DETECTING ILLEGAL CAMPFIRES BY DRONE-MOUNTED THERMAL SENSORS IN PROTECTED TROPICAL RAINFORESTS

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ABSTRACT

Thermal drones are increasingly used for conservation tasks such as biodiversity monitoring and wildfire management, but their utility in combating illegal activities in tropical rainforests remains underexplored. This study assesses the potential of thermal drones to detect campfires associated with illegal poaching and gold mining in Costa Rica's Osa Peninsula. We simulated illegal campfires placed under the forest canopy, and conducted 29 experimental thermal drone flights across five survey rounds along a 1-km riverbank. Hypothesised factors influencing detection success, including fire stage, time of day, and canopy cover, were analysed. The drone detected 21 of 23 campfires (91 per cent), with 73 per cent detected on the first flight. Increased canopy cover and older fires reduced detection success, but time of day had no significant impact. Detecting humans was more challenging than campfire detection. The findings suggest thermal drones can aid enforcement in tropical rainforests but should be used in repeated surveys to improve detection rates, especially in locations with dense canopies. Thermal drones could enhance efforts to monitor illegal hunting, mining and trespassing in remote protected areas, helping conservation teams save time and resources in challenging environments.

Keywords: remote sensing, neotropics, enforcement, trespassing, surveys, anthropogenic disturbance

INTRODUCTION

Drones provide a relatively low-cost tool, to rapidly and systematically observe both natural phenomena and anthropogenic disturbances at high resolution across broad temporal scales in challenging environments (Rodríguez et al., 2012). In recent years, thermal infrared sensors have been incorporated into drone camera systems enhancing their surveying capabilities. The technology relies on the contrasting temperatures of focal individuals or objects from their ambient environment, providing new opportunities for surveying wildlife and ecosystems, and surveillance in terms of both search and rescue and control and protection (Beaver et al., 2020, Mulero-Pázmány et al., 2014, Witczuk et al., 2018).

Thermal drone research has become increasingly popular in conservation and monitoring due to its ability to detect wildlife and habitat changes effectively. The list of species monitored using thermal drones increases each year including mammals (Gooday et al., 2018, Kays et al., 2019, Larsen et al., 2023, Whitworth et al., 2022), birds (Avila-Sanchez et al., 2024, Santangeli et al., 2020), and reptiles (Sellés-Ríos et al., 2022, Viljoen et al., 2023). Thermal drones have also been used to study land-use change across time in a variety of ecosystems such as grasslands, wetlands, savannas, riparian, coastal and marine habitats (Adedeji et al., 2015, Agarwal et al., 2019, Mancini et al., 2016, Natesan et al., 2018). Finally, terrestrial and maritime surveillance has improved by using this technology, focusing on forest fire alerts,

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rescue searches, fighting poachers and illegal gold miners, and detecting illegal logging in protected areas (Jeon et al., 2019, Jiménez-López & Mulero-Pázmány, 2019, Klimkowska & Lee, 2017, Mulero-Pázmány et al., 2014, Tang & Shao, 2015). Despite these advances, most studies have either been restricted to open areas or focused on the upper forest canopy itself, neglecting the dense understory where illegal activities occur and are harder to detect (Guimarães et al., 2020). As most of the world's biodiversity exists within tropical forest ecosystems (Pironon et al., 2020, Raven et al., 2020) and wildlife poaching remains a major challenge both inside and outside of tropical protected areas (Baillie et al., 2004, Lavadinović et al., 2021), having effective tools to monitor anthropogenic disturbances and illegal activities in these ecosystems is crucial. Therefore, there is a need to address the information scarcity on the utility of thermal drones to perform surveillance of illegal activities in closed-canopy tropical forest habitats.

A key challenge for wildlife professionals and Indigenous communities managing tropical forests is the difficulty in rapidly identifying and responding to illegal and destructive activities (Murrins-Misiukas et al., 2021). Protected areas are often large and management budgets small, leading to small ranger teams being tasked with patrolling vast areas that are difficult to access and patrol safely. As such, drones mounted with thermal cameras could prove a useful addition to the conservation toolkit, reducing arduous on-foot patrols and decreasing response times to environmentally damaging illegal activities. However, the efficiency of thermal drones in detecting illegal activities in tropical forests remains unknown.

Here we address the lack of information about the utility of thermal drones to detect illegal activities by assessing their ability to detect understory campfires and people in a closed-canopy tropical forest context. Specifically, we established campfires mimicking those used by poachers and gold miners in protected areas of the region along a 1-km stream bank, then flew test flights using a thermal drone to determine the detection probability for the fires and people. We first assess if campfires are detectable in forested environments, then determine the effects of three key variables hypothesised to influence fire detection probability: variation in fire stage (flaming fires should be easier to detect than embers), time of day (fires should be more detectable at night than in the day due to higher temperature differential), and canopy cover (increased canopy cover should decrease campfire detection probability). Finally, we assess the ability of the thermal drone to detect the people on the ground conducting illegal activities.

METHODS

Study site

The Osa Peninsula in the south Pacific of Costa Rica is home to one of the largest remaining tracts of Pacific lowland wet forest in Mesoamerica (Holdridge, 1967) and encompasses a system of protected areas (~80 per cent of the terrestrial surface has some degree of protection) containing both primary (of which less than half of the original area remains) (Weissenhofer et al., 2001) and secondary forest. Outside the protected areas is a landscape matrix of cattle farms, oil palm plantations, agriculture, and timber plantations. Before these protected areas were established, the Osa Peninsula experienced high levels of environmentally damaging activities, including logging, wildlife poaching and gold mining (Algeet-Abarquero et al., 2015, Borge & Herrera, 2006, Carrillo et al., 2000). Whilst illegal activities have decreased in the region since the economy has shifted towards ecotourism, both poaching and gold mining persist in some areas of the region (López-Gutiérrez, 2020, Wong, 2014).

The study site is on the Osa Conservation Campus (formerly known as Piro Biological Station, 8.40388 N, 83.33661 W, see Figure 1), embedded within the Golfo Dulce Forest Reserve that connects Osa's two National Parks – Corcovado and Piedras Blancas. Temperatures at the field site range between 23.4 °C and 28.8 °C (Whitworth et al., 2018). Rainfall averages 3,584 mm yr^{-1} and is seasonal, with a rainy season from June to November and a dry season from December to May (Taylor et al., 2015).

Based on local knowledge, illegal campfire activity is most likely to occur near small streams that lead into the main watersheds where there would be gold mining activities, and the campfires are known to be lit from dusk to dawn (17:00–7:00). To test if campfires could be detected by a drone mounted with a thermal camera in a tropical rainforest system, we ran a series of experimental flights. Our study flights were conducted in areas of > 40-year-old naturally regenerating secondary-growth forest within the Piro watershed.

Fire establishment

On five occasions (rounds) between May and August 2021, two members of the team were instructed to light up to three fires each at random locations at varying distances along the riverbank and stay in the region to maintain them (Figure 1A) imitating those used by gold miners and poachers in the tropical rainforest. Each one was built under black plastic tarpaulin to protect it from the rain (Figure 1B). During each round between one and six fires were lit, resulting in a total across all rounds of 23 fires. For each round, the fires were lit in two sets –

Figure 1. Survey area, location within Costa Rica, and examples of campfire simulation and its detection using a thermal-mounted camera. A = Campfires lit along the river and drone flight automated route, B = Campfire being lit prior to the drone flights imitating a fire of a gold miner or poacher in a tropical rainforest, C = Flaming campfire detected from the canopy using a thermal camera mounted on a drone (screenshot of a video recorded by the drone), D = Campfire embers detected from the canopy using a thermal camera mounted on a drone (screenshot of a video recorded by the drone), E = Person detected from the canopy using a thermal camera mounted on a drone (zoomed in screenshot of a video recorded by the drone).

morning and night – to reflect the times when fires were most likely to be lit in this region. Morning fires were lit at 04:30, night fires at 17:30. The fires were maintained in a 'flaming' state for the first two flights of each set (see Drone flights section below) and then they were left to turn into embers by the third flight (09:00 and 22:00), to mimic real campfire management and to test the effect of the campfire stage on its detectability. Location and quantity of fires were unknown to the drone pilot.

Drone flights

Flights were performed using the Autel Robotics drone, model EVO II DUAL CAMERA (registration number RPAS-1354-CR) flown by drone pilot Johan Ortiz (licence number 60-4140911). The model contains an Uncooled VOx Microbolometer sensor (field of view = H33° V26°, lens focal length 13 mm), the pixel size was 12 µm and wavelength range 8–14 µm. Five rounds of experimental flights were executed. During each round, six flights were completed. One flight was excluded due to an SD card error, resulting in a final sample size of 29 flights. Each round was split into two 'sets' of three flights, one set was completed at night-time (18:00, 20:00 and 22:00) and another set of three flights was completed in the morning (05:00, 07:00, 09:00).

We programmed the drone to automatically fly a planned route of 1 km (going up one side of the river for 500 m and then returning on the other side, the flight route taken was 15 m from the riverbank on each side – Figure 1A) at a speed of 10.8 km/h as this flight speed has been proven to increase detection rates of drone-based wildlife counts in this region (Whitworth et al., 2022) and an overall flight time of 20 minutes. The drone elevation was configured at a minimum height of 90 m and a maximum of 120 m from the ground, considering the changes in topography and maximum height of trees across the flight route. During experimental flights the 'Hottest' thermal camera setting was determined the most effective to spot campfires and people with orange marks highlighting the warmest points (Figure 1C–E), therefore this mode at an angle of 90 degrees was used. Before the flight round, the field of view of the thermal camera was tested at different flight heights to ensure optimal setting selection for campfire detection and the safe flight of the drone according to variations in topography and different tree heights.

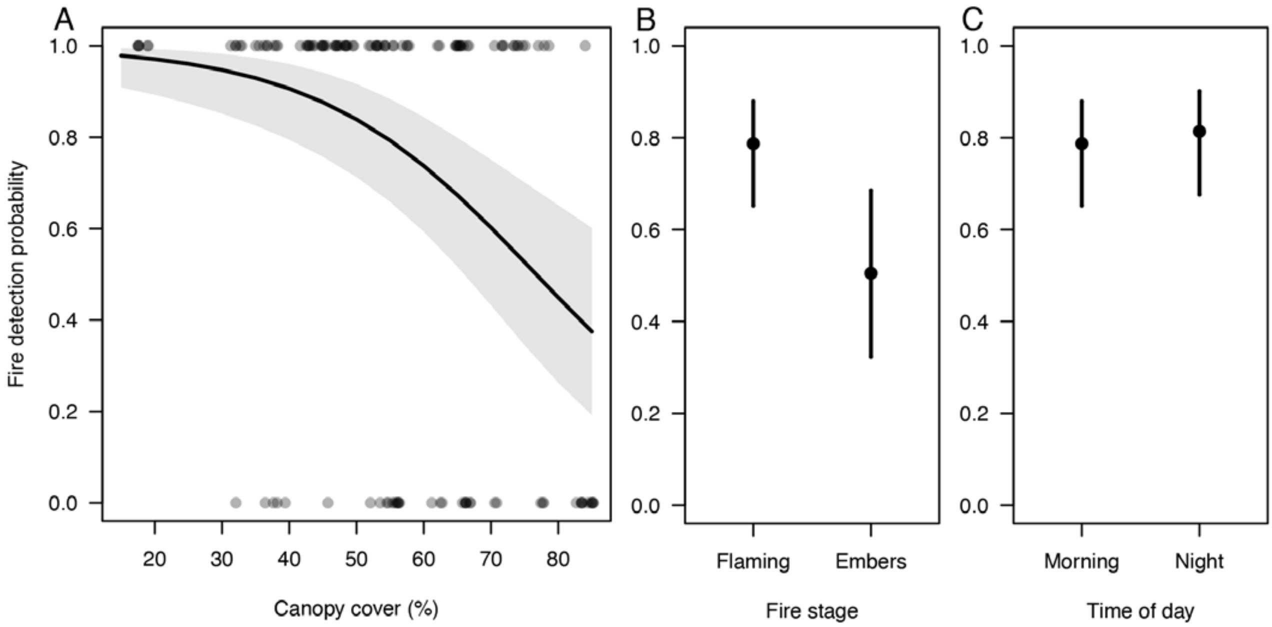

Figure 2. Predicted detection probabilities for fires in different contexts (canopy cover, fire stage, and time of day). A = detection probabilities (black line) and 95% confidence interval (grey area) across a natural range of canopy cover (for 'flaming' fires in the 'morning') and points showing the raw data for individual fire detections, B = detection probabilities (points) and 95% confidence interval (lines) at different fire stages (for 55% canopy cover in the 'morning'), C = detection probabilities (points) and 95% confidence interval (lines) at different times of day (for 55% canopy cover and 'flaming' fire).

Predictors of fire detection

We tested three covariates to reflect predictors of fire detection probability: fire stage, time of day, and canopy cover. To test the effect of the campfire stage on its detectability by a thermal drone, the fires were in a 'flaming' stage for the flights at 5:00, 7:00, 18:00 and 20:00 and then were left to turn into embers on the flights at 09:00 and 22:00, to mimic the real maintenance of gold miners' campfires in the region. To understand the effect of canopy cover on campfire detection, we used the natural heterogeneity in canopy cover at the fire locations. We quantified canopy cover by taking a photograph using the Canopeo 1.1.7 mobile app (http://www.canopeoapp.com/) parallel with the canopy at chest level, directly above the fire location. Mean canopy cover across all sites was 55 per cent (min = 18 per cent, max = 85 per cent). Surveys occurring between 5:00 and 9:00 were assigned as 'morning' and surveys occurring 18:00–22:00 as 'night'.

Data analysis

A single trained observer reviewed the video from the resultant drone flights, marking locations where they thought a campfire was present. These identifications were then compared with the known fire locations post-hoc. Events, where fires were successfully detected, were designated as 1, and events where the fire was missed were recorded as 0. To identify the factors (fire stage, time of day and canopy cover) that affected campfire detectability, we used a generalised linear model using the binomial family with a log link in the R statistical environment (R.4.4.0) (R Core Team, 2013). We applied a global model approach, including all the candidate covariates in a single model then using Wald tests to determine if there was statistical support for each given covariate. We used visualisations of effect size to determine if covariates had biologically meaningful effects. Model fit was assessed using standard residual plotting techniques.

RESULTS

Campfire detection using drones

Of the 23 campfires established across all five rounds, 21 were detected at least once on a given survey flight (overall detection probability of 91 per cent). Breaking this down into individual flights (six per round), 17 (73 per cent) had been detected after the first flight, 18 (78 per cent) after the second, 20 after the third and fourth (87 per cent), and 21 (91 per cent) after the fifth and sixth flights. No additional fires were detected on the sixth flight. There were no instances of 'fire' being designated by the drone observer when there was no fire present.

Predictors of campfire detection efficiency

We assessed three predictors of campfire detection probability: fire stage (flaming or embers), time of day (morning or night) and canopy cover. Increasing canopy cover had a strong negative effect on fire detection probability (Figure 2A, regression coefficient = -0.06, $p < 0.001$), with detection probabilities declining steeply above 40 per cent canopy cover. Flaming fires were 29 per cent easier to detect than just the embers (Figure 2B, 'embers' regression coefficient = -1.29, $p = 0.003$) and there was no statistical support for a difference in detection probability between morning and night-time (Figure 2C, 'night-time' regression coefficient = 0.17, $p = 0.691$).

Human detection

During each flight, we also recorded if the people tending the fires were successfully detected. Human heat signatures were successfully detected on 13 of the 29 occasions (44 per cent).

Discussion

This study demonstrates that campfires can be detected using thermal drones in tropical rainforest ecosystems with reasonably high efficiency. Campfires were detected after a single pass on three-quarters of occasions, with the detection rate increasing to nine out of ten after multiple flight passes had occurred. However, detectability was reduced for late-stage campfires and fires located under denser canopy cover. We were also able to detect humans on over a third of patrol flights. Below, we discuss the implications of these findings for control and protection activities in tropical forests contexts.

Thermal drones are an effective tool for monitoring campfires

Thermal drones have the potential to enable rangers to safely cover large areas and then organise targeted patrols to capture intruders 'in the act'. Drones can determine the exact location of fires, but also the presence of the perpetrators involved, helping rangers to organise a response consistent with the size and scale of the illegal activity occurring. Whilst thermal drone use has become common in fire management strategies, especially in detecting forest fires (Chen et al., 2018, Tang & Shao, 2015), this is the first demonstration of their use to detect small sub-canopy fires in a tropical forest context. Although the detection probability of older fires was reduced by 37 per cent relative to flaming fires, they were still detectable, consistent with previous work showing thermal cameras are an effective tool to detect subterranean peat fires (Burke et al., 2019) – as the ground temperature directly above the fire remained hotter than the ambient ground temperature (Usup et al., 2004). This broadens the window of detection for rangers looking for evidence of illegal activities.

Previous work suggests that objects are usually easier to detect at night-time (Hwang et al., 2015) as there is a higher contrast between the target object in cooler ambient environments (Spaan et al., 2019). However, we found no strong effect of time of day on fire detection probability, flaming fires were detected just as well in the morning (79 per cent) as they were at night (81 per cent). This difference is likely driven by most of the previous work focusing on detection of wildlife, which typically have thermal signatures slightly above that of the background, whereas hot campfires have a more marked thermal difference. This suggests that campfire surveys can be effective in the daytime too, supporting findings by Hambrecht et al. (2019), who did not find time of day as a significant factor in object detectability. Previous research has also suggested that daytime surveys may have a higher number of false positive detections (Doull et al., 2021). The lack of false positives here was likely due to the high relative difference in temperature between the fires and the ambient environment making them easy to discriminate from hot rocks or branches – the most common false positive objects in wildlife studies (Burke et al., 2018).

Drone surveys could reduce illegal activities as intruders are discouraged by the risk of being detected (Reischig et al., 2018). However, consistent with previous studies (Doull et al., 2021, Hambrecht et al., 2019), the probability of detection was greatly reduced in areas of high canopy cover (98 per cent detection probability at 15 per cent canopy cover, versus 37 per cent at 85 per cent canopy cover). Concerningly, this suggests that illegal activities may be harder to detect in intact forests, the locations where protection is most needed. Furthermore, illegal intruders could better hide their campfires from drones mounted with thermal technology should they learn the shortfalls of the tools used to identify them. If this approach is adopted by protected area managers and rangers, we urge the use of continual surveys to assess if trespassers learn to evade detection.

Improving campfire detection methods

Regardless, this tool shows potential for applied use by protected area managers. Here we used a quadcopter drone with relatively limited battery life, flight time and survey range. Despite its limitations, it rapidly covered a 1-km patrol area in just 20 minutes, successfully detecting campfires and human heat signatures. We used a human-observer to determine signals in the thermal imagery, and while this was still effective, it was time consuming. Applying machine learning technology to develop automated detection algorithms may enhance the efficiency of the work, and perhaps even detect people and fires with higher probability (Davis & Sharma, 2007, Hwang et al., 2015, Yeom, 2021). Use of automated systems may also facilitate flying at faster flight speeds and cover greater distances in patrols without the need to rely on human observers scanning the imagery. This would represent a valuable step forward in the development and use of this technology for protected area management scenarios.

The capability of these surveys would be further improved using drones with greater flight capacities. There are several fixed wing models with greater flight times and ranges (over 2 hours and 30 km, see Autel's Dragonfish models for example). While transmission to a handheld receiver would not be possible over that range, AI processing tools could be applied to footage once a patrol flight returns, allowing rapid identification and locations of illegal activities. In rainforest habitats this would be hugely beneficial in patrolling large areas where on-foot patrols might otherwise take many hours, or even days to complete. This technology could be critical for many national parks in tropical forests which are often restricted by tight funding budgets and limited personnel to protect large areas (Bruner et al., 2001, Watson et al., 2014). Crucial next steps for this work are to expand the assessment of campfire detection to include locations with different habitat types and topographies, fire sizes, environmental conditions (e.g. weather and seasonality), and assess the influence of increased drone path complexity. Extending these elements is essential in determining the transferability of our findings to other contexts and ecosystems.

Ultimately a major hurdle to widespread implementation of thermal drone technology remains the upfront costs of purchasing and maintaining the devices and getting sufficient training to utilise the tool safely and effectively. Such barriers could be overcome with investment in staff development and training, and through showcasing managers and decision-makers how drones might enhance the efficacy of ranger patrols. These efforts could be key to many countries in upholding their national and international commitments for protecting and safeguarding biodiversity. Crucially, thermal drones could help to detect and deter illegal activities, whilst simultaneously monitoring biodiversity (Gonzalez et al., 2016, Ivanova & Prosekov, 2024, McCarthy et al., 2021, Scholten et al., 2019, Witczuk et al., 2018). In fact, drone technology for biodiversity is fast becoming one of the most used tools in monitoring wildlife according to Ivanova et al. (2022).

In summary, this work marks a useful first step in the application of a burgeoning technology to assist with the control and protection efforts in tropical forest ecosystems and highlights the need for further testing and tool development. Similar surveys in other rainforest regions with different habitat conditions, or intruder behaviours, would be helpful to determine how broadly applicable and useful the technology could be. As a next step, this technology should be tested with real patrols in a protected area, to prove the real application alongside targeted follow-up patrols and arrests of intruders. Conservation funders, engineering departments, and drone technology companies could help to support and subsidise costs of the required trials and software development so that confidence and reliability can be established prior to broad-scale adoption for protected area management. This process needs to happen quickly given the rampant illegal resource extraction activities occurring throughout the world's tropical forest ecosystems.

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RESUMEN

Los drones térmicos se utilizan cada vez más para tareas de conservación, como la vigilancia de la biodiversidad y la gestión de incendios forestales, pero su utilidad en la lucha contra las actividades ilegales en las selvas tropicales sigue estando poco explorada. Este estudio evalúa el potencial de los drones térmicos para detectar hogueras asociadas a la caza furtiva ilegal y la minería de oro en la Península de Osa de Costa Rica. Simulamos hogueras ilegales situadas bajo el dosel del bosque y realizamos 29 vuelos experimentales con drones térmicos en cinco rondas de inspección a lo largo de una ribera de 1 km. Se analizaron las hipótesis sobre los factores que influyen en el éxito de la detección, como la fase del incendio, la hora del día y la cubierta de copas. El dron detectó 21 de 23 hogueras (91%), el 73% en el primer vuelo. El aumento de la cubierta de copas y los incendios más antiguos redujeron el éxito de la detección, pero la hora del día no tuvo un impacto significativo. La detección de personas fue más difícil que la de hogueras. Los resultados sugieren que los drones térmicos pueden ayudar a hacer cumplir la ley en las selvas tropicales, pero que deben utilizarse en estudios repetidos para mejorar los índices de detección, especialmente en lugares con copas densas. Los drones térmicos podrían mejorar la vigilancia de la caza, la minería y el allanamiento ilegales en zonas protegidas remotas, ayudando a los equipos de conservación a ahorrar tiempo y recursos en entornos difíciles.

RÉSUMÉ

Les drones thermiques sont de plus en plus utilisés pour des tâches de conservation telles que la surveillance de la biodiversité et la gestion des incendies de forêt, mais leur utilité dans la lutte contre les activités illégales dans les forêts tropicales humides reste sous-explorée. Cette étude évalue le potentiel des drones thermiques pour détecter les feux de camp associés au braconnage et à l'exploitation aurifère dans la péninsule d'Osa au Costa Rica. Nous avons simulé des feux de camp illégaux placés sous la canopée de la forêt et effectué 29 vols expérimentaux de drones thermiques au cours de cinq tournées d'étude le long d'une rive d'un kilomètre. Les facteurs hypothétiques influençant le succès de la détection, notamment le stade de l'incendie, l'heure de la journée et la couverture de la canopée, ont été analysés. Le drone a détecté 21 des 23 feux de camp (91 %), dont 73 % lors du premier vol. L'augmentation de la couverture végétale et les feux plus anciens ont réduit le succès de la détection, mais l'heure de la journée n'a pas eu d'impact significatif. La détection des humains a été plus difficile que celle des feux de camp. Les résultats suggèrent que les drones thermiques peuvent contribuer à l'application de la loi dans les forêts tropicales humides, mais qu'ils devraient être utilisés dans le cadre d'enquêtes répétées afin d'améliorer les taux de détection, en particulier dans les endroits où la canopée est dense. Les drones thermiques pourraient renforcer les efforts de surveillance de la chasse illégale, de l'exploitation minière et des intrusions dans les zones protégées éloignées, en aidant les équipes de conservation à gagner du temps et à économiser des ressources dans des environnements difficiles.