

Estimating colony size of the wrinkle-lipped bat, *Chaerophon plicatus* (Chiroptera: Molossidae) at Gomantong, Sabah, by quantitative image analysis

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The Gomantong cave system, Kinabatangan, Sabah (Malaysia) hosts one of the largest bat colonies known from north Borneo. The nightly exodus of *Chaerophon plicatus* from this site is an economically valuable tourist attraction, and must impose significant controls on the regional ecology. Monitoring ecosystem health requires monitoring bat population size, but no quantitative assessments for the Gomantong colony are available in the literature. Traditional censusing techniques (based on packing density and roost area or on roost exodus counts) yield notoriously unreliable results. Here we have applied innovative image analysis and counting techniques to videographic, photographic and terrestrial laser scanning data obtained in July 2012. The colony exits in a consistent stream along a narrow exit trajectory. The laser scanning of the large cave entrance allowed precise measurement of bat position. Video data provided 0.02-second time resolution. Average flight speed was calculated (10.38 ± 0.85 m/sec), bat exit rate was estimated at three minute intervals (peaking at 14,000 bats/minute) and then summed over the 40 minutes of bat flight. The resultant colony size estimate of 275,625–276,939 (95% confidence interval) individuals of *C. plicatus* in Gomantong Caves in 2012 demonstrates that the technique is viable, provides a realistic basis for ecosystem management, and can be repeated to monitor ecosystem change. The estimated insect consumption by the colony of this size is 927 ± 191 metric tons of insects per year over an estimated 270 km² area, a very important component in maintaining ecosystem stability in the Gomantong Forest Reserve and the Kinabatangan Wildlife Sanctuary, as well as pest control over the large agricultural tracts of the region.

Key words: Borneo, Kinabatangan, bats, caves, colony size, image analysis, terrestrial laser scanning

INTRODUCTION

Chaerophon plicatus (family Molossidae, subfamily Molossinae) is a widely distributed bat throughout lowland South Asia and Southeast Asia, from India east to the Philippines and south to Lombok (Heaney *et al.*, 1998; Molur *et al.*, 2002). The species is a facultative cave-dweller, and in suitable locations forms very large cave colonies. In northern Borneo, spectacularly large colonies are well-known from Simud Hitam Cave (Gomantong Forest Reserve, Sabah — Fig. 1) and Deer Cave (Mulu National Park, Sarawak). A formerly very large colony, now much reduced, occupies Niah Cave (Niah National Park, Sarawak — Medway, 1958; Struebig *et al.*, 2010). Foraging areas have not been explicitly measured for this species, but by analogy to the North American member of the

same subfamily — *Tadarida brasiliensis* (Ammerman *et al.*, 2012) which has measured nightly foraging ranges averaging 41 km around the Carlsbad Caverns (New Mexico) colony (Best and Geluso, 2003).

It can be presumed that major *C. plicatus* colonies are top insect predators over very large expanses of lowland rainforest and agricultural mosaics. These colonies feed on some nine kg of insect prey per 1,000 bats per night (based on mass scaled feeding rates of *T. brasiliensis* from Kunz *et al.*, 1995; *C. plicatus* mean body mass of 15.5 g from Leelapaibul *et al.*, 2005 versus 12.3 g for *T. brasiliensis* from Wilkins, 1989), and their accumulated guano supports rich subterranean ecosystems (Chapman, 1983) including a number of endemic species (Ng, 1991; McFarlane *et al.*, 2009).

Techniques for censusing bat colonies are reviewed in Kunz *et al.* (2009). Large cave roosting colonies of molossid bats, especially *T. brasiliensis* which forms very large colonies across the American southwest, have traditionally been counted either by assessments of roost (cave ceiling) area multiplied by packing density, or by roost exodus counts (usually photographic — e.g., Humphrey, 1971 or videographic — e.g., Miller *et al.*, 1988). These types of assessments have a long history, beginning around 1937 (Allison, 1937), but have been fraught with problems. For example, early estimates of ca. 25 million *T. brasiliensis* in the summer breeding colony within Eagle Creek Cave, Arizona, were exaggerated by an order of magnitude, apparently due to the cave being recorded as 96 m in

length, rather than the correct 57.3 m (McFarlane and Keeler, 1990). A more realistic colony size assessment in 1969 led to an erroneous but widely-read and influential report on the apparent 99.9% collapse in colony size (Cockrum, 1970). Similarly, an unrealistic estimate of the density of the flight column leaving Carlsbad Caverns (New Mexico, USA) produced a much-quoted but quite erroneous estimate of nine million individuals in 1936 (Allison, 1937). As demonstrated by Betke *et al.* (2008) and Hristov *et al.* (2008), the correct figure can be shown to be between 600,000 and 800,000. Indeed, Betke *et al.* (2008) have shown that in the five major *T. brasiliensis* caves they studied with thermal imaging counts, all had significantly overestimated colony sizes reported in early reports, in some cases

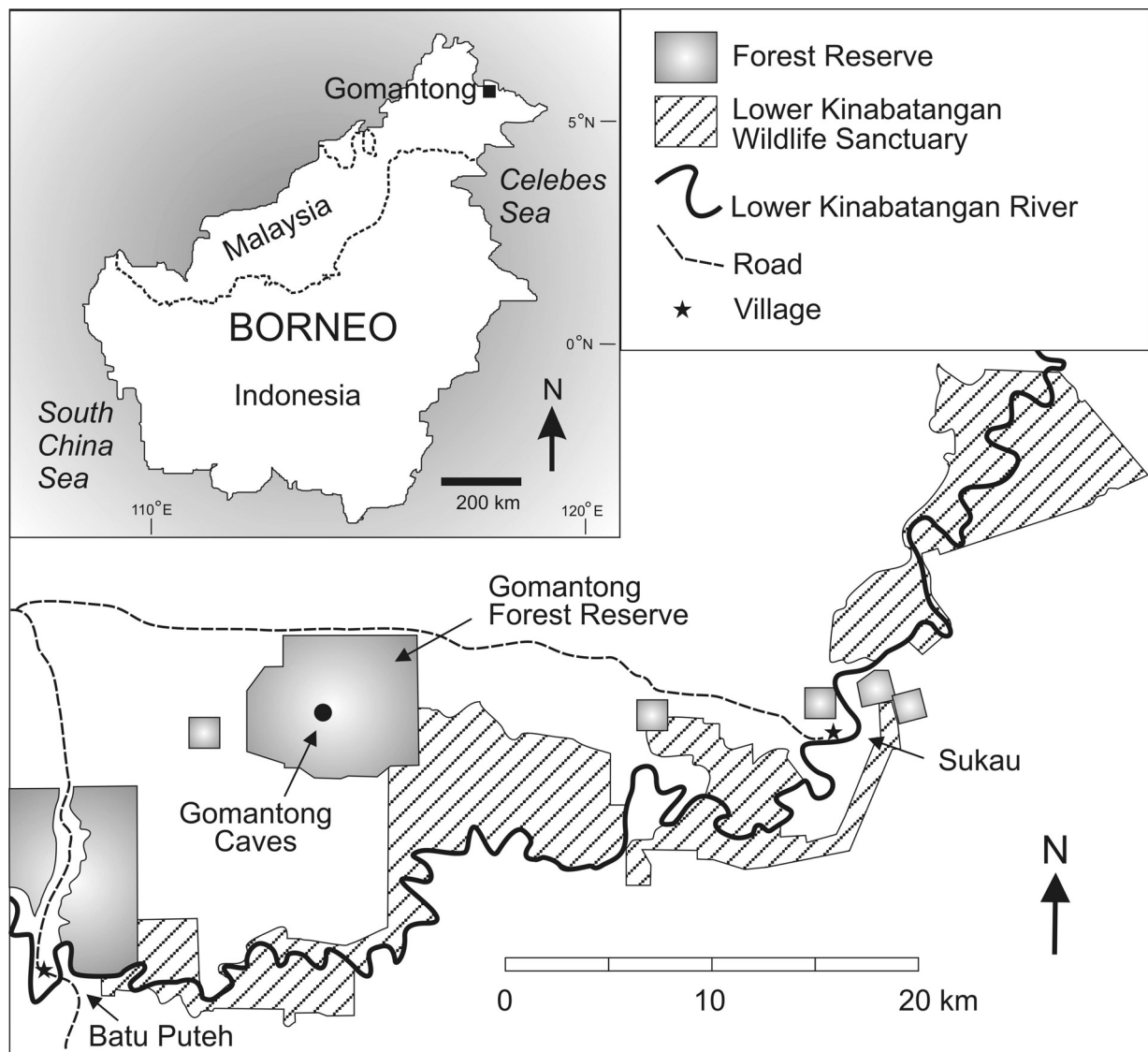


FIG. 1. Location map showing the Gomantong caves and their relationship to the Kinabatangan protected areas

by more than an order of magnitude. Quantitative image analysis (e.g., Hallam *et al.*, 2010) provides a new level of precision for large bat colony assessment, and is applied here to generate the first true colony size estimate for a Bornean cave.

The Gomantong caves have an informally reported bat diversity of 12 species (Abdullah *et al.*, 2007), the majority of which are present in small numbers or do not co-roost with *C. plicatus*. The colony of *C. plicatus* which roosts at Gomantong has been described in popular media as numbering ‘600,000–2 million’ (Abdullah *et al.*, 2005), but has never been quantitatively assessed. Here we provide the first such assessment, based on replicable photographic methods, and briefly consider the impact of the colony on the local environment.

MATERIALS AND METHODS

Gomantong Forest Reserve is a 51 km² lowland dipterocarp forest that is the largest intact component of the 260 km² Kinabatangan Wildlife sanctuary. Most of the remainder of the Lower Kinabatangan River drainage area has been converted to oil palm cultivation. The central feature of the Gomantong Forest Reserve is a 228 m high limestone hill containing the Gomantong caves. Simud Hitam (5.530550N, 118.071734E) is the lower of the two main caves, which total some 2.03 kms of passage. A large colony of *C. plicatus* roosts in a blind-ending fissure passage, locally named Hagob Kabilau (Wilford, 1964), within Simud Hitam cave, Gomantong (Fig. 1). Significant numbers of *C. plicatus* do not roost elsewhere at Gomantong, and the Hagob Kabilau roost is shared with only comparatively small numbers of *Rhinolophus philippinensis* and *Hipposideros cervinus*. This colony begins exiting the roost approximately an hour before sunset (18:26 hrs local time), flies in an anti-clockwise spiral pattern within the ‘Great Lighthole’, and finally leaves the lighthole in a consistent stream passing east of the Lobing Payau entrance (Fig. 2). The bat flight was recorded as high-definition video in both July 2012, and again in July 2014. Cameras used were a Sony HDR-HC1E and Canon Legria Hv40, 1080i (2012), and a Canon XA20 1080p (2014), the latter providing the highest resolution, non-interlaced, 50 frames per second recording. Cameras were positioned to silhouette the bats against the sky, and artificial illumination was not required. The 2014, 1080p, data were used for bat speed calculations, but did not record the full bat flight. Research was conducted under the auspices of the Forestry Department (Sabah), and the Sabah Biodiversity Center.

Geometry, physical access and the large scale of the cave entrance precluded precise determination and scaling of the camera-to-bats position in the field. However, Simud Hitam cave was documented by terrestrial laser scanning (TLS) in 2012, with additional work in 2014, using a Faro3D TLS scanner operating a 1/4 resolution and producing centimeter-scale resolution (McFarlane *et al.*, 2013). By matching the 2014 video frame imagery to the TLS 3D triangulated irregular network (TIN) mesh model in Blender v2.73 software (www.blender.org) the video camera locations were matched to the TIN model. Blender was then used to circumscribe a virtual ‘flight box’ of precise dimensions through which the exiting bat stream passes

(Fig. 3). The 1080p, 50 frames/second recording rate provides a sequence of time slices of 0.02 s in duration. Individual bats can be traced through successive frames imaging a 5.0 m long ‘flight box’ (up to 5.3 m for more distant trajectories due to perspective), to derive transit time. We used a Monte-Carlo approach to determine random flight distances in the range 5.0–5.3 m for 100 simulations, and calculated flight speed as:

$$V = 1/(T/D)$$

where T is the transit time (frames per second) and D the randomized flight box length.

To then assess the number of bats exiting the cave per unit time, stills from the video footage from 2012 were scaled using the wingspan of the bats visible in high-resolution still photography of the same scene. Wilkins (1989) measured the forearm length of *T. brasiliensis* to be 42.3 ± 2.8 mm, with a wingspan of 300.6 mm. *Chaerephon plicatus* has a forearm length of 40–43.5 mm (Payne and Francis, 1985); we assume an in-flight wingspan of 300 mm for *C. plicatus* in this study, consistent with a value of 317 ± 13 mm given by Leelapaibul (2003) for the species in Thailand. Scaled video images were used to establish a virtual flight box, and the bat exit rate was calculated as:

$$E_x = N_{\text{bats}}/(L_{\text{path}}/F_{\text{speed}})$$

where E_x is the exit rate in bats/second, N_{bats} is the number of bats observed in the counting frame, L_{path} is the length of the flight path enclosed in the counting frame, and F_{speed} is the flight speed of the bats.

Recording was started approximately 10 minutes before the start of the bat exodus (18:15 hrs local time) and continued for some ten minutes after the end of the exodus (19:15 hrs local time). Exit rate was averaged for three consecutive frames, at three-minute intervals during the entire bat flight (ca. 40 minutes). For the final estimate of total bat colony size, we combined flight speed error and bat counting errors according to standard error propagation theory (Zar, 2010) to derive a mean and standard deviation on bat exit rate for each minute of the total flight, and totaled these to find colony size.

RESULTS

Camera to center-of-bat-flight-column distance was determined to be 41.94 m. Flight speed for 12 individual bats passing through the 5.0–5.3 m virtual flight box was 10.38 ± 0.85 m/s (± 1SD), which is marginally faster though entirely consistent with very precise measurements of 9.38 ± 0.02 m/s (± 1SD) for the slightly smaller *T. brasiliensis* imaged exiting a Texas cave reported by Theriault *et al.* (2010), and somewhat slower than the estimated 11 m/s (no quoted SD) reported for *T. brasiliensis* by Best and Geluso (2003). Exit rate generally rises with time, peaking 40 minutes into the flight and then dropping precipitously to zero (Fig. 4). Standard error of the mean exit rate varies from 18 to 202 bats/minute. The mean estimate of the size of the bat colony exiting the cave on 17th July 2012 was 276,282 ± 335 (± 1 SE), or 275,625–276,939 individuals (95% confidence limits).

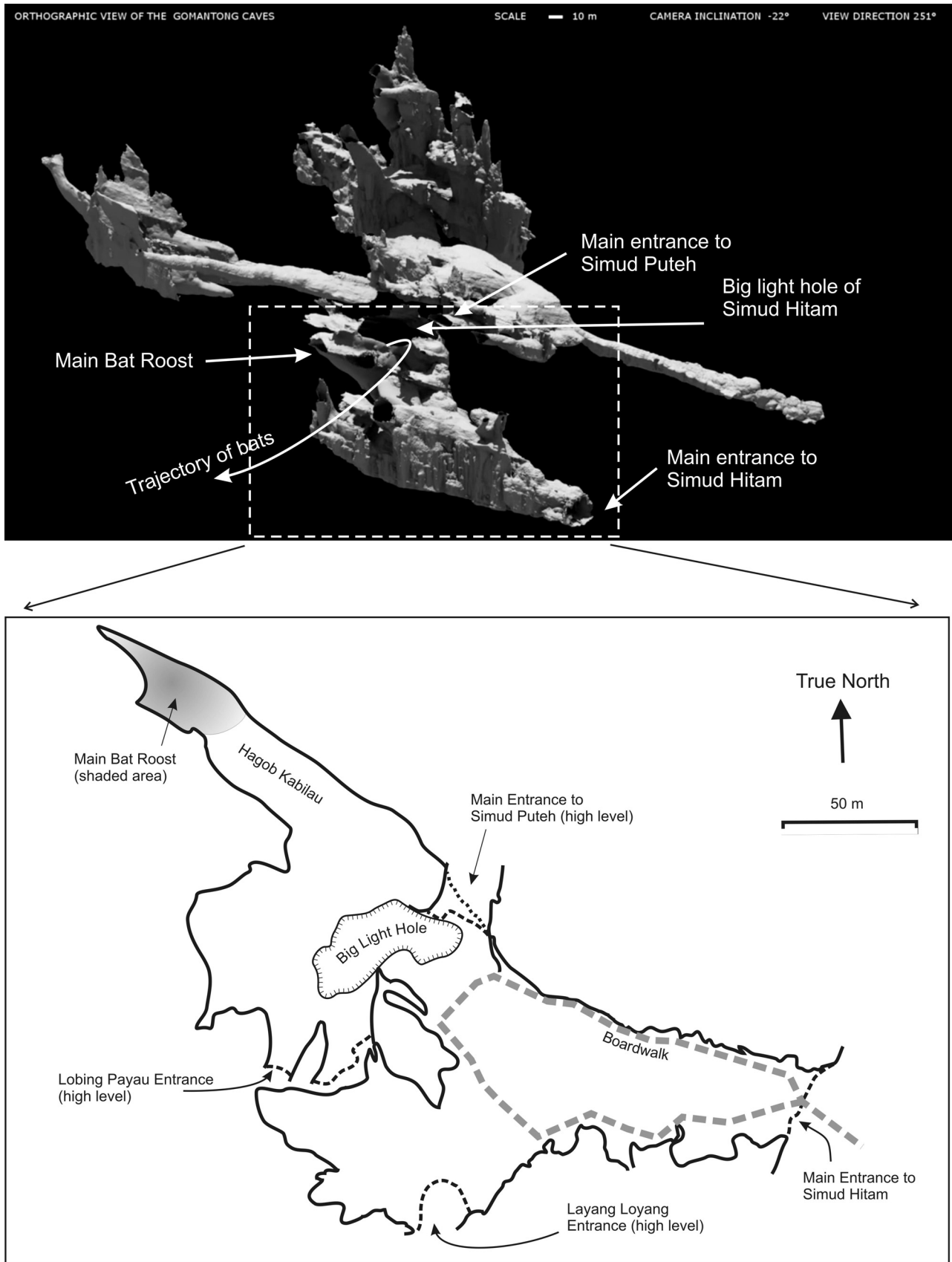


FIG. 2. Three dimensional model of Simud Hitam, showing the bat flight path (data from terrestrial laser scanning — McFarlane *et al.*, 2013) aligned with plan view of the cave (modified from cartography by GVR)

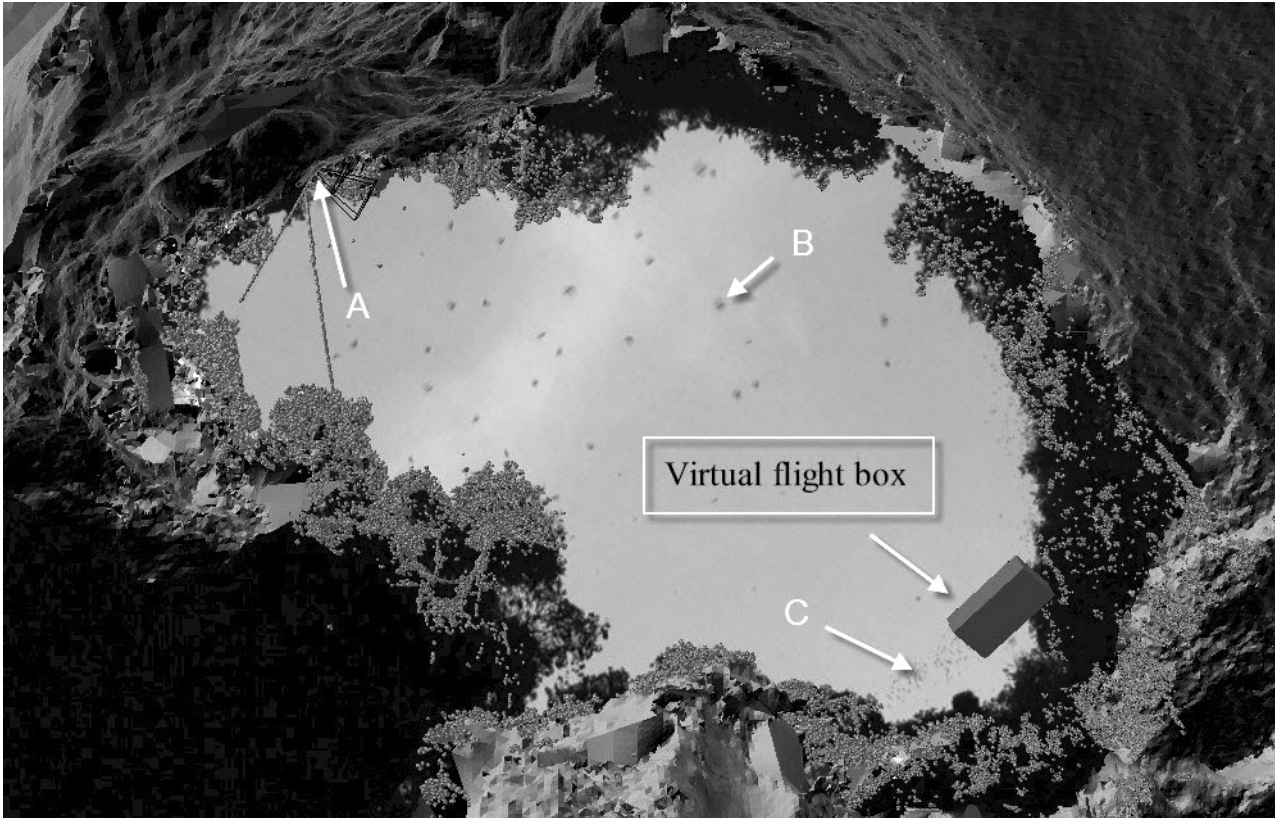


FIG. 3. Virtual ‘flight box’ developed from terrestrial laser scanning model, seen in vertical (upwards) view of the Great Light Hole, Simud Hitam. A — denotes the camera’s position, B — swiftlets in flight, and C — bats exiting the virtual flight box

DISCUSSION

Current state-of-the-art bat exodus counting techniques involving thermal imaging devices can provide extremely accurate counts under suitable conditions (e.g., Hristov *et al.*, 2008). However, they are limited by the high cost of the devices (> Euro 40,000) and low resolution (typically around 15% of the resolution of standard 1080p video) which constrains their use to situations in which the devices can be placed in relatively close proximity to the cave entrance. Our technique utilizes low cost (< Euro 1,000) universally-available digital video or camera equipment which has the added benefit of high resolution and greater flexibility in camera placement. In this study we utilized terrestrial laser scanning data to retrospectively determine camera-to-bat distances, but this information could equally well be obtained with a simple laser distance meter (< Euro 100). The limitations of our technique are lower counting precision ($\pm 1\%$), and potential problems with imaging when the bat flight extends into complete darkness, as is common in smaller bat colonies.

The colony size estimate presented here is based on a single day’s bat flight. Hristov *et al.* (2010) have shown that cave molossid counts can show significant variation between days, especially when weather conditions are unfavorable and fewer bats leave the roost. However, on 17th July 2012, we

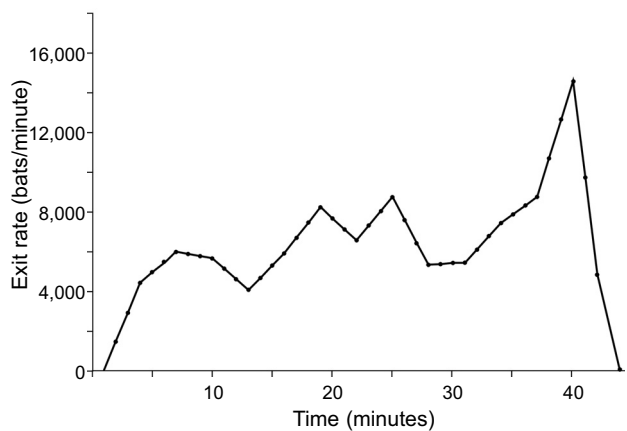


FIG. 4. Exit rate of *C. plicatus* at Gomantong, 17th July 2012, plotted with a three-point moving average against elapsed time. Local time at 0 minutes bat flight was 18:23 hrs

examined the interior of the roost thoroughly after the bats had left and determined that the colony had fully exited, so that our estimate is not compromised by an incomplete exodus.

Our quantitative count of the *C. plicatus* colony in Simud Hitam is substantially smaller than widely-disseminated anecdotal estimates ranging as high as two million individuals. In this respect, our results mirror comparable studies of *T. brasiliensis* in the southwestern USA which have been routinely overestimated in almost all cases (McCracken, 2003; Betke *et al.*, 2008). Nevertheless, the significance of the Simud Hitam colony should not be underestimated.

The colony of ca. 790,000 *T. brasiliensis* in Carlsbad Caverns, USA (Hristov *et al.*, 2010) are known to forage over an area of some 2.5×10^3 km² (based on a 41 km linear foraging radius reported by Best and Geluso, 2003, and conservatively assuming a semi-circular range centered on the cave). The Simud Hitam *C. plicatus* colony can therefore be confidently assessed to be one of the dominant insectivores over the entire 270 km² of the Kinabatangan Wildlife Sanctuary (Fig. 1), one of Sabah's most important biodiversity refugia, and well beyond over primarily oil-palm (*Elaeis guineensis*) plantations. The role of birds and/or bats in regulating herbivorous insect pests in these plantations has been experimentally demonstrated and may maintain palm fruit yields 9–26% higher than in bird/bat-excluded plots (Koh, 2008). The role of insectivorous bats as pest control agents in oil palm agricultural systems has not yet been examined, but must be presumed to be substantial, as is the case with *T. brasiliensis* and cotton agriculture in Texas, USA (Cleveland *et al.*, 2006) and rice cultivation in Thailand (Wanger *et al.*, 2014) and the Mediterranean (Puig-Montserrat *et al.*, 2015).

A number of studies address food consumption by insectivorous bats. Kunz *et al.* (1995) report nightly gross food intake for *T. brasiliensis* as $59.4 \pm 12.38\%$ of pre-ingestion body mass. Using a mean body mass of 15.5 g for *C. plicatus* (Leelapaibul *et al.*, 2005), gross nightly insect consumption is predicted to be 9.2 ± 1.9 kg live mass/1,000 bats, equivalent to some 927 ± 191 metric tons per year.

Further counts of the Simud Hitam *C. plicatus* colony in future years, taken with due attention to the determination of counting error, are warranted to establish a baseline for monitoring the ecological health of the Kinabatangan Wildlife Sanctuary. The technique presented here has general applicability

to *C. plicatus* colonies elsewhere in Southeast Asia, provided that the physical geometry of the cave entrances permit accurate scaling of the imagery.

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