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FIELD NOTE **Open Access**

Case study of UAS ignition of prescribed fire in a mixedwood on the William B. Bankhead National Forest, Alabama

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Abstract

Background For at least four decades, practitioners have recognized advantages of aerial versus ground ignition for maximizing the effectiveness of prescribed fires. For example, larger areas can be ignited in less time, or ignition energy may be variously targeted over an area in accordance with the uneven distribution of fuels. The maturation of wireless communication, geopositioning systems, and unmanned aerial systems (UAS) has enhanced those advantages, and UAS approaches also provide further advantages relative to helicopter ignitions, such as reduced risk to human safety, lower operating costs, and higher operational flexibility. In a long running study at the Bankhead National Forest in northcentral Alabama, prescribed fire has been used for nearly 20 years. Most of the burns have been hand-ignited via drip torches, while some have been aerially ignited via helicopter. In March 2022, for the first time, a UAS was used to ignite prescribed fires across a landscape that included a long-term research stand. This field note relates comparisons of both fire behavior and fuel consumption metrics for the UAS-ignited burn versus previous burns on the same stand, and versus burns of other research stands in the same year.

Results The UAS-ignited prescribed fire experienced burn effects similar to those from ground-ignited prescribed fires on the same stand in previous years, as well as those from ground-ignited prescribed fires on other stands in the same year.

Conclusion This post hoc analysis suggests that UAS ignition approaches may be sufficient for achieving prescribed burn goals, thereby enabling practitioners to realize the advantages offered by that ignition mode.

Keywords Prescribed fire, Unmanned aerial systems, Fuel consumption, Thermocouple probes, Fire management, Aerial ignition

Resumen

Antecedentes Por al menos cuatro décadas, los practicantes de quemas prescriptas han reconocido las ventajas de la ignición aérea versus la ignición terrestre para maximizar la efectividad de las quemas prescriptas. Por ejemplo, grandes áreas pueden ser encendidas en menos tiempo, o la energía para lograr la ignición pude ser orientada dentro de áreas determinadas de acuerdo con la disposición irregular de los combustibles. La evolución de la comunicación, de los sistemas de geolocalización, y muchos sistemas de vehículos aéreos no tripulados (VANT o UAS en Idioma Inglés), han enfatizado estas ventajas, y las aproximaciones usando VANT pueden proveer además de mayores ventajas en relación con igniciones mediante helicópteros, tales como una reducción en el riesgo humano, menores costos

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operativos, y una mayor flexibilidad operacional. En un estudio a largo plazo en el Bosque Nacional de Bankhead en el Norte-Centro de Alabama, las quemas prescriptas han sido usadas por alrededor de veinte años. La mayoría de estas quemas fueron iniciadas usando antorchas de goteo, mientras que algunas fueron iniciadas mediante el uso de helicópteros. En marzo de 2022, por primera vez, un VANT fue usado para iniciar una quema prescripta a través de un paisaje que incluía un rodal establecido mucho tiempo atrás. Esta nota de campo relata las comparaciones tanto del comportamiento del fuego, como las mediciones en el consumo del combustible para la quema iniciada mediante el VANT versus quemas previas en el mismo rodal y también versus quemas realizadas en otros rodales en el mismo año.

Resultados Las quemas iniciadas por VANT experimentaron efectos similares a aquellas realizadas en el mismo rodal en años anteriores, de igual manera que aquellas realizadas mediante antorchas de goteo en otros rodales, pero en el mismo año.

Conclusiones Este análisis *a posteriori* sugiere que las igniciones realizadas mediante VANT fueron suficientes como para alcanzar los objetivos de las quemas prescriptas, y por lo tanto permitieron a los practicantes de las quemas darse cuenta de las ventajas que ofrece este modo de ignición.

Introduction

Prescribed fire offers many potential benefits to ecosystems, including the promotion of fire-tolerant species regeneration, increased wildlife habitat diversity, and hazardous fuels reduction (Calkin et al. 2015; Keyser et al. 2018). Many ecosystems were adapted to periodic fire before the artificial suppression of fire in the 20th century. This artificial fire suppression has allowed encroachment of woody vegetation and non-native species, and it has made reproduction of certain desirable species more difficult. Prescribed fire is widely used to achieve various forest management objectives (Brose 2014; Arthur et al. 2015). For example, restoration of open woodlands is often aided by prescribed fire, which is used to create desired structure and to stimulate understory plants (Arthur et al. 2015; Keyser et al. 2018).

The U.S. Department of Agriculture, Forest Service, uses UAS for natural resource management on federal lands. The Forest Service has taken significant steps to establish a formal UAS program to ensure appropriate, safe, and cost-effective flight missions. These steps include appointing a UAS program manager, establishing a UAS executive steering committee, and conducting test missions and evaluations.

UAS present several potential advantages for prescribed fire operations. Compared to helicopter ignitions, UAS ignitions are much less expensive (Beachly 2017). Ground crew operations can be more flexible, with options for reassigning crews from interior ignition duties to exterior ignitions or fireline monitoring (Lawrence et al. 2023). Difficult or inaccessible terrain can be reached and ignited (Twidwell et al. 2016). The speed of ignition is enhanced, enabling more strategic ignition patterns taking advantage of existing winds and slopes, as well as the opportunity to proceed with a “go-no go” decision in narrower burn prescription windows (Rothermel 1985). Safety is increased by removing ground fire crews from fire interiors and by avoiding aerial crews in riskier helicopter operations (Beachly 2017; Twidwell et al. 2016).

Despite these benefits, UAS ignitions must reliably produce fires that achieve burn objectives. Aerial ignitions in prescribed fires are understudied (Hiers et al. 2020), and the nascent status of UAS technology applied to prescribed fire ignitions implies that there has been little time for studies of UAS ignitions to appear in the literature. One recent example of research along these lines is Lawrence et al. (2023), which relates the experience of a private contractor incorporating UAS into its prescribed fire operations. The authors found statistically significant reductions in char height, substrate burn severity and vegetation burn severity for UAS-ignited burns compared to non-UAS-ignited burns during the same time period, but not compared to non-UAS-ignited burns during earlier time periods. The UAS-ignited burns also resulted in greater area burned per burn day compared to non-UAS-ignited burns during both the same and earlier time periods. The authors concluded that although the UAS-ignited burns had somewhat less severe fire effects, the company’s fuel management objectives for the prescribed burns were always met.

This field note relates one experience of a UAS-ignited prescribed burn and places this experience in the context of comparable prescribed burns, either on the same forest stand in earlier years or on different stands in the same year. At the William B. Bankhead National Forest (BNF) in north central Alabama, USA, an ongoing study since 2006 has been examining the effects of prescribed fires with return intervals of either 3 years or 9 years on vegetation composition and structure and on fuel dynamics. In this project, study stands are embedded within landscape-scale burns. The study contains 4 replications (blocks) initiated from 2006 to 2008, with nine treatments in each block covering a range of thinning and burning. Spring 2023 marked the completion of the 6th burn cycle for all four blocks. The research study objectives are to discern how varying levels of thinning and burn frequency affect management goals of shifting the forest species mix to more oak dominance (Schweitzer et al. 2016). Multiple publications detail a variety of results from the past 17 years, including woody reproduction changes (Schweitzer et al. 2018), overstory survival dynamics (Craycroft and Schweitzer 2023), ground flora response (Willson et al. 2018; Barefoot et al. 2019), and avian and herpetofaunal response (Wick et al. 2013; Sutton et al. 2013). In this case study, we compare the burn results from a UAS-ignited prescribed fire on the BNF to other prescribed fires in the same locale. Our goal is to assess whether specific parameters from the UAS-ignited burn were different from other burns conducted within the same forested landscape.

Methods

Study area

The BNF is a 73,000-ha national forest located in north-central Alabama. The treatment stands, all located in the northern portion of the BNF, were selected to be similar based on average stand age, composition, and size. They range in area from 9 to 19 ha, in age from 30 to 60 years old, and in pre-treatment basal area from 28 to 30 m^2 ha^{-1} (Schweitzer et al. 2019). The study sites are mixed pine-hardwood forests, dominated by loblolly pine (*Pinus taeda* L.), with lesser amounts of Virginia (*P. virginiana* Mill.) and shortleaf (*P. echinata* Mill.) pine. Upland oaks are common and include chestnut (*Quercus prinus* L.), white (*Q. alba* L.), northern red (*Q. rubra* L.), scarlet (*Q. coccinea* Munchh.), black (*Q. velutina* Lam.), and southern red (*Q. falcata* Michx.) oaks. Other commonly prevalent hardwoods include hickories (*Carya* spp.), yellow-poplar (*Liriodendron tulipifera* L.), red maple (*Acer rubrum* L.), and black cherry (*Prunus serotina* Ehrh.).

The UAS-ignited prescribed fire subsumed one research study forest stand (referred to herein as “S1”). This provided an opportunity for comparing burn characteristics of this burn with other, non-UAS-ignited burns, because relevant data were already being collected as part of the ongoing research study. In this exploratory analysis, we provide one set of comparisons controlling for location and another set of comparisons controlling for year. Since the burns in 2022 covered the 6th burn cycle, we refer to the UAS-ignited burn as S1B6; earlier burns on the same stand are noted as S1B1, …, S1B5. No data were collected for S1B2, the second burn on S1. Burns on five other stands in 2022 are referred to as S2B6, …, S6B6. The S1B6 burn in 2022 occurred on 6 March; the other burns in 2022 occurred on 31 January and 25 March. The previous burns on stand S1 all took place between January and March. Table S1 in the Supplemental Information provides weather conditions for the burns.

The point ignition pattern implemented by the UAS was accomplished by programming the UAS to fly in a grid pattern that ignited the ridgetops. Flanking and backing fires then carried into the drains in the undulating topography. The strip ignition patterns for the hand ignitions also mostly started on the ridgetops. These landscape-level burns often result in fire behavior that includes flanking, backing, and the occasional head fire as topography changes. Ignition was done by hand crews for S1B1, S1B4 and S1B5; S1B2 and S1B3 were ignited using helicopter and hand ignitions, but we do not have data from S1B2. All other 2022 burns were hand-crew ignitions in stands that had received 5 previous burns.

Equipment used

The UAS comprised a hexacopter drone, specifically a DJI Matrice 600 Pro (DJI; Shenzhen, Guangdong, China), and the IGNIS platform (Drone Amplified; Lincoln, NE, USA) (Fig. 1). The hexacopter was powered by six TB48S intelligent batteries. Six sets of batteries were available, along with a generator in the field for recharging, and each set allowed for approximately 15 min of flight time. Pyro-Shot Dragon Egg ignition spheres (SEI Industries; Delta, British Columbia, Canada) were loaded into the upper hopper of the IGNIS platform, and they were then injected with ethylene glycol, or full-strength antifreeze,

Fig. 1 DJI Matrice 600 Pro drone with attached hopper filled with dragon eggs. (Photo credit: Dr. Callie Schweitzer)

in the lower portion prior to release. A geofence was established along the boundaries of the 441-ha burn area, and then 2712 Dragon Eggs were dropped over 18 flights, amounting to 196 min of flight time.

Metrics

Two categories of metrics were available for this analysis. The first category comprised three metrics derived from time series of thermocouple probe (TCP) temperature readings: the "Near-Ground Heat Index," (NGHI), which was the maximum temperature (max. temp.) recorded by each TCP; time to max. temp.; and the integrated area under the temperature-time profile (AUC). Following methods from Iverson et al. (2004), up to eight HOBO data recorders (HOBO U12 Series Datalogger, Onset Computer Corporation; Cape Cod, MA, USA) and 0.5-cm-thick TCPs (HOBO TCP6-K12 Probe Thermocouple Sensor, Onset Computer Corporation; Cape Cod, MA, USA) were distributed per measurement plot per burn. Each stand had five measurement plots. Dataloggers were buried approximately 0.152 m (6 in.) deep, and after burial, duff and litter layers were replaced over mineral soil. The TCPs were installed with vertical orientation, with tips approximately 0.254 m (10 in.) above the litter layer. Temperature data were recorded at 2-s intervals from the morning before until the night following the burn. Burn continuity was sometimes patchy, particularly in the first year of the study; thus, time series with maximum temperatures lower than 32.2 °C were omitted. The NGHI metric is the maximum recorded temperature for the time series. The time to max. temp. metric is the number of minutes elapsed from initial temperature increase until the max. temp. is reached. Finally, the AUC metric is the area under the curve of the temperature-time profile from initial temperature rise until max. temp., i.e., the integration of the time series from the local start time until the local peak. We used the max. temp. time point as the end boundary for the integration, rather than the return-to-ambient-temperature time point, due to the fact that the decreasing slope of the temperature-time profile following max. temp. is largely an artifact of the cooling properties of the TCPs along with ambient weather conditions, rather than any true representation of heat input, as described in McGranahan (2020). Because several TCPs were deployed per measurement plot and each TCP provided a unique time series of temperatures, we average the metrics to the stand level for comparison among burns.

The second category of metrics comprised fuel consumption estimates for the following four fuel classes: 10-h, 1-h, litter, and duff. Pre-fire fuels were collected in the late fall after abscission, and post-fire fuels were collected generally within 2 weeks following each burn. Two 15.24-m (50 ft) planar intercepts were established within each measurement plot. For each transect, two distances were randomly selected. At those distances along the transects, two 0.0929-m^2 (1 ft^2) samples were marked, one 0.914 m (3 ft.) to the right and the other 0.914 m (3 ft.) to the left of the transect line. In these four samples per plot, all down woody debris was collected, transported to the lab, and separated into litter, duff, 1-h, and 10-h fuel categories. Fuel samples were oven-dried in paper bags at the lab at 79.4 °C for 48 h (72 h for duff); immediately after drying, samples were weighed to 0.01 g using an Ohaus 810-g precision scale (Ohaus Corporation; Parsippany, NJ, USA). The percent consumption for each of the four fuel categories was computed by dividing the post-fire mass by the pre-fire mass and subtracting that quotient from 100%. Negative consumption estimates occurred for some fuel categories and time points. This could happen for several reasons, including incompletely consumed larger fuels changing to smaller fuel categories (i.e., 100-h fuels becoming 10-h fuels, 10-h fuels becoming 1-h fuels, etc.), additional 10-h and 1-h fuel falling on the transect post-burn, and highly variable fuel spatial distribution (McDaniel et al. 2016). In these cases, consumption was set at 0% at the plot level before averaging the plot-level consumption estimates to the stand level.

Comparison approach

The study stands are embedded within zones of the BNF that are targeted for regular cyclical burns. Ignition via UAS was not done for research purposes, but for demonstration of feasibility of this technology on this forest as well as training of personnel. Consequently, no formal statistical hypotheses were formulated before the event. Moreover, the objective of the current article is to simply describe the experience from this burn, placed in context relative to other comparable burns. Therefore, for all metrics considered here, we provide estimates of means, placed in context of their 95% confidence intervals or, for the fuel consumption estimates, relative to the standard error of the mean.

Results

The study stand included in the UAS-ignited prescribed burn on 6 March 2022 yielded 23 TCP temperature time series. The average (standard deviation) NGHI was 116.4 °C (57.1 °C); the average time to max. temp. was 8.5 min (5.9 min); and the average AUC was 9.6 K degree-seconds (deg.-secs.) (4.5 K deg.-secs.) (Table 1). By comparison, the average NGHI on the same study stand for four previous burns was 43.1 °C (9.0 °C), 115.8 °C (44.0 °C), 86.3 °C (45.6 °C), and 85.5 °C (46.2 °C); the average time to max. temp. was 14.7 min (7.4 min), 7.4 min

Table 1 Estimated NGHI, time to max. temp., and AUC with 95% confidence intervals

Burn			**NGHI (°C)**			**Time to max. temp. (min)**			**AUC (deg.-secs.)**		
			95% CI			**95% CI**			**95% CI**		
Stand	**No.**	**Date**	**Avg.**	**Low**	**High**	**Avg.**	**Low**	**High**	**Avg.**	**Low**	**High**
S1	B1	1/27/2007	43.1	#	#	14.7	#	#	3830	#	#
S1	B3	3/9/2013	115.8	98.0	133.6	7.4	5.9	8.9	9949	8625	11,274
S1	B4	2/12/2016	86.3	69.3	103.3	5.7	4.0	7.4	8655	7610	9700
S1	B5	3/1/2020	85.5	67.6	103.4	4.2	3.0	5.4	5521	3811	7231
S1	*B6*	*3/6/2022*	*116.4*	*91.8*	*141.1*	*8.5*	*5.9*	*11.0*	*9634*	*7720*	*11,549*
S2	B6	1/31/2022	148.7	128.9	168.5	3.8	3.0	4.6	7911	6097	9724
S3	B6	1/31/2022	223.2	199.8	246.5	2.8	2.2	3.4	7418	6467	8369
S4	B6	3/25/2022	129.2	110.3	148.0	6.1	5.0	7.2	12,309	10,591	14,026
S5	B6	3/25/2022	191.2	164.4	218.1	3.0	2.3	3.8	8199	7296	9102
S6	B6	3/25/2022	137.8	114.6	160.9	5.3	4.0	6.6	10,703	9256	12,150

Notes: *NGHI* Near-ground heat index, *max. temp* maximum temperature, *min* minutes, *AUC* Area under the curve *deg.-secs,* degree-seconds, *Avg* Average, *CI* Confidence interval. #: CIs not meaningful for S1B1, 01/27/2007, because only 2 thermocouple time series available

(3.7 min), 5.7 min (4.6 min), and 4.2 min (3.0 min); and the average AUC was 3.8 K (0.5 K), 9.9 K (3.3 K), 8.7 K (2.5 K), and 5.5 K deg.-secs. (4.4 K deg.-secs.) (Table 1). The five stands burned on other days in 2022, all by ground-ignited fires, had average NGHI of 148.7 °C (51.0 °C), 223.2 °C (62.5 °C), 191.2 °C (70.6 °C), 129.2 °C (47.7 °C), and 137.8 °C (58.5 °C); average time to max. temp. of 3.8 min (2.1 min), 2.8 min (1.6 min), 3.0 min (2.1 min), 6.1 min (2.7 min), and 5.3 min (3.2 min); and average AUC of 7.9 K (4.7 K), 7.4 K (2.5 K), 12.3 K (4.3 K), 8.2 K (2.4 K), and 10.7 K deg.-secs. (3.7 K deg.-secs.) (Table 1). Figure 2 displays the NGHI results along with 95% confidence intervals for each estimated mean. Figure 3 displays the time to max. temp. results, again with 95% confidence intervals for the estimated means.

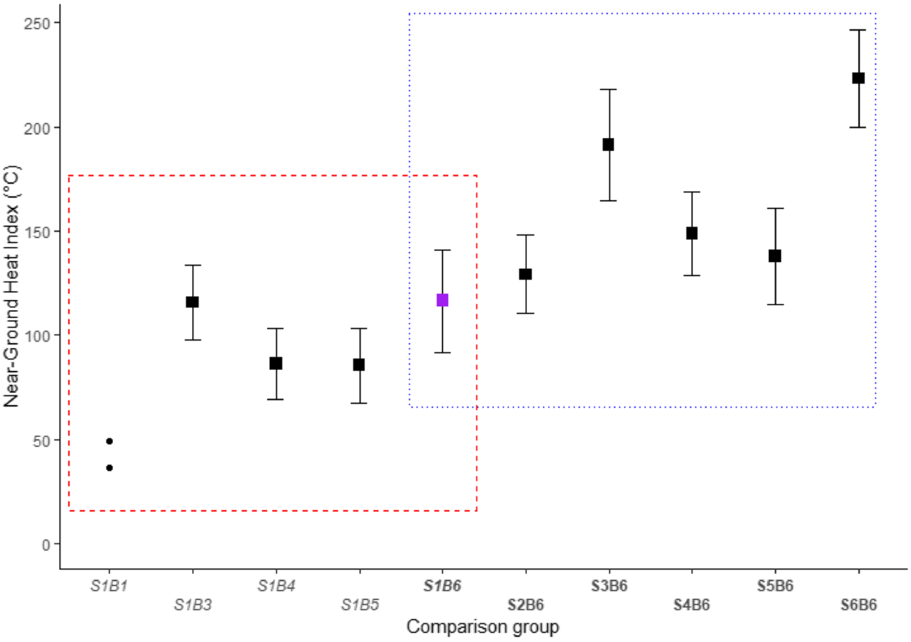

Fig. 2 Average near-ground heat index with 95% confidence intervals, by stand and burn date. SxBx indicates Stand x, Burn x. The UAS-ignited burn was S1B6. Red dashed box groups all burns for Stand S1. Blue dotted box groups all burns for stands during year 2022. Burn 1 on Jan. 27, 2007, only yielded two temperature time series, so the individual values are plotted rather than the confidence interval

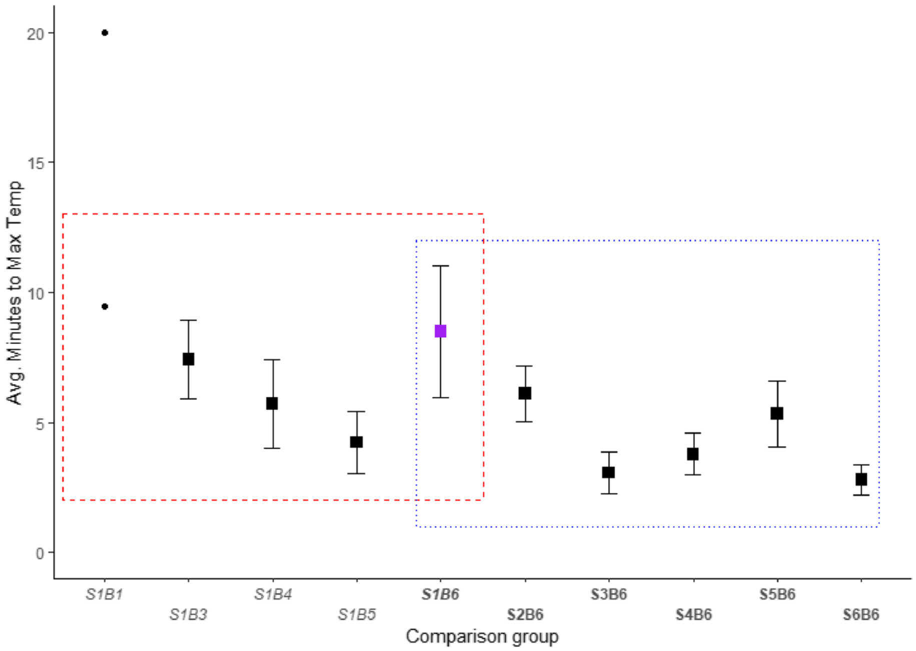

Fig. 3 Estimated mean time to max. temp. with 95% confidence intervals, by stand and burn date. SxBx indicates Stand x, Burn x. The UAS-ignited burn was S1B6. Red dashed box groups all burns for Stand S1. Blue dotted box groups all burns for stands during year 2022. Burn 1 on Jan. 27, 2007, only yielded two temperature time series, so the individual values are plotted rather than the confidence interval

For the fuel consumption metrics, the UAS-ignited burn experienced mean consumption percents of 65.0 (37.8), 63.0 (11.4), 22.0 (24.4), and 82.4 (10.0), for 10-h, 1-h, duff, and litter fuel categories, respectively (Fig. 4). For burns on the same stand in earlier burn cycles, average consumption percents ranged from 21.8 to 39.1 for 10-h; from 9.9 to 27.3 for 1-h; from 0.0 to 26.6 for duff; and from 2.0 to 41.4 for litter. For other stands burned in 2022, average consumption percents ranged from 8.8 to 66.2 for 10-h; from 30.6 to 74.7 for 1-h; from 15.5 to 60.4 for duff; and from 69.2 to 92.7 for litter.

Discussion

Across all forest ownership classes, the 13 southeastern states used prescribed fire on 2.5 million ha in 2019, the highest of any US region (Melvin 2020). On national forests in the southeast, UAS-ignited burns increased from 6336 ha in 2020 to 43,409 ha in 2023 (Terry Owen, U.S. Department of Agriculture, Forest Service, Region 8 Office Fire and Aviation Unit, Atlanta, GA, USA, personal communication). Using UAS technology to increase prescribed fire safety and capacity must align with management goals, from effectively treating planned acres to obtaining desired biological effects. Fire management officers have reported that UAS enable precise ignition targeting and access for hard-to-reach areas. The fire management staff is most impressed with the ability of the UAS to increase fire personnel safety. Kerry Clark, Fire Management Officer on the BNF, said,

> *As technology makes our jobs easier, we must be willing to adapt. The UAS technology is the wave of the future. As we continue to treat more landscapes with prescribed fire, the UAS is proving to be as effective in meeting our goals as helicopter and hand ignitions. But most importantly, the use of the UAS takes away considerable risk – risk to staff who have to fly with the helicopter, risk to staff who are igniting interior burns. It makes our jobs easier and safer. (Kerry Clark, US Department of Agriculture, Forest Service, BNF Fire Management Office, Double Springs, Alabama, USA, personal communication). This case study suggests that management goals may be achieved via UAS ignition approaches.*

The results of comparing metrics from the UAS-ignited burn with earlier burns on the same stand, or with burns on other stands in the same year (2022), are ambiguous. For NGHI, the S1B6 burn was near the higher end of the range of earlier burns on S1, and at the lower end of the range for burns on other stands in 2022 (Fig. 2). For time to max. temp., the S1B6 burn was towards the higher end of the range for both comparison groups, although it displayed more variation in this metric than did the other burns (Fig. 3).

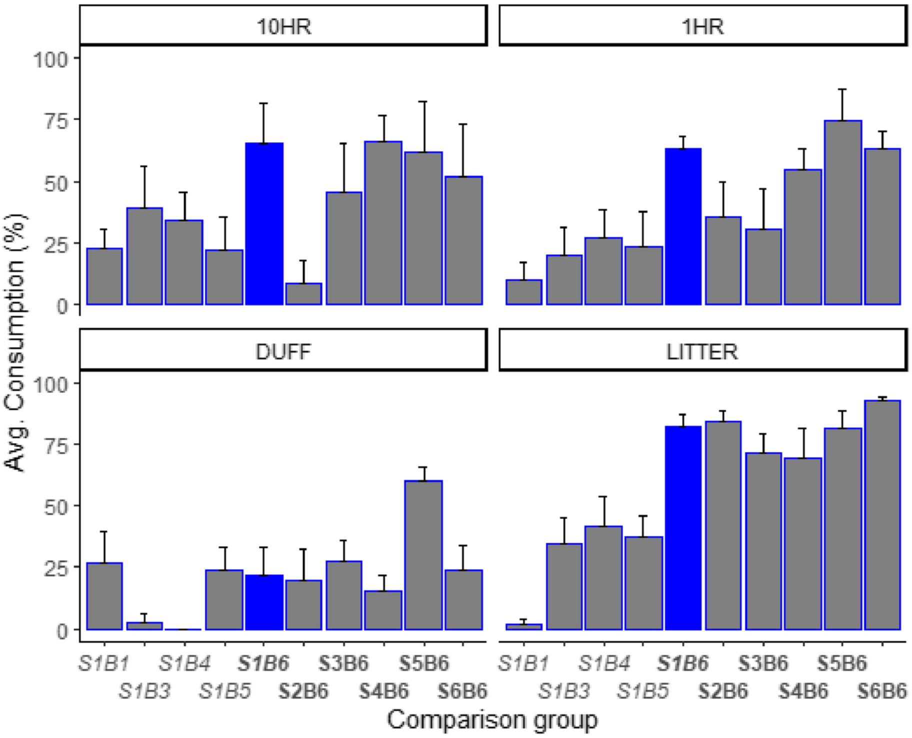

Fig. 4 Percent consumption by fuel type, stand, and burn number, with bars indicating one standard error of the estimated mean. SxBx indicates Stand x, Burn x. The UAS-ignited burn was S1B6. All B6 burns were in 2022. S1B2 consumption not shown, as there was no burn data for that burn cycle for S1

For AUC, which incorporates both NGHI and time to max. temp., the S1B6 burn was consistent with the other burns (Table 1). For NGHI, time to max. temp., and AUC, the UAS metrics were most similar to the results from the helicopter-ignited burn (S1B3), probably to some extent due to common point ignition firing patterns. This correlation is intriguing, but the data available here are too limited to establish firm conclusions. For fuel consumption, the S1B6 burn compared to earlier burns on S1 had higher average consumptions of 10-h, 1-h, and litter fuels, but similar consumption of duff (Fig. 4). Thus, this stand may have received a more thorough burn compared to years past. Comparing to other stands burned in 2022, the fuel consumption results were largely consistent.

This is the experience from one burn only; therefore, we cannot extrapolate too far from these results. More examples of fire effects comparisons between UAS- and non-UAS-ignited prescribed fires are needed and may be anticipated in the short term given the increasing UAS ignition adoption mentioned above. We believe that all these metrics are useful ones to track over time, and that researchers should attempt to obtain similar data for future prescribed burns. Nevertheless, at this point, we think it important to remark again that the context here is large burns on the scale of several hundreds of hectares. Variability in fire behavior and burn effects is quite high on such a scale. Weather, topography, fuel composition and distribution, vegetation, ignition patterns, and other factors, and the interactions among all of these, impact fire effects for any given burn (Hiers et al. 2020, Craycroft and Schweitzer 2023). In such a complex system, it is likely impossible to quantify the effects of UAS ignition versus ground ignition, for example. However, we can reasonably determine whether a burn met the burn objectives or not. Assuming burn objectives are consistently met with UAS ignitions, then prescribed burn practitioners can begin to consider potential benefits in terms of safety, flexibility, cost efficiency, and spatial coverage that may come from implementing that approach.

Supplementary Information

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Supplementary Material 1.

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Authors' contributions

JC: conceptualization, methodology, software, validation, formal analysis, writing—original draft preparation, writing—reviewing and editing, visualization. CS: conceptualization, resources, supervision, writing—original draft preparation, writing—reviewing and editing.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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