an insufficient number of batteries for the average burn day. Although batteries could be charged in the field, charging times of 30–45 min were too time-consuming to enable continuous flying. This was further exacerbated on very hot days because overheated M600 batteries from recent use would require considerable time to cool before they could be charged again. To address this, two more sets of M600 batteries were purchased, with six total sets or approximately three hours of flight time almost always accommodating day-of battery needs. There was never an occasion where more than two IGNIS batteries were necessary for 1 day of burning. Pyro-Shot Dragon Egg ignition spheres (SEI Industries; Delta, British Columbia, Canada) and ethylene glycol, or full-strength antifreeze, were also necessary for igniting.

UAS burn procedural changes: pre-burn and day-of

The M600 with a fully loaded IGNIS unit falls beneath the 25-kg threshold, placing it within the realm of Federal Aviation Administration (FAA) Part 107 Rules and Regulations (Federal Aviation Administration 2016). Pilots were certified and complied with FAA Part 107 guidelines, and UAS vehicles were registered with the FAA at their "FAADroneZone" website. A current application for FAA Part 137 Certification for carrying hazardous materials is ongoing with the Fargo, North Dakota's Flight Standards District Office (FSDO).

Consideration of controlled airspace was always made prior to incorporating the UAS into any burn planning. For all 58 UAS burns conducted between 2019 and 2022, none of them encroached upon controlled airspace or required air traffic control (ATC) approval for flying, and there were no examples where denied ATC approval prevented a UAS burn. Burn units were typically in remote areas, whereas controlled airspace is often found adjacent to or within highly developed areas. However, on two occasions, contact was made with a smaller municipal airport in Harris County, TX, because of the airport's proximity to burn units. During the same period, 62 non-UAS burns were also conducted, with the unavailability of a Pilot-in-Command (PIC) being the most frequent reason for excluding the UAS. For nine of those 62 burns, the UAS was being used on a different burn, while a non-UAS burn was being conducted on the same day. In June of 2021, a second UAS aerial ignition system was acquired and used on a prescribed burn for the first time on July 21, 2021. However, there was never an occasion where two trained pilots were using both UAS systems on separate burns simultaneously. On seldom occasions, the UAS was not used because the unit size was too small and deploying it represented an unnecessary logistical challenge. Examples include two burns in Bexar County that were within the city limits of San Antonio, TX. Unit sizes were 3.72 ha during a burn in 2020 and 6.88 ha in 2021. Fuel-type was tallgrass prairie, so the UAS was of little utility in this scenario. However, the smallest UAS burn from 2019 to 2021 was 11.6 ha in Newton County, TX. This unit, and other examples of relatively small units, were ignited with the UAS if the fuel model was dense vegetation and difficult to traverse on foot.

Infrequently, a burn unit's fuel composition alone was a reason for ruling out the UAS for interior igniting. However, careful consideration of whether a burn unit was favorable for using UAS aerial ignition was made prior to establishing plans. Suitable fuel continuity and fuel types, such as 1-h fuels like grass or pine straw, were characteristics of a potentially more successful UAS burn because of the spot ignition patterns applied by the IGNIS. Conversely, burn units that contained minimal herbaceous fuels, significant amounts of woody understory fuels, and/or scattered and broken fuels were not always as receptive to the spot ignition patterns of the UAS but still attempted where the UAS was available.

During a burn, a UAS Pilot-in-Command (PIC) and Visual Observer (VO) would work together on preflight procedures, charging batteries, piloting, igniting, and maintaining visual line-of-sight of the UAS during flight operations. Helpful IGNIS app features during burning included a protective geofence to delineate igniting boundaries, and the ability to change mission planning parameters such as transect spacing, transect orientation, ignition sphere spacing, and altitude (Beachly et al. 2017a, 2018) (Fig. 3). Mission planning features were adjusted in real-time and in response to changing fire behavior. Personnel normally used for interior ignition would be reallocated to lighting flanking fires and monitoring firelines during UAS burns.

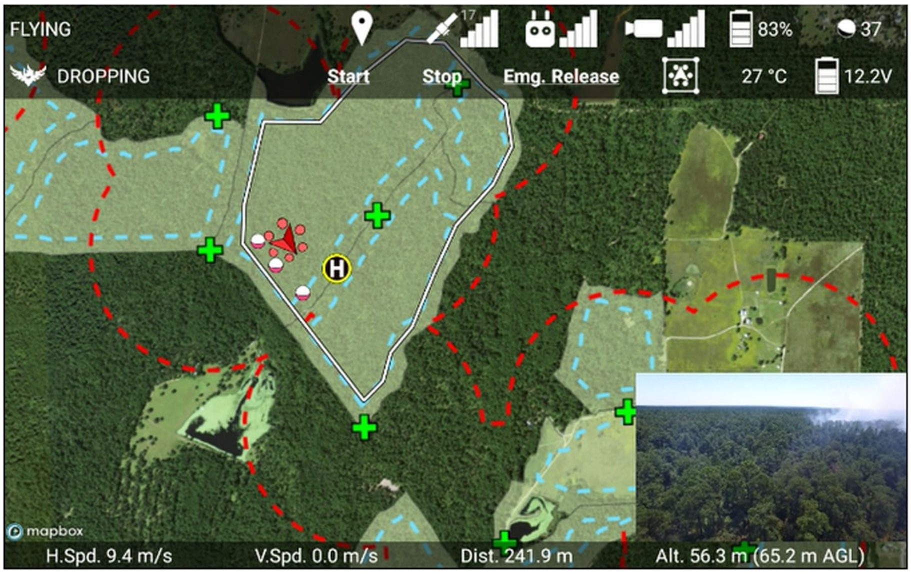

Fig. 3 A screenshot of the IGNIS app during an interior ignition flight mission. The geofence is the white polyline surrounding the arrow figure, or the M600's current location. The map symbols, such as crosses, polygons, and buffers, are part of the map overlay that was created and added beforehand. Telemetry data is found at the bottom of the screen, and the video feed is on the bottom, right. Ignition sphere drop points are also symbolized as red and white circles

Prescribed burn data management

Burn database

We used data from the Raven Environmental Services burn database, which includes a record of each burn, along with accompanying metadata. Suitable data for analysis was used from years 2012 to 2021, with years 2019 to 2021 including 58 UAS burns. All records included the date burned, client information, state, county, burn compartment and tract, total tract hectares, the percentage and section of tract burned, and hectares burned. Once UAS aerial ignition was introduced in 2019, the burn database began to account for primary ignition method, either aerial or ground.

Post-burn assessment

From 2013 to the present, post-burn assessments on CBC were completed using protocols developed by the US Department of Interior and outlined in the Fire Monitoring Handbook (FMH) (USDI National Park Service 2003). CBC has 37 forest plots randomly distributed throughout its boundaries, with plots occurring in a variety of settings, such as heavily forested areas, seed-tree forests, sparsely forested savanna, one native grassland plot, and management units that range from no-burning to annual burning. A "Forest Plot," as defined by the Fire Monitoring Handbook, is a 50m × 20m area that consists of two transects that traverse the plot's long sides and a third parallel transect running through the center of the plot area. These three transects were used to collect substrate and vegetation burn severity data, with data recorded using the FMH Burn Severity Data Sheet (FMH-21) (USDI National Park Service 2003). Severity Ratings are outlined in the Coding Matrix provided in the National Park Service's Fire Monitoring Handbook (USDI National Park Service 2003). Scaled from one being the most severe to five being unburned, values were averaged separately for substrate and vegetation, with the final value representing the overall burn severity for each category. An assessment of the percentage of the plot area unburned was also made by tallying the number of points that received a severity rating of five and dividing by 30 total points.

Additionally, scorch height, percent crown scorched, and char height averages were all calculated for overstory trees within a plot area and recorded on the Tree Post-burn Assessment Data Sheet (FMH-20) (USDI National Park Service 2003). Scorch height was defined as the highest point where foliar death was measured for each overstory tree, with foliar death being conspicuous discolored canopy vegetation after burning. Average char height was measured to the maximum point of black charring on the bark of the tree, whether continuous in extent from the ground or not. Percent crown scorch was taken as an estimate of overall scorched foliage for each overstory tree's canopy. When sampling the one non-forested plot in years 2015 and 2019, the Tree Postburn Assessment Data Sheet was not used, and associated data not collected. Additionally, where percent crown scorch was zero, the FMH protocols stipulate that crown scorch height not be collected. This is in contrast to the absence of tree char, which results in a value of zero instead of a null value. These details are noted because they resulted in slightly different sample sizes for each post-burn assessment metric when analyzing data. Post-burn assessment data was collected approximately a week after a burn was conducted on a management unit containing a FMH plot. This allowed enough time for crown scorch to become conspicuous, while not allowing enough time to elapse so that substrate and vegetation conditions were not assessed immediately post-burn.

Statistical analysis

Analysis of UAS burning vs non-UAS burning

Data was organized into three independent groups of non-UAS burning from 2012 to 2018, non-UAS burning from 2019 to 2021, and UAS burning from 2019 to 2021. These groups served as predictor variables for seven response variables, including ha day^{-1} burned, and six post-burn assessment metrics: substrate burn severity, vegetation burn severity, percent unburned, percent crown scorch, scorch height (m), and char height (m). Post-burn assessment data was used from years 2013 to 2021, and as previously mentioned, sample sizes were different amongst some post-burn assessment metrics because of one non-forested plot on CBC and details pertaining to FMH data collection protocols. Additionally, response variable ha day^{-1} burned leveraged a relatively large sample size because data was not limited to CBC. Data was also available over a larger timescale, so we used this opportunity to analyze a 10-year time period (2012–2021).

Burning from all three groups was assessed on a per-day basis, and the assumption of independence of groups was concluded for a variety of reasons. When comparing the two non-UAS groups, they occurred during different time periods and were explicitly independent of one another. For non-UAS vs UAS burning from 2019 to 2021, UAS burns were conducted opportunistically and rarely in response to fuel type, unit size, weather parameters, or crew size availability. Frequently, non-UAS burns occurred from 2019 to 2021 because of the lack of a PIC to fly the UAS, and not because of any specific criteria. There were many instances where relatively large unit sizes were burned in a day with the UAS between 2019 and 2021. Again, this was opportunistic in nature, with multiple units almost always being prepared in anticipation of burning, whether with or without the UAS. In the event the UAS was available, a large unit or units might have been burned if circumstances permitted doing so.

Our analysis was designed around testing the hypothesis that ha day^{-1} burned and six post-burn assessment metrics for populations of each group were equal (H_o). Before analyzing study groups, the Shapiro-Wilk test was first used to determine whether they were normally distributed, and then the non-parametric Levene's test was used to determine if they met the assumption of homogeneity of variance (Nordstokke and Zumboq 2010). For all groups, one or both assumptions were violated so we determined the non-parametric Kruskal-Wallis test was most appropriate for our analysis (McKight and Najab 2010). We followed with a Dunn's test to make pairwise comparisons of groups. All our statistical tests were conducted with significance at the $\alpha = 0.05$ level and in RStudio, version 2022.07.2+576.

Programmatic impact of the UAS

To assess the impact of the UAS on our burn program from a larger and multi-year perspective, we also analyzed how much we were accomplishing on the average burn day each year from 2012 to 2021. The sum of ha year^{-1} burned and days year^{-1} burned were calculated (n = 366 total burns), and their correlation was analyzed in SPSS (IBM; New York, NY, USA). We examined all non-UAS burning from 2012 to 2021 and both UAS and non-UAS burning from 2012 to 2021.

Results

Analysis of UAS burning vs non-UAS burning

Post-burn assessment metrics yielded a variety of outcomes when comparing non-UAS burning before (2013–2018) and after (2019–2021) the incorporation of the UAS, and UAS burning (2019–2021) (Fig. 4). The Kruskal-Wallis test showed a significant difference of means for four of six metrics, including substrate severity ($\chi^2 = 9.34$, df = 2, $P = 0.009$), vegetation severity ($\chi^2 = 11.18$, df = 2, $P = 0.004$), percent crown scorch ($\chi^2 = 6.29$, df = 2, $P = 0.043$), and char height ($\chi^2 = 6.69$, df = 2, $P = 0.035$). After following with a pairwise comparison of groups, we identified that significant differences were usually between UAS burning and non-UAS burning after the incorporation of the UAS. For example, substrate severity ($P = 0.007$), vegetation severity ($P = 0.003$), and char height ($P = 0.030$) were all significantly different, or less severe, fire effects when using UAS aerial ignition. It is noted that lower values for substrate and vegetation burn severities represent a more severely burned outcome. Conversely, burning was not significantly different between UAS burning and non-UAS burning before the incorporation of the UAS for any of those three metrics ($P > 0.05$). On two occasions, we identified a significant difference between non-UAS burning before and after the incorporation of the UAS. This included vegetation severity (P = 0.039) and percent

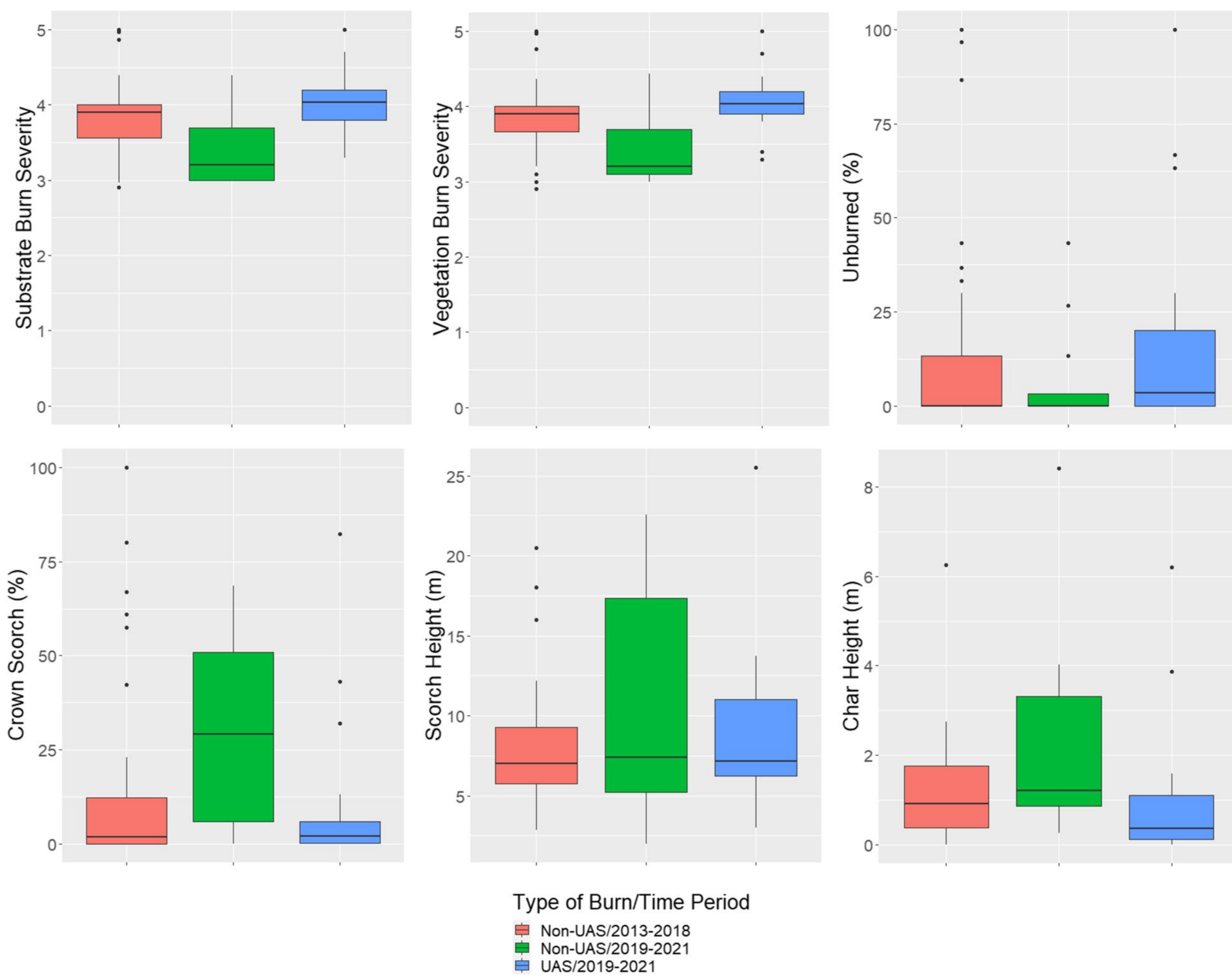

Fig. 4 Box plots of six post-burn assessment metrics for the three analyzed groups: (1) non-UAS burning from 2013 to 2018, (2) non-UAS burning from 2019 to 2021, and (3) UAS burning from 2019 to 2021. Post-burn assessment data was collected on Cook's Branch Conservancy in Montgomery County, TX, starting in 2013. It is important to note that more severe fire effects are represented by lower values for substrate and vegetation burn severities. Burning was analyzed on a per day basis. Sample sizes, median values, mean values, and significance test results between groups can be found in Table 1

crown scorch (P = 0.043), with both instances showing less severe fire effects for non-UAS burning before the incorporation of the UAS.

For the remaining Kruskal-Wallis tests, we failed to reject the null hypothesis for percent unburned (χ^2 = 2.37, df = 2, P = 0.31) and scorch height (χ^2 = 0.35, df = 2, P < 0.84). Average percent unburned did not exceed 19% for any of the three groups, and median values of zero or close to zero (Table 1). Average percent unburned for non-UAS burning after the incorporation of the UAS was relatively low, despite not being significantly different from the other two groups. Scorch height displayed relatively similar outcomes for all three groups (Table 1).

Means for ha day^{-1} burned amongst burning groups were significantly different upon initial testing (χ^2 = 45.12, df = 2, P < 0.001). After following with pairwise comparisons, we found that ha day^{-1} burned for non-UAS burns before and after the incorporation of the UAS were significantly different from UAS burning (P = <0.001), but not from one another (P = 0.69) (Table 1). On average, the UAS burned 108 ha day^{-1} from 2019 to 2021, or 61 ha day^{-1} more than non-UAS burns during the same years, and 58 ha day^{-1} more than non-UAS burning from 2012 to 2018 (Fig. 5). This translates to a 129% and 122% increase, respectively.

Programmatic impact of the UAS

Total area burned using the UAS between 2019 and 2021 was 6273 ha on 58 burns. Both UAS and non-UAS burning occurred from 2019 to 2021, with the UAS accounting

Table 1 Results for pairwise comparison of groups using Dunn's test. Post-burn assessment response variables are divided into each of their analyzed groups: (1) non-UAS burning before the incorporation of the UAS, (2) non-UAS burning after the incorporation of the UAS, and (3) UAS burning. The *P*-value column is organized to facilitate all three pairwise comparison of groups, and an asterisk denotes statistically significant differences between groups ($\alpha = 0.05$). Each row-column cross for a response variable (row) and *P*-value (column) group represents specific pairwise comparison results for those respective groups

Response variable	Type of burn/time period	*n*	Mean (± SE)	Median	*P*-value	
					Non-UAS/before	Non-UAS/after
Ha day^{-1} burned	Non-UAS/before	245	50 (2.0)	44		
	Non-UAS/after	67	47 (4.5)	41	0.69	
	UAS	58	108 (10)	92	0.001>*	0.001>*
Substrate burn severity	Non-UAS/before	57	3.8 (0.07)	3.9		
	Non-UAS/after	13	3.4 (0.14)	3.2	0.096	
	UAS	17	4.0 (0.11)	4.0	0.27	0.007*
Vegetation burn severity	Non-UAS/before	57	3.9 (0.06)	3.9		
	Non-UAS/after	13	3.4 (0.14)	3.2	0.039*	
	UAS	17	4.0 (0.10)	4.0	0.28	0.003*
Unburned (%)	Non-UAS/before	57	14 (3.7)	0		
	Non-UAS/after	13	6.7 (3.8)	0	0.91	
	UAS	17	19 (7.2)	3.3	1	0.37
Crown scorch (%)	Non-UAS/before	56	12 (2.9)	1.8		
	Non-UAS/after	12	31 (7.6)	29	0.043*	
	UAS	17	11 (5.3)	2.0	1	0.11
Scorch height (m)	Non-UAS/before	39	8.0 (0.62)	7.0		
	Non-UAS/after	11	11 (2.2)	7.4	1	
	UAS	13	8.9 (1.7)	7.1	1	1
Char height (m)	Non-UAS/before	56	1.1 (0.14)	0.91		
	Non-UAS/after	12	2.3 (0.67)	1.2	0.16	
	UAS	17	1.0 (0.40)	0.36	0.58	0.030*

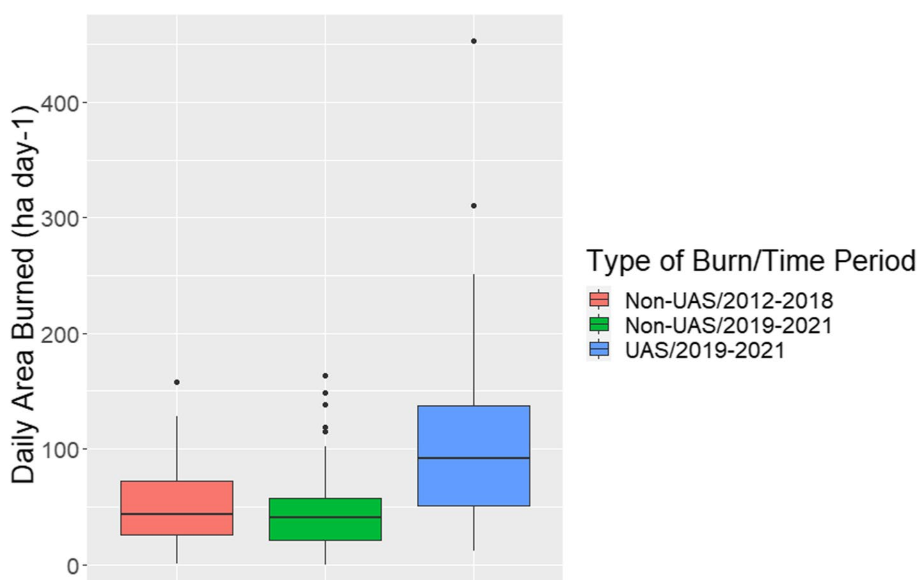

Fig. 5 Box plots of ha day^{-1} burned for the three analyzed groups: (1) non-UAS burning from 2012 to 2018, (2) non-UAS burning from 2019 to 2021, and (3) UAS burning from 2019 to 2021. Sample size was larger for these groups because data was not limited by variables such as weather or post-burn assessment metrics. The data used includes prescribed fires that were conducted across multiple ecoregions of Texas and Louisiana and was analyzed on a per day basis. Sample sizes, median values, mean values, and significance test results between groups can be found in Table 1

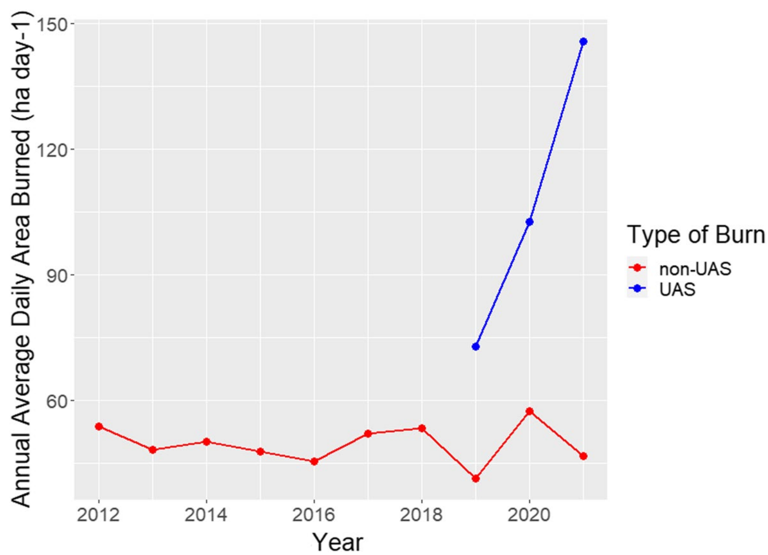

Fig. 6 The trend in ha day^{-1} burned from 2012 to 2021 by Raven Environmental Services of Huntsville, TX. Burn data shown is comprehensive and includes prescribed burns from multiple ecoregions, counties, and parishes of Texas and Louisiana ($n = 341$). This also includes all UAS burning from 2019 to 2021 ($n = 58$)

for 65% of the total area burned in 2019, 53% in 2020, and 79% in 2021. For all non-UAS burning from 2012 to 2021, there remained a strong correlation between the number of hectares burned and number of days burned each year ($r = 0.96$). This correlation was relatively low ($r = 0.57$) when considering both UAS and non-UAS burning from the same time period. The amount of ha day^{-1} burned began an upward trend following the incorporation of the UAS in 2019, with the UAS burning 78% more ha day^{-1} on average that year (Fig. 6). On November 19, 2019, the IGNIS 1.0 was upgraded to the IGNIS 2.0, resulting in improved hopper capacity and performance. Following that, years 2020 and 2021 continue this upward pattern, with the UAS burning 81% and 211% more ha day^{-1} than non-UAS burns, respectively. Using instances where crew size was documented, burning from 2019 to 2021 averaged 4.9 people on UAS burns ($n = 47$) and 3.9 people on non-UAS burns ($n = 55$). This increase in one person was accounted for by the PIC responsible for operating the UAS that day.

Total ignition spheres used in that time was 49,964, and total flight time was 66 h. Major cost of operating the UAS included the system cost and ignition spheres. Our first system included the cost of the M600, M600 flight controller, three sets of M600 batteries, Zenmuse X3 camera, IGNIS unit, two IGNIS batteries, and tablet, totaling $40,760. Our second system was outfitted with a Zenmuse XT2 dual-vision camera and amounted to a larger system cost of $50,260. However, DJI discontinued the manufacture of the DJI Matrice 600 Pro at the end of 2021, and Drone Amplified has since adapted the IGNIS to the newer Alta X UAS (Freefly Systems; Woodinville, WA, USA). An updated system cost of $74,645 includes the Alta X, IGNIS, camera, carrying cases, extra batteries, and spare parts (e.g., Ross Carrie, personal communication). For ignition spheres, an average UAS burn of 108 ha included a cost of $310 based on an average of 7.8 spheres ha^{-1}, or $2.66 ha^{-1} for all UAS burning. This represented an additional cost to our operations and has not been offset by other aspects of a UAS burn. The flight time required to ignite 100 ha provides reference to the time efficiency of UAS aerial ignition, at an average of 63 min.

During 3 years of operations, we had two incidents where the UAS was damaged during a prescribed fire. In both instances, the UAS tipped over during takeoff, and propellers, propeller housings, or both were damaged upon impacting the ground. The first incident was operator error, and the second was because a propeller with incorrect directionality was installed on a propeller arm. Following this incident, an entire propeller arm was replaced at a cost of $325. The largest M600 maintenance cost was the installation of motor mount reinforcements for $688, followed by a new replacement tablet for the first system for $650, and a set of propellers for the first system for $360. Except for the motor mount reinforcements, all other maintenance was performed by in-house staff. One IGNIS 1.0 unit used during the first approximate year of operation was retired primarily due to its being upgraded and replaced by two IGNIS 2.0 units. The older IGNIS 2.0 unit has undergone 41 h of operation since its incorporation on November 19, 2021, and experienced one major mechanical failure since then. A bearing failure on the hopper corkscrew, which feeds spheres into the dropper portion of the IGNIS, failed and prevented further operation for the day. This occurred on January 28, 2021, after 28 h of total operation. However, a bearing was located in the local area, the unit was fixed overnight, and burning with the UAS was able to commence the following day. Due to anticipated availability issues following the discontinuation of the M600 by DJI, batteries were assessed for health and remaining lifespan on September 27, 2022. The three oldest sets that were purchased in November of 2018 had an average number of discharges of 58, 56, and 59, and an average remaining lifespan of 86%, 86.5%, and 85.7%. Of these three sets or 18 total batteries, ten of them had minimal amounts of swelling, none of which impacted their usability or performance.

Discussion

Interpretation of results

The results of our quantitative analysis include some mixed outcomes, but generally demonstrate that UAS aerial ignition burns were more efficient in terms of ha day^{-1} burned and resulted in less severe fire effects. Additionally, several costs, such as the system cost, ignition sphere cost, and the cost involved in training personnel, were required when incorporating the UAS into our burn program. While UAS burning resulted in an increase of 129% in ha day^{-1} burned during 2019–2021, it only required an increase of one extra staff member to pilot the UAS, on average. However, this increase in efficiency coincides with some changes in post-burn fire severity when compared to non-UAS buns. UAS burns were generally less severe in terms of substrate burn severity, vegetation burn severity, and char height, while not significantly different when considering percent unburned, percent crown scorch, and scorch height. In our experience, this reduction in fire effects never resulted in an unfavorable outcome as far as our fuel management goals were concerned. Most notably, percent unburned was not significantly different between UAS and non-UAS burns, indicating that while burn results were less severe using the UAS, they were still effectively treating an area. The dot fire ignition method of the spheres is a potential explanation for this reduction in severity. Someone carrying a headfire strip on foot arguably can generate more aggressive fire behavior, which one might do in response to low-intensity fire conditions. On the other hand, the UAS and its dot fire ignition pattern could not recreate a continuous headfire strip in the same manner. Our approach to intensifying fire behavior with the UAS was to narrow ignition sphere drop spacing and transect spacing, but this had to be balanced alongside the resulting increase in flight time, required battery life, and ignition sphere usage.

When analyzing non-UAS burning before and after the incorporation of the UAS, ha day^{-1} was not significantly different, but many of the post-burn assessment metrics were more severe during non-UAS burning from 2019 to 2021. We speculate this could be the result of a handful of relatively severe non-UAS burns from 2019 to 2021 within our relatively small sample size for post-burn assessment metrics in that group ($n \leq 13$). It is worth noting that both substrate burn severity and vegetation burn severity results fall within median and mean ranges of 3.2 to 4.0 for all three analyzed groups (Table 1). Despite their significant difference, the groups generally fall within a predictable window of the total range of fire effects for these metrics, which are rated from 1 to 5. For example, a 3 is "lightly burned" and a 4 is "scorched," as described by the Fire Monitoring Handbook (USDI National Park Service 2003). Overall, our interpretation is that UAS burns were measurably less severe when compared to handcrew burning, assuming one is analyzing results from the same time frame and fuel model, as we have in our analysis. While less severe, fire effects and fuel management goals are however satisfactory and still resulted in a completely treated burn area.

The lack of correlation between ha burned and days burned each year after the incorporation of the UAS is arguably one of the most noteworthy takeaways from our perspective. It communicates the difficulty of burning more ha day^{-1} under normal circumstances and without the UAS ($r = 0.96$), and the magnitude of UAS aerial ignition's impact following its use ($r = 0.57$). However, this is considered alongside the cost of acquiring the entire UAS system, and properly certifying and training staff. The context and scope of our burn program allowed us to manage these requirements in a fairly expeditious manner. Because our burn program consists of personnel and equipment resources that are smaller than that of government agencies, our training, piloting, UAS maintenance, program development, and compliance requirements were reasonably managed by one primary individual and help from a supportive staff member at times. Our attempts to become FAA Part 137 certified to carry hazardous materials has been one difficult hurdle to overcome, but recent correspondence with the Fargo, North Dakota Flight Standards District Office, has suggested that there might be guidance on our specific usage soon (e.g., Sean Mosher, personal communication). While the increase in ha day^{-1} burned is emphasized in our analysis, it is not the only underlying goal of our adopting UAS aerial ignition. This new technology also helped to mitigate those aforementioned challenges, such as reduced burn windows from climate change, the WUI problem, and public perception of fire. We focus the remaining discussion on our personal experience with the technology, and how three years of using the UAS led us to these conclusions.

Impact of UAS aerial ignition on prescribed fire

Where and how UAS aerial ignition mitigated these challenges were highly circumstantial, and specific to each burn project. For example, treatment areas that were remote and unencumbered by WUI and smoke mitigation issues benefited from the ability to burn much larger areas with the UAS. Additionally, the ability to relocate personnel away from interior ignition responsibilities, and focus them on igniting and patrolling firelines, further enabled larger unit size while still conducting a safe burn. Prior to incorporating the UAS, the largest unit size burned by Raven between 2012 and 2018 was 172 ha, compared to 453 ha after its use. Where large-area burns were possible, this increase in capability enabled burn objectives in less than half as many days, in some cases. Because prescribed fire is heavily dependent on specific weather conditions, this jump in efficiency greatly enabled management goals in the limited number of suitable days available.

Burns of this larger scale were infrequent, though, with smoke management and WUI often constraining unit size. For example, Raven burned 121 ha or more in a day 8.7% of the time, and 202 ha or more in a day 1.5% of the time between 2012 and 2021. During that same period, the average unit size was 68 ha for all burning. The UAS and its impact may not have been a dramatic increase of ha day^{-1} burned on every occasion, but it enabled safer and more effective prescribed fire operations, regardless of unit size. This is especially true because of the previously mentioned ability to reallocate personnel from interior ignition duties to other responsibilities. This not only enables line-holding efforts, but it eliminated the inherent hazards of hand crew interior ignition methods. Those hazards include dehydration, navigation challenges in thick understory vegetation, tripping and falling hazards, and crewmembers entrapping one another while igniting. The UAS could also navigate more precisely, quickly, and with greater awareness than that of hand crews (Beachly et al. 2017b). In the event a fire emergency occurred, namely a spot-over, the UAS ensured that personnel were already well-poised to respond.

These increases in safety helped to mitigate other major prescribed burning challenges. Namely, landowner concern regarding the risk of escaped fires was arguably reduced because of personnel reallocation. Furthermore, burning with the UAS created new approaches to interior ignition timing, resulting in better smoke management. Throughout a burn day, atmospheric conditions leading to optimal smoke transport occur around 3–4pm (Waldrop and Goodrick 2012). Completing the interior ignition phase of a burn within this favorable window was often crucial, particularly where WUI is present. The UAS could perform this task in a window of time previously unobtainable when using hand crew methods, allowing for more targeted timing of interior ignition and a decreased likelihood of negatively impacting surrounding areas with smoke.

These new igniting capabilities could be leveraged and strategized in numerous ways outside of smoke management, too. Ignition timing and techniques could be altered quickly and in response to changing environmental conditions and fire behavior (Beachly et al. 2017a, 2018). This flexibility enabled fuel management goals in several ways. For example, when fire behavior was excessive and threatening to damage forested overstory, a smaller ignition window could be moved to a less impactful time of day. On one occasion, an early and brief afternoon shower temporarily raised relative humidity, a situation that might normally eliminate burning altogether. However, the UAS's efficiency still allowed the burn to commence after some drying, and valuable time and resources were not lost.

For burn programs of a larger scale, such as the US Forest Service or Bureau of Land Management, UAS aerial ignition provides an alternative to manned aircraft operations. The risks involved in these operations have a history of fatal accidents, with one occurring on the Sam Houston National Forest as recently as 2019 (Gabbert 2022). The UAS and IGNIS platform used in this study might not be capable of completely substituting for manned operations but can minimally displace some portion of them. The daily cost to operate the UAS is estimated to be around $14,200 less than manned operations and can help agencies accomplish more burning objectives with the same financial resources (Detweiler 2020). Furthermore, UAS aerial ignition can potentially serve as a force multiplier for agencies like the US Forest Service and US Department of Interior. Our case study demonstrated a large increase in burn efficiency, despite our only adding one additional person to pilot the UAS, on average. Opportunities to leverage the UAS might include traditional prescribed fire seasons, supporting peak wildfire season during summer months, or even enabling prescribed burning during less conventional windows, like the spring or winter seasons, when staff is relatively limited.

Limitations

FAA Part 107 rules that restrict beyond-line-of-sight flying are arguably one of the largest hindrances to conducting UAS aerial ignition operations, currently. This hurdle is particularly challenging in fuel models like the East Texas Pineywoods, where a tall, forested landscape, combined with very little topography in some cases, makes observing the UAS during flight difficult. Our solution to this was to either move numerous times during a burn, or operate from a disjunct and open area that was reasonably proximate to the burn unit. For example, a large prairie located 300–500 m from the burn unit might still be more advantageous than launching in a heavily forested area along the unit's boundary. Additionally, operational range from the PIC was sometimes decreased in forested landscapes. From hilltop views in Brown County, TX, the farthest we operated from was approximately 2.1 km, whereas some heavily forested areas restricted our operating range to 500–600 m.

Both battery life and hopper capacity were interrelated limitations at times. Typically, it was our goal to optimize the use of our battery life by discharging batteries completely, while also expending all our ignition sphere payload. The reality, however, was that fire behavior, fuel type, fuel conditions, and weather did not always allow one to strategize in exactly this manner. Furthermore, a long flight into and out of an igniting area might deplete a considerable amount of battery life. These types of scenarios occurred when unfavorable launch sites were not located conveniently next to a burn unit. In these situations, recharging batteries in the field might be demanding, unless operators had access to a significant amount of M600 battery sets. To some extent, these limitations are circumstantial, however. A well-resourced agency or business could manage these challenges with more batteries and personnel to assist with battery-charging responsibilities.

Because DJI recently discontinued the manufacture of the Matrice 600 Pro, it is conceivable that parts availability and eventually firmware support will be challenges for users that still have not acquired the newer Alta X UAS. There is also the challenge of not only licensing, but also training UAS pilots to use the system. Personnel with a background in both fire and UAS operation will be required to fill these roles. Maybe even more significant is the demand for training curriculum and certification, and how that is structured within agencies that are still learning to adopt UAS aerial ignition into their fire programs. Finally, complying with FAA Rules and Regulations is and continues to be a complex and elusive challenge for users of the system. The agency currently has limited guidance for how to certify commercial users that operate a system for this purpose.

Conclusions

Using our burn program as a case study, our findings support that UAS aerial ignition can promote more achievable fuel management and conservation goals. It does so by enabling larger burns with minimal staffing increases in some appropriate scenarios, while maintaining satisfactory fire effects when compared to non-UAS burning. Furthermore, it arguably promotes an enhanced level of safety for fire personnel and fire operations overall. This is of particular importance to fire managers who are confronted with an increasingly complex WUI environment, limited days of appropriate prescribed fire weather, and a strained public perception of prescribed fire following recent escaped fires. It is conceivable that the UAS can substitute for some manned operations where larger agencies are using those methods, leading to potentially safer operations. Future research efforts might investigate how effectively and to what extent UAS aerial ignition can replace manned operations, and how its use can eliminate the inherent hazards associated with them. Wildland firefighter shortages, combined with increasingly frequent and volatile wildfires, also invite discussion and investigation into how UAS technologies can assist with this problematic trend. The technology remains in its infancy, and so there is still significant room for identifying where and how UAS aerial ignition can be best applied in prescribed fire and wildland fire operations. While it is not a comprehensive solution to the litany of challenges encountered in today's fire environment, it is arguably an important tool that should be leveraged within a larger strategic approach to conducting safe and successful fire operations.

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Authors' contributions
BL designed the study, collected the data pertaining to the UAS, analyzed all data, interpreted the data, and wrote the manuscript. KM collected and organized Raven Environmental Services burn database. EK collected post-burn assessment data. All authors contributed to prescribed fire data used in the study and read and approved the final manuscript.

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