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POLICY FORUM

Combining drones and satellite tracking as an effective tool for informing policy change in riparian habitats: a proboscis monkey case study

Danica J. Stark[1,2], Ian P. Vaughan[1], Luke J. Evans[2,3], Harjinder Kler[4] & Benoit Goossens[1,2,5,6]

[1]Organisms and Environment Division, Cardiff School of Biosciences, Cardiff University, Sir Martin Evans Building, Museum Avenue, Cardiff CF10 3AX, United Kingdom
[2]Danau Girang Field Centre c/o Sabah Wildlife Department, Wisma Muis, Kota Kinabalu, Sabah 88100, Malaysia
[3]Department of Global Ecology, Carnegie Institution for Science, 260 Panama Street, Stanford, California 94305
[4]HUTAN/Kinabatangan Orang-utan Conservation Programme, PO Box 17793, Kota Kinabalu, Sabah 88874, Malaysia
[5]Sabah Wildlife Department, Wisma Muis, Kota Kinabalu, Sabah 88100, Malaysia
[6]Sustainable Places Research Institute, Cardiff University, 33 Park Place, Cardiff CF10 3BA, United Kingdom

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Correspondence
Danica J. Stark and Benoit Goossens, Organisms and Environment Division, Cardiff School of Biosciences, Cardiff University, Sir Martin Evans Building, Museum Avenue, Cardiff CF10 3AX, United Kingdom.
Tel: +44 29 208 74545; Fax: +44 29 208 74116; E-mails: danicastark@gmail.com; goossensbr@cardiff.ac.uk

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Abstract

Rapid reaction times to undesirable events are becoming increasingly important for the protection and conservation of habitats and species. This study demonstrates how Unmanned Aerial Vehicles, or drones, and satellite tracking of individual animals can be combined to identify important conservation issues (e.g. deforestation). When quickly disseminated, the information can lead to a rapid change in conservation policy. An adult male proboscis monkey, belonging to a one-male social group, was GPS tracked for 6 months in Sabah, Malaysian Borneo during 2012. Riparian habitats featured heavily (25.4% of total time, 88.6% of all sleeping sites) in the group's home range. A fixed-wing drone was used in 2015 to map the habitat in high-resolution. These data revealed that 47.54 ha of forest had been cleared shortly before the drone flights. GPS tagging data revealed the importance of this area for a one-male proboscis monkey group. A total of 30.1% of the proboscis monkeys' home range area had been cleared, as well as 11.4% of sleeping sites. Furthermore, drone images revealed that the felling extended to the river's edge, disregarding water resources laws requiring riparian reserves of a minimum of 20 m. Following this discovery, a press release including drone imagery combined with GPS data, was published linking habitat destruction to a species that is economically important for the tourism industry in Sabah. The day following dissemination of the data, the Sabah State Government ordered an immediate cessation on further land clearing at sensitive riparian reserves along the river. We propose that this combination of satellite and aerial data provides potential for an effective conservation tool for endangered, iconic and economically important species. This visually compelling data, feasible over large spatial scales, can directly inform policy change in a quick and timely manner.

Introduction

Anthropogenic actions can result in the removal of wildlife from their natural habitats, as well as the degradation of habitats due to legal, accidental and illegal human activities (i.e. logging, fire, hunting, pollutant spills (Butchart et al. 2010)). The ability to monitor habitats in near real-time has become increasingly important for the protection and conservation of broad ecosystems, specific habitats, or even individual species. Once an infraction or undesirable event has been detected, the reaction times of the administration, enforcement or policy-makers can be crucial for continued protection or management of an area (Navarro et al. 2012). By being able to prevent or curtail detrimental events, future impacts are minimised and are, therefore, easier to manage (Manyangadze 2009).

Environmental monitoring networks have been established for a variety of purposes, such as monitoring water quality, detecting harmful algal blooms, or detecting forest fires, to provide a source of data for policy-makers and governmental agencies, as well as to facilitate rapid and effective management responses (Glasgow et al. 2004; Manyangadze 2009; Navarro et al. 2012). Real-time, remote monitoring, in particular, has advanced the field of animal movement research (Wall et al. 2014). Satellite tracking is a powerful tool that can highlight the home range nuances of a species without observer bias (Stark et al. 2017). It can also provide evidence of active resource selection (e.g. for feeding or sleeping) that may otherwise be difficult to obtain in logistically remote locations or challenging terrain, particularly for shy or cryptic species (Chabot and Bird 2015; Schweiger et al. 2015). Additionally, satellite tracking can provide real-time locations of animals, which can be used to detect changes in movement patterns, or send alerts due to cessation of movement, allowing the researcher to respond accordingly (Wall et al. 2014).

Autonomous unmanned aerial vehicles (referred to as "drones" hereafter) are a remote-sensing platform commonly used for near real-time imagery of an area. Applications for drones are continuously diversifying and they are being used increasingly as a tool to supplement more traditional methods in wildlife studies (see reviews by Chabot and Bird 2015 and Linchant et al. 2015). Drones are also practical for wildlife habitat research and monitoring due to their ease of use, low cost, low environmental impact, versatility and their ability to cover areas which may otherwise be inaccessible (Dufour et al. 2013; Evans et al. 2015; Ivošević et al. 2015). Many of the habitat-related studies using drones have focussed on wetlands, coastal areas and riparian habitats, detecting finer-scale habitat details undetectable by ground surveys, leading to improved habitat classifications and vegetation biomass calculations (Husson et al. 2014; Chabot and Bird 2015). Through frequent and repeatable flights, drones have also been used in the detection of illegal activities. These range from logging, mining, poaching and habitat encroachment (Coulter et al. 2012; Paneque-Gálvez et al. 2014; Chabot and Bird 2015), to detecting camps or campfire smoke in areas where human presence is prohibited (Koh and Wich 2012).

Illegal activities are of particular concern for riparian zones, which are amongst the most severely altered and degraded habitats across the world (Nilsson and Berggren 2000). Human settlements tend to develop along waterways because of the importance of rivers for transportation and movement (Yeager and Blondal 1990; Meijaard and Nijman 2000). However, riparian zones have a fundamental function in the ecosystem, and their removal or alteration can have negative effects on existing ecosystems (Fernandes et al. 2011; Kuglerová et al. 2014). Furthermore, riparian zones often have higher levels of animal and plant diversity than non-riparian forests, and can act as important corridors during migration and dispersal (Naiman et al. 1993; Spackman and Hughes 1995). Although there is no standard optimal design for the ideal width of a riparian zone, there is often national or regional legislation in place to maintain some level of riparian protection (Blinn and Kilgore 2001; Lee et al. 2004; Kuglerová et al. 2014).

Proboscis monkeys (*Nasalis larvatus*) are large-bodied folivorous primates endemic to the island of Borneo, and are heavily associated with riverine, lake, swamp and mangrove forests. Proboscis monkeys tend to sleep near rivers as protection against predation (Thiry et al. 2016), and generally do not travel more than a half day's journey away from water before returning back (Matsuda et al. 2009a). Due to their habitat preferences, the majority of studies on proboscis monkeys have been restricted to riverbank observations (Bennett 1988; Bernard et al. 2010). Proboscis monkeys can live in disturbed or secondary forest, but generally avoid severely disturbed areas, agricultural areas, extensive grasslands and human settlements (Salter et al. 1985; Bernard and Zulhazman 2006). Proboscis monkeys are classified as Endangered (Meijaard et al. 2008) and are one of the focal species for tourism in Borneo (Leasor and Macgregor 2014). In the Malaysian State of Sabah, only 15.3% of the proboscis monkey groups are found in fully protected areas, and 42.8% are found outside forest reserves (Sha et al. 2008).

The largest known population of proboscis monkeys in Sabah is in Lower Kinabatangan Floodplain, 37.6% of which is found in unprotected areas (Sha et al. 2008). The forests have varying degrees of protection, with about 27 000 ha in the Lower Kinabatangan Wildlife Sanctuary (LKWS) and 15 000 ha as Virgin Jungle Forest Reserves (VJFR), interspersed with about 10 000 ha of unprotected (private) or state forest (Fig. 1) (Ancrenaz et al. 2004). The forested areas are surrounded by large and small-scale agriculture, mainly for oil palm (*Elaeis guineensis*), as well as human settlements. In addition to the protected status of the LKWS and VJFR, a 20 m riparian zone along both banks of every river greater than 3 m in width is designated as a riparian reserve under Sabah's Water Enactment 1998 Section 40(1), which includes the Kinabatangan River and its estuaries or tributaries (State of Sabah 1998). Furthermore, the Land Ordinance (Sabah Cap 68) specifies that riparian reserves in Sabah are property of the State (State of Sabah 2013).

Combining proboscis monkey GPS tracking data with high-resolution remote sensing datasets, such as those obtained using drones, can potentially provide

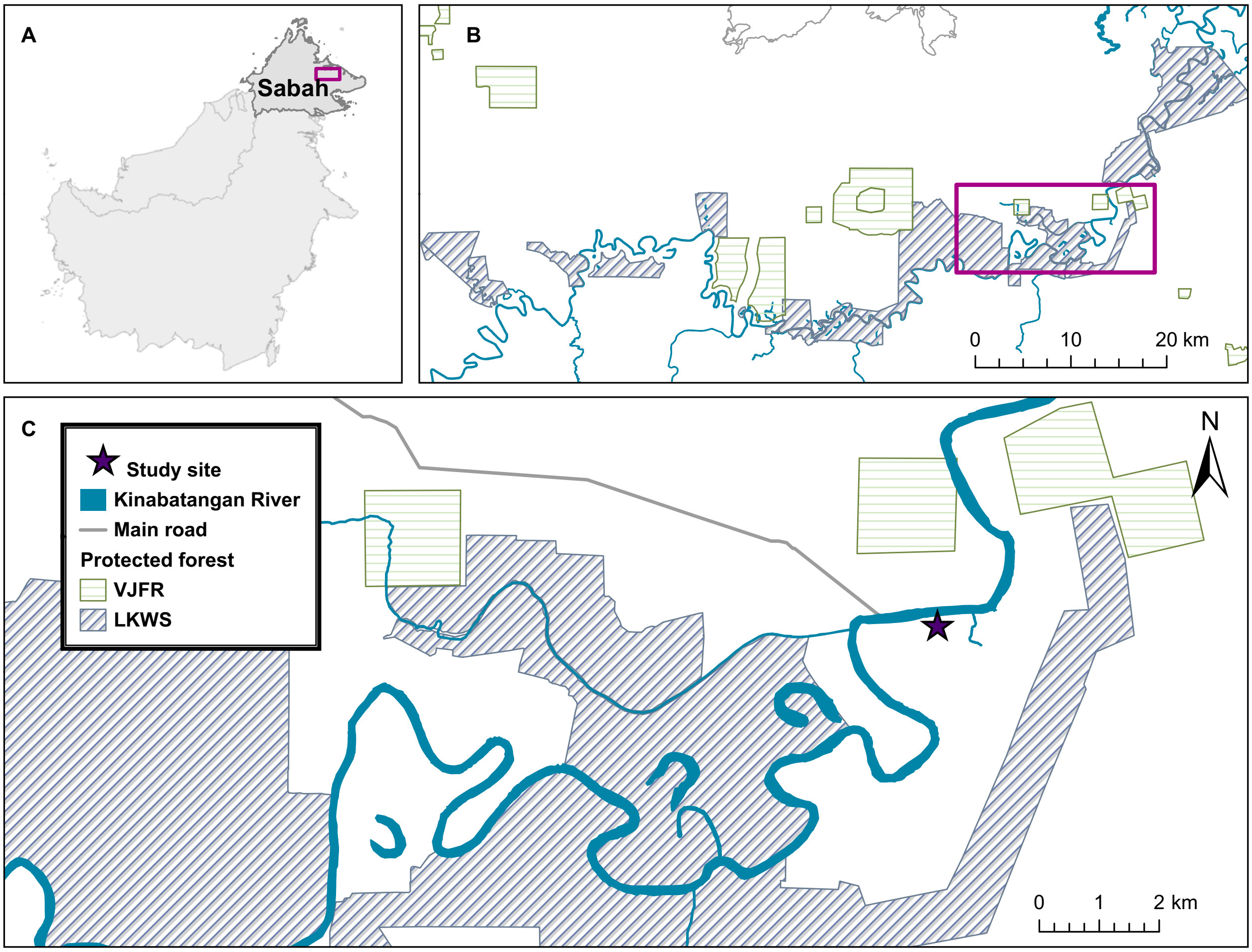

Figure 1. Study site (C) within the Lower Kinabatangan Floodplain in Sabah, Malaysian Borneo (A). Dark hashed areas indicate protected forest within the Lower Kinabatangan Wildlife Sanctuary (LKWS) and light striped areas indicate protected Virgin Jungle Forest Reserve (VJFR) (B). The white area indicates a mixture of private and state forest, human settlements and large- and small-scale agriculture.

opportunities for detailed analysis of interactions between animals and their habitat (Schweiger et al. 2015). In this study, we aim to (1) demonstrate the increased effectiveness of drone datasets when paired with the satellite tracking data of an endemic, endangered species to rapidly raise awareness and facilitate policy changes regarding riparian habitat destruction; (2) compare the extent of forest clearing in the area after the tracking period was complete to investigate the potential impact deforestation could have on the ranging of a one-male group of proboscis monkeys; and (3) show how these visually compelling data can engage the general public and initiate discussions on policy reform and conservation action.

Forest Imagery

In July 2015, 273.51 ha of unprotected forest were mapped using a fixed-wing drone. This forest connects the protected forest blocks under the LKWS jurisdiction (Lot 3) and Pangi VJFR, and provides important habitat for many of Borneo's symbolic species, including proboscis monkeys and orangutans (*Pongo pygmaeus*) (Ancrenaz et al. 2004), as well as serving as an important corridor for elephants (*Elephas maximus borneensis*) (Estes et al. 2012). The forest extends along the south bank of the main river, and is bisected by a tributary (Fig. 1).

To estimate the extent of forest prior to the most recent logging, images from Google Earth Pro (Google Earth 7.1 2014) were digitised and processed in ArcGIS 10 (ESRI 2011). Areas that were already non-forested prior to the clearing event were determined based on ground-truthing from surveys in 2012 and by the size of oil palm trees or the condition of the non-forested areas in the 2014 Google Earth image (i.e. worn houses, well-established gardens, etc.). As the annual dynamism (mean tree mortality and recruitment) in Southeast Asian tropical forests is

1.59 ± 0.39% (Phillips et al. 1994), the 2014 image was assumed to be representative of the forest cover during 2012. The non-forested areas were delineated in ArcGIS Editor, and the area calculated and subtracted from the total forested area based on the Google Earth image.

A drone (Bormatec-MAJA: Bormatec, Mooswiesen, Ravensburg, Germany) was fitted with a Canon S100 digital camera (Ota, Tokyo, Japan) that was customised with firmware enhancement created using a Canon Hack Development Kit (CHDK). In order to obtain >60% sequential picture overlap, the flights were flown at an altitude of 315 m, with transects 170 m apart, and an inter-image gap of 3 sec.

Of the area covered by the drone, 13.06 ha was already non-forested during the satellite tracking period in 2012, consisting of houses, gardens, and small-scale oil palm plantations. From the drone images, it was calculated that a further 47.54 ha had been cleared in late May 2015, accounting for 18.3% of the forested area (Fig. 2).

Home range and habitat loss

Within the unprotected forest study site, an adult male proboscis monkey had been fitted with a GPS collar in May 2012 and tracked for 169 days. The utilization distribution was estimated using biased random bridges, with the total home range defined by the 90% contours of the utilization distribution, and core range as the 50% contours (see Stark et al. 2017 for detailed methodology). Sleeping sites were defined as the GPS fixes at 1900 h.

The home range of the proboscis monkey group was estimated to be 49.18 ha (core range 14.55 ha), which fell entirely within the area surveyed by the drone. The riparian reserve was heavily utilised, with 25.4% of all GPS points found within these legally defined 20 m riparian reserves, as were 88.6% of all sleeping sites (Fig. 3 and S1). A total of 9.4% (6.09 ha) of the core and home ranges fell within the legally protected riparian reserve (1.48 ha and 4.61 ha respectively).

A total of 0.98 ha of forest was cleared within 20 m of the main river and tributary. Of the riparian reserve cleared, 0.63 ha was within the proboscis monkeys' home range. Approximately 11% of the sleeping sites were located in areas that were subsequently logged, of which all but one had been within the legally protected, government mandated riparian reserve. Moreover, 30.1% of the total home range area (14.08 ha), and 24.9% of the core range area was cleared (3.62 ha) (Fig. 3). On 123 of the 169 days tracked, the proboscis monkeys entered the area that was later cleared in 2015, with an average of 4.6 ± 2.7 fixes (30.7%) a day within those areas (Table S1).

Dissemination of findings

The riparian reserve had been cleared by a local landowner under the Federal Government's Rubber Industry Smallholders Development Authority (RISDA) (Daily Express 2015). This Federal Government agency did not consult with the State Government's Wildlife Department which manages the conservation areas adjacent and close

Figure 2. The 273.51 ha area surveyed by the drone with corresponding pre-logged images in 2012 (top figure) and the logged areas detected by the drone images in 2015 (in brown, lower figure); grey indicates the areas that were not forested during the tracking period of the proboscis monkey (2012).

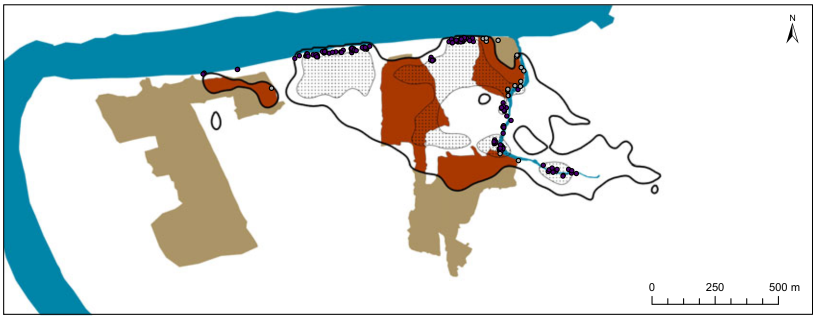

Figure 3. Extent of clearing in relation to the home range and sleeping site selection of the collared proboscis monkey. Dark orange area highlights the logging that occurred within the home range (dark outline) and core range (patterned area) of the group. Points indicate all sleeping sites throughout the study period, with the light points indicating those affected by the logging.

to the private lands that were targeted by the RISDA scheme. Money was given as an incentive to clear the privately owned property, and then the landowners were provided with rubber trees to plant on their land. Using the drone and satellite tracking datasets, a press release was prepared by DJS and BG to highlight the association of the habitat destruction to a species that is economically important for the tourism industry in Sabah (Borneo Post 2015) (Fig. 4). The press release was published in local and national newspapers, as well as on the main social media outlet (Facebook) for Danau Girang Field Centre (DGFC). This Facebook page is used regularly for publishing press releases and other urgent conservation issues, and therefore any heightened interest in this particular press release would not simply be because it was the only urgent conservation issue posted. The impact the press release had through social media was assessed by (1) the number of reaches per post (the total number of unique people the post had been served to) and (2) post engagements (the number of unique people who engaged in certain ways with the post; e.g. commenting, liking, sharing or clicking on particular elements of the post) (Wijedasa et al. 2013). The number of reaches and engagements of the press release posts were compared to those of all the other posts on the DGFC Facebook page, spanning from a month before and after the press release date.

There were a total of 69 posts on the Danau Girang Facebook page from July 1 to August 31st 2015, four of which were based on the press release that included the drone and satellite imagery. The four posts based on the new imagery had more than three times as many reaches per post as the remaining 65 posts (mean number of users = 6273.5 (sec = 4781.1) and 2039.4 (sec = 159.8), respectively). The average number of post engagements

Figure 4. Examples of the drone images used in the press release, showing the extent of clearing and removal of the riparian reserve in relation to proboscis monkey GPS fixes (white points).

for the drone and satellite tracking posts increased to 573.5 (sec = 492.9) users from 165.72 (sec = 14.7) users. The following day, the Sabah State Government announced that there would be an immediate cessation of land clearing along sensitive riparian reserves in the Kinabatangan River (The Star 2015). A formal investigation was conducted which confirmed a number of infractions had taken place (Sabah Forestry Department 2016).

Discussion & Conclusions

Here, we present the first known case of the effective combination of drone and satellite tracking data and its application in prompting immediate conservation action. We showed the importance that riparian reserves have in the daily ranging and sleeping selection of proboscis monkeys, with a quarter of all points falling within the reserve. Furthermore, >88% of all sleeping sites were within this riparian reserve. We then showed with the drone dataset that 30% (14.8 ha) of the groups' total home range area was cleared in 2015, including 11% of their sleeping sites.

In addition to the quantitative data extracted, the visually compelling images captured by combining drones and satellite tracking can be utilised as a powerful awareness tool for the general public. Social media has the power to influence policy-makers, increase accountability, and encourage shifts in behaviour. This can result in unprecedented government responses (Nghiem et al. 2012). Due to the long-established culture of wildlife consumption and insufficient knowledge in environmental issues in Asian-Pacific countries (Lo et al. 2012; Kwan et al. 2016), there is a disconnect between more tangible conservation issues, such as animal abuse, and more conceptual issues, such as deforestation or wildlife trade. There is also a belief that pro-environmental behaviour is motivated by scientific background (Lo et al. 2012), and therefore does not have a wide-spread emotional impact on lay people. Public engagement on emotive issues, such as with animal abuse, are heightened when compared to intangible long-term conservation issues (Wijedasa et al. 2013). For example, when an organization highlighting conservation issues in Malaysia reported an incident showing a picture of tourists harassing a green turtle, it generated a 405-fold increase in reaches, and caused an investigation and ultimately forced public apologies (Wijedasa et al. 2013). A week later, when the same organization reported on the illegal wildlife trade of tiger claws, it generated only a 6-fold increase in social media "reaches", as it did not spark the same emotional outrage as animal abuse (Wijedasa et al. 2013). By linking the culturally intangible issue of the destruction of a riparian reserve to the moral outrage involving a family unit of proboscis monkeys, one of Sabah's iconic species, it invoked a strong emotional response, with a threefold increase in the number of reaches, and resulted in an immediate cessation of land clearing ordered along sensitive riparian reserves along the Kinabatangan River. Furthermore, as the study site is one of the key destinations for local and international tourists to see proboscis monkeys (Fletcher 2009; Leasor and Macgregor 2014), public engagement may have been stronger than if the habitat loss had happened in a less popular area.

An issue highlighted in this case is the importance of aligning conservation with economic incentives and regulation when multiple agencies are involved. The initiative in this case study promised participants economic incentives and rubber trees to plant once the area was cleared, but there was no responsibility or accountability taken by the initiative for any laws broken. The participants were not provided with information on land use or watershed laws prior to clearing (e.g. no cutting of riparian reserves, no open burning). Once an offence was committed, there was no legal or financial support to the local landowner, despite the role of the RISDA scheme in the situation, nor was the RISDA scheme required or requested to finance the reforestation of the riparian reserve. Furthermore, past experience has shown that planting rubber trees in this region has failed due to elephant conflict with young rubber trees (*pers com*), and therefore the clearing could have been avoided altogether, not just of the riparian reserve. It is important that when initiatives like this are proposed, all relevant parties (including wildlife and forestry departments) are involved in finding the most suitable areas, and giving the participants the full information on the laws. This cooperation can maximise success as well as minimise negative effects on the environment. There must also be an agreement of who will be held responsible if a land-clearing related offence is committed. There needs to be an update in the legislation clarifying when a violation has been committed, as well as specifying the responsible party for restoring the damaged land. Furthermore, there needs to be consistency in enforcement and convictions, so that big companies are held to the same standards as the local landowners.

Riparian and floodplain forests are important habitats for proboscis monkeys (Bennett and Sebastian 1988; Matsuda et al. 2009b). To reduce the risk of predation, proboscis monkeys tend to select sleeping sites close to rivers as protection, reducing the area they need to guard from predators (Matsuda et al. 2011; Thiry et al. 2016). This is particularly the case for groups with vulnerable or small individuals, that is, reproductively active groups (such as the focal group of this study), as opposed to all-male groups (Thiry et al. 2016). The removal of trees changes the composition and structure of both edge and interior forest, as well as exposes the newly created edge to different environmental conditions (Broadbent et al. 2008). Furthermore, while some mammal species avoid edge habitats, others such as the Sunda clouded leopard (*Neofelis diardi borneensis*) increase their relative habitat use near edge habitats (Brodie et al. 2015). The Sunda clouded leopard is one of the main predators of proboscis monkeys (Matsuda et al. 2011), and therefore increased edges could potentially also increase the risk of predation events.

The loss of the riparian zone is not only detrimental to the particular proboscis monkey troop whose home range was partially destroyed in this study, but has overarching deleterious effects on the ecosystem as a whole. Despite widespread concerns about the negative effects of riparian zone destruction, forestry practices are still increasing in intensity in order to meet global demand (Laudon et al. 2011; Kuglerová et al. 2014). The heightened rate of habitat loss means that traditional research studies are often too slow to prevent habitat alteration. By providing compelling research and visual aids, using a combination of satellite tracking and drone imagery, rapid responses by authorities and policy makers can be more effective when dealing with time-sensitive issues. Furthermore, the awareness raised using these means can also identify the need to update policies to identify responsible parties, and hold them accountable, should encroachment occur in the future.

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Data Availability

All relevant data are within the paper and its Supporting Information files.

Conflict of Interest

The authors declare no conflicts of interest.

References

Ancrenaz, M., B. Goossens, O. Gimenez, A. Sawang, and I. Lackman-Ancrenaz. 2004. Determination of ape distribution and population size using ground and aerial surveys: a case study with orang-utans in lower Kinabatangan, Sabah, Malaysia. *Anim. Conserv.* **7**, 375–385.

Bennett, E. L. 1988. Environmental correlates of ranging behaviour in the banded langur *Presbytis melalophos*. *Folia Primatol.* **47**, 26–38.

Bennett, E. L., and A. C. Sebastian. 1988. Social organization and ecology of proboscis monkeys (*Nasalis larvatus*) in mixed coastal forest in Sarawak. *Int. J. Primatol.* **9**, 233–255.

Bernard, H., and H. Zulhazman. 2006. Population size and distribution of the proboscis monkey (*Nasalis larvatus*) in the Klias Peninsula, Sabah, Malaysia. *Malayan Nat. J.* **59**, 1531–1563.

Bernard, H., I. Matsuda, G. Hanya, and A. H. Ahmad. 2010. Characteristics of night sleeping trees of proboscis monkeys (*Nasalis larvatus*) in Sabah, Malaysia. *Int. J. Primatol.* **32**, 259–267.

Blinn, C. R., and M. A. Kilgore. 2001. Riparian management practices: a summary of state guidelines. *J. Forest.* **99**, 11–17.

Borneo Post. 2015. Iconic species for eco-tourism loses more habitat in Kinabatangan. *Borneo Post*. Available at: http://www.theborneopost.com/2015/07/30/iconic-species-for-eco-tourism-loses-more-habitat-in-kinabatangan/ (Accessed October 24, 2016).

Broadbent, E. N., G. P. Asner, M. Keller, D. E. Knapp, P. J. C. Oliveira, and J. N. Silva. 2008. Forest fragmentation and edge effects from deforestation and selective logging in the Brazilian Amazon. *Biol. Cons.* **141**, 1745–1757.

Brodie, J. F., A. J. Giordano, and L. Ambu. 2015. Differential responses of large mammals to logging and edge effects. *Mamm. Biol.* **80**, 7–13.

Butchart, S. H. M., M. Walpole, B. Collen, A. van Strien, J. P. W. Scharlemann, R. E. A. Almond, et al. 2010. Global diversity: indicators of recent declines. *Science* **328**, 1164–1168.

Chabot, D., and D. M. Bird. 2015. Wildlife research and management methods in the 21st century: where do unmanned aircraft fit in? *J. Unmanned Veh. Syst.* **3**, 137–155.

Coulter, L., D. Stow, Y. H. Tsai, C. Chavis, C. Lippit, G. Fraley, et al. 2012. Automated detection of people and vehicles in natural environments using high temporal resolution airborne remote sensing. In Proceedings of the ASPRS 2012 Annual Conference. Scramento, California, USA, March 19–23, 2012.

Daily Express. 2015. *New riparian reserves cleared in the heart of Sukau*. Daily Express. Available at: http://www.dailyexpress.com.my/news.cfm?NewsID=101608 (Accessed October 26, 2016).

Dufour, S., I. Bernez, J. Betbeder, S. Corgne, L. Hubert-Moy, J. Nabucet, et al. 2013. Monitoring restored riparian vegetation: how can recent developments in remote sensing sciences help? *Knowl. Manage. Aquat. Ecosyst.* **410**, 10.

ESRI. 2011. ArcGIS Desktop: Release 10.

Estes, J. G., N. Othman, S. Ismail, M. Ancrenaz, B. Goossens, L. N. Ambu, et al. 2012. Quantity and configuration of available elephant habitat and related conservation concerns in the Lower Kinabatangan Floodplain of Sabah, Malaysia. *PLoS ONE.* **7**, e44601.

Evans, L. J., T. H. Jones, K. Pang, M. N. Evans, S. Saimin, and B. Goossens. 2015. Use of drone technology as a tool for behavioral research: a case study of crocodilian nesting. *Herpetol. Conserv. Biol.* **10**, 90–98.

Fernandes, M. R., F. C. Aguiar, and M. T. Ferreira. 2011. Assessing riparian vegetation structure and the influence of land use using landscape metrics and geostatistical tools. *Landscape Urban Plan.* **99**, 166–177.

Fletcher, C. J., 2009. Conservation, livelihoods and the role of tourist: a case study of Sukau village in the Lower Kinabatangan District, Sabah, Malaysia. MSc Dissertation, Lincoln University.

Glasgow, H. B., J. M. Burkholder, R. E. Reed, A. J. Lewitus, and J. E. Kleinman. 2004. Real-time remote monitoring of water quality: a review of current applications, and advancements in sensor, telemetry, and computing technologies. *J. Exp. Mar. Biol. Ecol.* **300**, 409–448.

Google Earth 7.1. 2014. Sukau Village: surrounding forest, Sabah, Malaysia N5.503451 E118.288931, elevation 15M, Terrain layer. Available at: http://www.google.com/earth/index.html (Accessed July 24, 2015).

Husson, E., F. Lindgren, and F. Ecke. 2014. Assessing biomass and metal contents in riparian vegetation along a pollution gradient using an unmanned aircraft system. *Water Air Soil Pollut.* **225**, 1957.

Ivošević, B., Y. Han, Y. Cho, and O. Kwon. 2015. The use of conservation drones in ecology and wildlife research. *J. Ecol. Environ.* **38**, 113–118.

Koh, L. P., and S. A. Wich. 2012. Dawn of drone ecology: low-cost autonomous aerial vehicles for conservation. *Trop. Conserv. Sci.* **5**, 121–132.

Kuglerová, L., A. Ågren, R. Jansson, and H. Laudon. 2014. Towards optimizing riparian buffer zones: ecological and biogeochemical implications for forest management. *For. Ecol. Manage.* **334**, 74–84.

Kwan, B. K. Y., J. H. Y. Cheung, A. C. K. Law, S. G. Cheung, and P. K. S. Shin. 2016. Conservation education program for threatened Asian horseshoe crabs: a step towards reducing community apathy to environmental conservation. *J. Nat. Conserv.* **35**, 53–65.

Laudon, H., R. A. Sponseller, R. W. Lucas, M. N. Futter, G. Egnell, K. Bishop, et al. 2011. Consequences of more intensive forestry for the sustainable management of forest soils and waters. *Forests* **2**, 243–260.

Leasor, H. C., and O. J. Macgregor. 2014. Proboscis monkey tourism: can we make it "ecotourism"? in A. E. Russon and J. Wallis, eds. *Primate tourism: a tool for conservation?*. Cambridge University Press.

Lee, P., C. Smyth, and S. Boutin. 2004. Quantitative review of riparian buffer width guidelines from Canada and the United States. *Environ. Manage.* **70**, 165–180.

Linchant, J., J. Lisein, J. Semeki, P. Lejeune, and C. Vermeulen. 2015. Are unmanned aircraft systems (UASs) the future of wildlife monitoring? A review of accomplishments and challenges. *Mamm. Rev.* **45**, 239–252.

Lo, A. Y., A. T. Chow, and S. M. Cheung. 2012. Significance of perceived social expectation and implications to conservation education: turtle conservation as a case study. *Environ. Manage.* **50**, 900–913.

Manyangadze, T. 2009. Forest fire detection for near real-time monitoring using geostationary satellites. MSc Dissertation, International Institute for Geo-Information Science and Earth Observation Enschede, The Netherlands.

Matsuda, I., A. Tuuga, and S. Higashi. 2009a. Ranging behavior of proboscis monkeys in a riverine forest with special reference to ranging in inland forest. *Int. J. Primatol.* **30**, 313–325.

Matsuda, I., A. Tuuga, and S. Higashi. 2009b. The feeding ecology and activity budget of proboscis monkeys. *Am. J. Primatol.* **71**, 478–492.

Matsuda, I., A. Tuuga, and H. Bernard. 2011. Riverine refuging by proboscis monkeys (*Nasalis larvatus*) and sympatric primates: implications for adaptive benefits of the riverine habitat. *Mamm. Biol.* **76**, 165–171.

Meijaard, E., and V. Nijman. 2000. Distribution and conservation of the proboscis monkey (*Nasalis larvatus*) in Kalimantan, Indonesia. *Biol. Cons.* **95**, 15–24.

Meijaard, E., V. Nijman, and J. Supriatna. 2008. *Nasalis larvatus*. IUCN Red List of Threatened Species, Version 2010.4. Available at: www.iucnredlist.org. (Accessed September 30, 2015).

Naiman, R. J., H. Decamps, and M. Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. *Ecol. Appl.* **3**, 209–212.

Navarro, G., I. E. Huertas, E. Costas, S. Flecha, M. Díez-Minguito, I. Caballero, et al. 2012. Use of a real-time remote monitoring network (RTRM) to characterize the Guadalquivir Estuary (Spain). *Sensors* **12**, 1398–1421.

Nghiem, L. T. P., E. L. Webb, and L. R. Carrasco. 2012. Saving Vietnam's wildlife through social media. *Science* **338**, 10–12.

Nilsson, C., and K. Berggren. 2000. Alterations of riparian ecosystems caused by river regulation. *Bioscience* **50**, 783–792.

Paneque-Gálvez, J., M. K. McCall, B. M. Napoletano, S. A. Wich, and L. P. Koh. 2014. Small drones for community-based forest monitoring: an assessment of their feasibility and potential in tropical areas. *Forests* **5**, 1481–1507.

Phillips, O. L., P. Hall, A. H. Gentry, S. A. Sawyer, and R. Vásquez. 1994. Dynamics and species richness of tropical rain forests. *Proc. Natl Acad. Sci. USA* **91**, 2805–2809.

Sabah Forestry Department. 2016. Felling of tree case in the riparian reserve (State Land) near Kg. Sukau in Kinabatangan District on 21/07/2015: Prosecution To Proceed. Sabah Forestry Department. Available at: http://www.forest.sabah.gov.my/media-centre/broadcast/press-release/524-tree-felling-case-in-riparian-zone-kgsukau-kinabatangan (Accessed October 26, 2016).

Sabah State Government. 1998. *Sabah Water Resources Enactment*. Kota Kinabalu.

Sabah Land Ordinance (ver 2013). *State of Sabah Land Ordinance (Sabah Cap. 68)*. Land Ordinance.

Salter, R. E., N. A. MacKenzie, N. Nightingale, K. M. Aken, and P. P. K. Chai. 1985. Habitat use, ranging behaviour, and food habits of the proboscis monkey, *Nasalis larvatus* (van Wurmb), Sarawak. *Primates* **26**, 436–451.

Schweiger, A. K., M. Schütz, P. Anderwald, M. E. Schaepman, M. Kneubühler, R. Haller, et al. 2015. Foraging ecology of three sympatric ungulate species – behavioural and resource maps indicate differences between chamois, ibex and red deer. *Mov. Ecol.* **3**, 1–12.

Sha, J. C. M., H. Bernard, and S. Nathan. 2008. Status and conservation of proboscis monkeys (*Nasalis larvatus*) in Sabah, East Malaysia. *Prim. Conserv.* **23**, 107–120.

Spackman, S. C., and J. W. Hughes. 1995. Assessment of minimum stream corridor width for biological conservation: species richness and distribution along mid-order streams in Vermont, USA. *Biol. Cons.* **71**, 325–332.

Stark, D. J., I. P. Vaughan, D. A. Ramirez Saldivar, S. K. S. S. Nathan, and B. Goossens. 2017. Evaluating methods for estimating home ranges using GPS collars: a comparison using proboscis monkeys (*Nasalis larvatus*). *PLoS ONE* **12**, e0174891.

The Star. 2015. *Sabah halts land clearing at habitat of proboscis monkey*. The Star, Available at: http://www.thestar.com.my/news/nation/2015/07/31/rape-of-riparian-reserves-sabah-halts-land-clearing-at-habitat-of-proboscis-monkey/ (Accessed October 26, 2016).

Thiry, V., D. J. Stark, B. Goossens, J.-L. Slachmuylder, R. Vercauteren Drubbel, and M. Vercauteren. 2016. Use and selection of sleeping sites by proboscis monkeys, *Nasalis larvatus* along the Kinabatangan River, Sabah, Malaysia. *Folia Primatol.* **87**, 180–196.

Wall, J., G. Wittemyer, B. Klinkenberg, and I. Douglas-Hamilton. 2014. Novel opportunities for wildlife conservation and research with real-time monitoring. *Ecol. Appl.* **24**, 593–601.

Wijedasa, L. S., S. A. Aziz, A. Campos-Arceiz, and G. R. Clements. 2013. Opinion: does social media "like" conservation? *Sci.* Online magazine, April 8 2013; Available at http://www.the-scientist.com/?articles.view/articleNo/34852/title/Opinion–Does-Social-Media–Like–Conservation-/ (Accessed October 27, 2016).

Yeager, C. P., and T. K. Blondal. 1992. Conservation status of the proboscis monkey (*N. larvatus*) at Tanjung Putting National Park, Kalimantan Tengah, Indonesia. Pp. 220–228 in G. Ismail, M. Mohamed, S. Omar, eds. *Forest Biology and Conservation in Borneo, Center for Borneo Studies Publication No. 2*, Kota Kinabalu.

Supporting Information

Additional supporting information may be found online in the supporting information tab for this article.

Figure S1. The forested area surveyed by the fixed-wing drone (light green) with corresponding pre-logged images in 2012 (grey) and the logged areas detected by the drone images in 2015 (dark).

Table S1. Compositition of the number of GPS fixes per day that were located in areas that subsequently cleared in 2015 (N = 566 fixes; 123 days).

