Opinion

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Mapping infectious disease landscapes: unmanned aerial vehicles and epidemiology

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The potential applications of unmanned aerial vehicles (UAVs), or drones, have generated intense interest across many fields. UAVs offer the potential to collect detailed spatial information in real time at relatively low cost and are being used increasingly in conservation and ecological research. Within infectious disease epidemiology and public health research, UAVs can provide spatially and temporally accurate data critical to understanding the linkages between disease transmission and environmental factors. Using UAVs avoids many of the limitations associated with satellite data (e.g., long repeat times, cloud contamination, low spatial resolution). However, the practicalities of using UAVs for field research limit their use to specific applications and settings. UAVs fill a niche but do not replace existing remote-sensing methods.

Applications of UAVs

Increasing attention has been focused on the potential uses of UAVs. UAVs have been used for various civilian purposes ranging from law enforcement, fire fighting, and parcel delivery to wildlife population monitoring [Handwerk, B. (2013) Five surprising drone uses (besides Amazon delivery). *National Geographic* (http://news.nationalgeographic.com/news/2013/12/131202-drone-uav-uas-amazon-octocopter-bezos-science-aircraft-unmanned-robot/)] [1,2]. UAVs offer the potential to collect detailed geospatial information in real time at relatively low cost. UAVs can also be an effective method of monitoring situations too dangerous or costly for traditional aerial surveys, such as mapping forest fires and ice floes in the Arctic or conducting antipoaching patrols [Dillow, C. (2014) Drones are invading the Arctic! *CNBC* (http://www.cnbc.com/id/101417956)] [3]. These advantages have led to the application of UAVs for ecological research studies evaluating land use and cover change and conducting aerial surveys of large wild animals such as dugongs, rhinoceros, and orangutans [3–7]. Additionally, UAVs have been used in agriculture to monitor vegetation levels, crop growth, and distribution of weeds [8,9].

There are also numerous potential applications for UAVs in public health. UAVs can be used to locate people and monitor human population movements of nomadic and migrant groups to allow targeting of surveillance and public health interventions [10]. UAVs have also been used to facilitate access to and sample collection from remote locations. For example, a UAV was developed to allow the transportation of test samples from remote rural clinics to national laboratories in South Africa [11]. UAVs can also be used for disaster management and emergency relief operations to monitor situations as well as to deliver medical supplies to inaccessible or dangerous locations. During the aftermath of Typhoon Haiyan in the Philippines, UAVs were used by aid organisations to assess the extent of the typhoon damage and plan relief measures and reconstruction [Klaptocz, A. (2014) Mapping the Philippines after Typhoon Haiyan. *Drone Adventures* (http://www.droneadventures.org/2014/05/07/mapping-the-philippines-after-typhoon-haiyan/)]. Aid organisations have also started piloting the use of UAVs to deliver medical supplies to areas inaccessible by road in Haiti, the Dominican Republic, and Lesotho [Hickey, S. (2014) Humanitarian drones to deliver medical supplies to roadless areas. *The Guardian* (http://http://www.theguardian.com/world/2014/mar/30/humanitarian-drones-medical-supplies-no-roads-technology)].

UAVs can also be used to collect other types of environmental data of public health relevance. Environmental factors such as radiation and air pollution vary spatially, with important consequences for human health. Monitoring equipment has been fitted to UAVs to measure levels of environmental toxins and pollutants [12,13]. Further applications could include mapping health infrastructure, such as water and sanitation systems and locations of health facilities.

Within infectious disease epidemiology, UAVs provide a new alternative to collect detailed georeferenced information on environmental and other spatial variables

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influencing the transmission of infectious diseases. Land-use change, for example through deforestation or agricultural expansion, has been widely documented as a major driver of infectious disease emergence and spread [14–18]. Anthropogenic environmental changes can modify the transmission of zoonotic and vector-borne diseases by disrupting existing ecosystems and altering the geographic spread of human populations, animal reservoirs, and vector species [19,20]. For example, the emergence of malaria in new areas of South America and Southeast Asia has been associated with the clearing of tropical forests resulting in changes in anopheline mosquito densities and contact with people [21]. Changes in forest cover affect the life cycle and distribution of disease vectors by altering microclimates, availability of breeding sites, and ecological community structures [22]. Simultaneously, deforestation is associated with higher levels of human activity within forest environments, leading to increased exposure to forest-breeding vectors [23]. Understanding rapidly changing patterns of human settlement and vector distribution in this context is vital for predicting disease risks and effectively targeting disease-control measures.

Satellite data versus aerial data

Epidemiologists rely on accurate spatial and environmental data to describe variations in vector-borne and zoonotic disease risk, establish early warning systems, model disease transmission, and estimate disease burden [24]. These data can include detailed information on land cover, climatic variables, and distributions of human and animal populations. Geospatial data can be obtained from a range of sources, such as satellite-based remote sensing, aerial surveys, and ground-based Global Positioning System (GPS) surveys.

Satellite remote sensing is increasingly being used to obtain environmental data on land cover, vegetation, soil type, surface water, and rainfall for infectious disease research [25]. Satellite data are characterised by varying spatial, temporal, and spectral resolutions. Temporal resolution relates to the frequency with which a satellite returns to a specific location, while spectral resolution is defined by the wavelength interval size on the electromagnetic spectrum and the number of intervals measured by the satellite's sensor. Higher spectral resolution allows image classification or transformation (such as for vegetation indices) using information beyond the visible range of the electromagnetic spectrum. A new generation of sensors such as QuickBird, IKONOS, and GeoEye (http://www.digitalglobe.com) provide imagery with very high spatial resolution (<1 m) but are limited by relatively low temporal and spectral resolutions [26]. Cloud cover, a common issue in tropical areas, may also limit the usefulness of the data, particularly if an area is visited infrequently [27]. Additionally, obtaining high-resolution data can be prohibitively expensive. If data are needed for specific time points, this may require paying a premium to specifically task sensors to collect data for defined areas of interest. Effective analysis and application of satellite data also requires suitably trained personnel as well as specialised software.

More accessible to most public health programmes, satellite data from sensors such as Landsat (http://landsat.gsfc.nasa.gov/) and the Moderate Resolution Imaging Spectroradiometer (MODIS) (http://modis.gsfc.nasa.gov/) are freely available in the public domain. These sensors produce very detailed spectral data but, compared with sensors such as QuickBird, have much coarser spatial resolutions (15–60 m for Landsat, 250–1000 m for MODIS, depending on wavelength). Data from these sensors are well suited to studies of infectious diseases or disease vectors at regional, national, or subnational level that incorporate information on either land cover or other environmental variables (e.g., [28–36]). They are less well suited, however, to studies that require either very detailed environmental mapping or frequent monitoring of land use and habitat.

Alternatively, due to these limitations, many ecological studies rely on the use of aerial surveys conducted by light aircraft to monitor land cover and conduct wildlife population estimates. Aerial surveys are a standard method of estimating population sizes of large animals and can also be used to collect aerial photographs for habitat assessments [37–39]. Aerial surveys can also use light-detection and ranging (LiDAR) systems, a technology that measures distance by the reflected light from targets illuminated by lasers, to create high-resolution maps of land cover and measure canopy heights [40,41]. Studies may also utilise ground-based GPS surveys to map the distribution of human settlements and wildlife populations. To identify malaria cases and evaluate risk factors in forested areas of Vietnam, GPS surveys were conducted to identify the locations of villages and nomadic groups [42]. Both aerial and ground-based surveys can provide highly accurate information but are extremely resource intensive and may not always be feasible or affordable.

The use of UAVs can supplement other remote-sensing data used for infectious disease epidemiology. UAVs allow the mapping of small geographical areas at user-defined time points and spatial resolutions. UAVs can be used to obtain high-resolution aerial photographs as well as collect data on other variables such as elevation. Epidemiologists can respond quickly to changing disease reports to map areas immediately and as frequently as required. However, despite these advantages, the use of UAVs is not always an appropriate technology.

Case study: mapping environmental risk factors for zoonotic malaria

Between December 2013 and May 2014, we conducted 158 flights with an UAV to collect data for an epidemiological study. The flights were conducted in two study sites in Sabah, Malaysia and one site in Palawan, the Philippines. These activities were completed as part of a larger, multidisciplinary study to characterise biomedical, environmental, and social risk factors for human infection with the zoonotic malarial parasite *Plasmodium knowlesi* (http://malaria.lshtm.ac.uk/research/projects/malaria-research-epidemiology-20). Maintained by long- and pig-tailed macaques, *P. knowlesi* is an emerging pathogen likely to be affected by deforestation and changing patterns of land use resulting in increased contact between people, mosquito vectors, and wildlife reservoirs [43,44]. The study requires detailed spatial information to integrate human

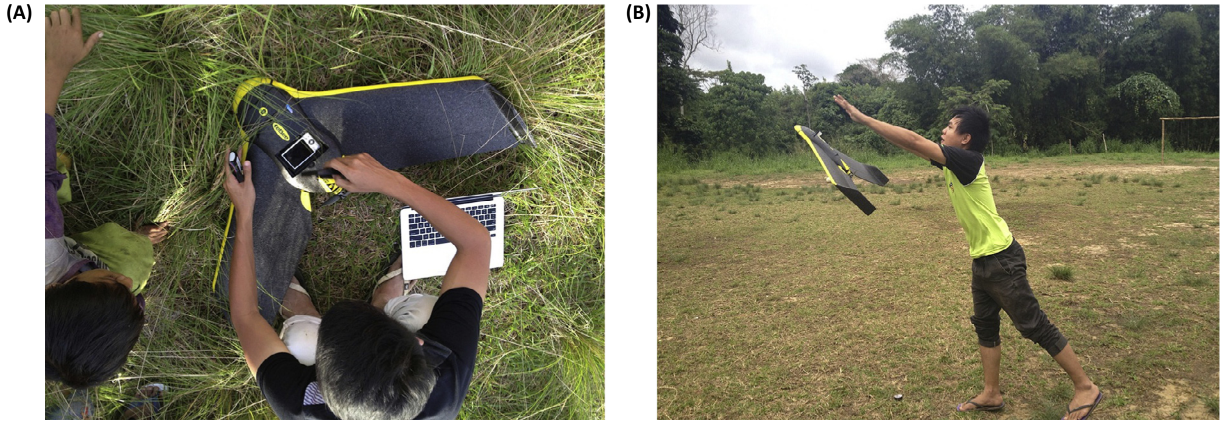

Figure 1. Use of the Sensefly eBee to map land cover in Malaysia. **(A)** Setting up the Sensefly eBee before a flight. **(B)** Launching the Sensefly eBee.

and macaque movement and vector bionomics to understand the epidemiology of infection.

The commercially available Sensefly eBee UAV was used for all mapping exercises (Sensefly, Cheseaux-Lausanne, Switzerland; Figure 1). The eBee can fly for up to 50 min and uses a 16-megapixel digital camera to record aerial images, which can be used to produce maps and digital surface models. All UAV flight plans were programmed and monitored using eMotion2 software (Sensefly, Cheseaux-Lausanne, Switzerland) and post-flight image processing was completed using Postflight Terra 3D (Pix4D SA, Lausanne, Switzerland). ArcGIS (ESRI, Redlands, USA) was used for data analysis and generation of 3D models (Figure 2). Previews of aerial photographs and digital surface models were generated in real time, while full data processing took several hours.

Within the study sites, the eBee was flown at approximately 350–400 m above the take-off point. Publicly available digital elevation data from the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM; http://www.jspacesystems.or.jp/ersdac/GDEM/E/index.html) was used to develop flight plans. Of 158 flights, 127 (80%) generated usable data. The most common reasons for failed flights were high winds, rain, and battery failure. Of these flights, six (5%) were obscured by low clouds and needed to be repeated. The average area covered by a single flight was 124 hectares (1.24 km^2) with an image overlap of 80–90% and an average resolution of 11.22 cm per pixel. Mapping exercises were conducted on 26 days between December 2013 and May 2014, with repeated flights over areas identified as having high rates of land-use change (Figure 3). The resulting maps were overlaid with GPS data on locations of households and malaria cases and used to characterise land-use types and create a spatial sampling frame for further sampling (Figure 4) [45].

Benefits of UAV mapping

For this project, spatially and temporally detailed data on the dynamics of land use and land cover are required to explore interactions between environmental factors,

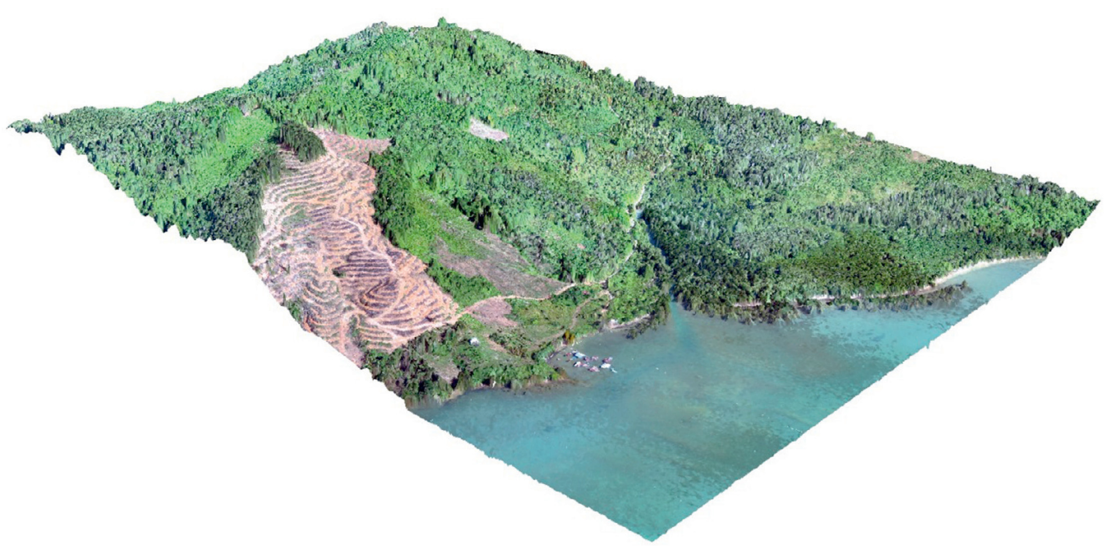

Figure 2. 3D model of the study site in Sabah, Malaysia.

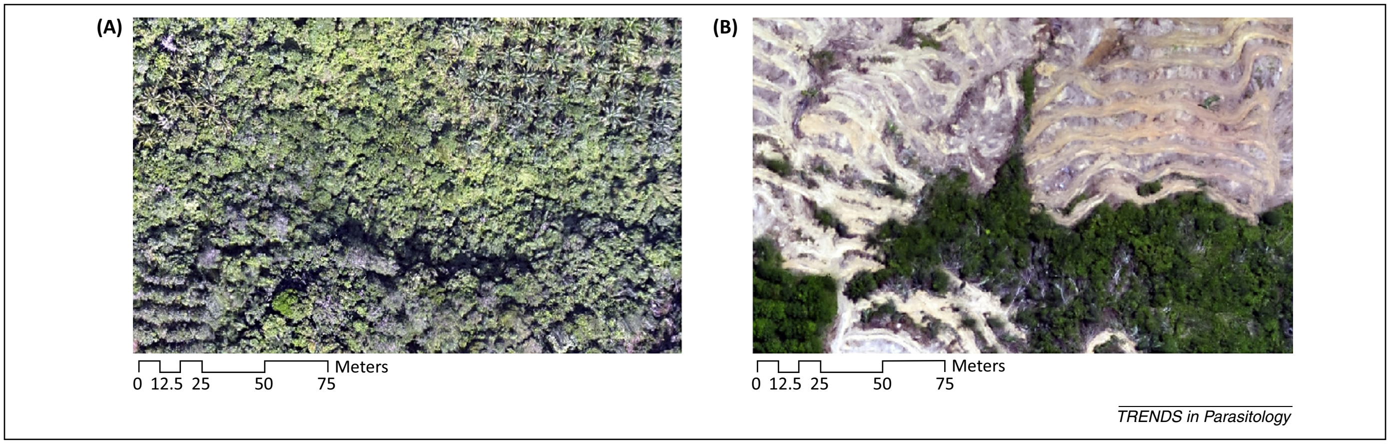

Figure 3. Mapping changes to land cover at the study site in Sabah, Malaysia. **(A)** Study site in February 2014. **(B)** Same study site in May 2014 after the start of clearing to create a rubber plantation.

disease vectors, and human and primate hosts in the light of increasing disease transmission. As is commonly the case in tropical settings, it proved impossible to obtain recent cloud-free satellite data for our field sites via the archives of satellite-data providers. Images on Google Earth (http://www.earth.google.com), which uses data from the same archives, were out of date and inadequate for characterising the study site (for example, large-scale clearings at one study site appeared as intact forest in Google Earth). The paucity of available satellite data and lack of certainty in the ability to obtain data for key time points moving forward were the principal reasons for electing to conduct land-cover/land-use mapping using an UAV.

Data from UAVs share many of the characteristics of high-resolution satellite data, although in the case of UAVs the user has more control over the spatial resolution of the resulting images (depending on flight altitude, images from UAVs typically have a spatial resolution of 4–20 cm; currently, the highest spatial resolution available from commercial high-resolution satellite sensors is 41 cm). As with satellite data, UAVs can produce 'stereo' images that, using

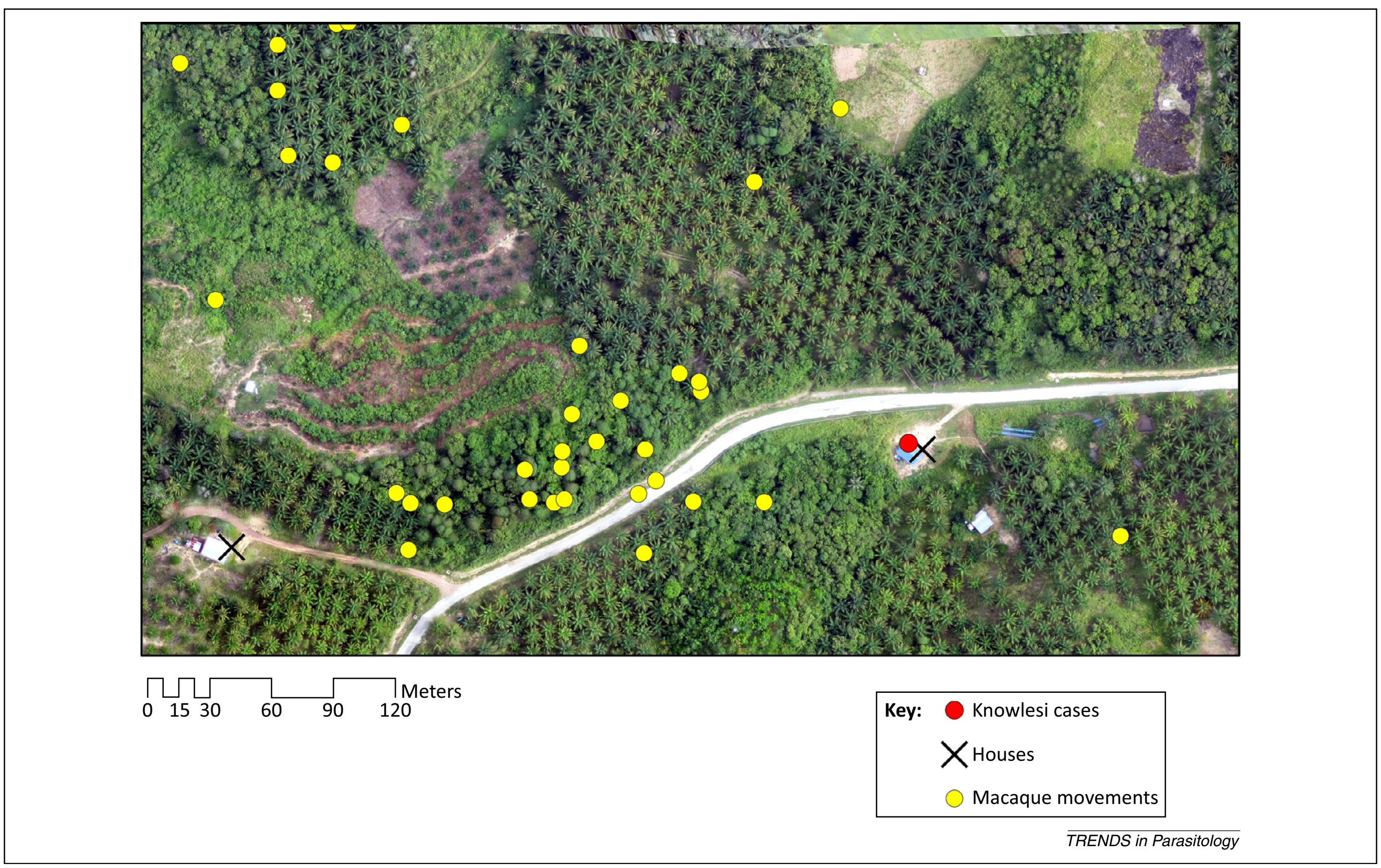

Figure 4. Macaque movements around human *Plasmodium knowlesi* case household.

standard photogrammetric tools, can be used for DEM generation, 3D visualization, and feature extraction.

One of the main benefits of using UAVs is the ability to obtain data in real time and to repeatedly map areas of interest as frequently as required. In one of our sites in Sabah, development began on clearing secondary forest to establish a rubber plantation. As the clearing occurred within a limited geographical area, the progress of the clearing and the resulting land changes could be mapped quickly and updated routinely. This ability to map changes as they occur is critical for understanding how land-use change affects the distribution of human populations and disease vectors.

Depending on the size of the area to be covered and the resolution of data needed, the costs of purchasing and operating an UAV can compare favourably with purchasing high-resolution satellite data over repeated time points. A wide range of UAV models is available, with low-cost options like the Conservation Drone available for several hundred dollars and high-end, specialised drones costing hundreds of thousands of dollars [6]. For our purposes, we chose a commercially available fixed-wing UAV costing approximately US$25 000 for the UAV and associated software. While less expensive models of UAV are available, this UAV could be easily used without significant training or technical knowledge, allowing multiple members of the project team to be trained in operating the UAV. Various models of UAV are commercially available with different specifications. The choice of an UAV model should depend on the financial and technical resources available, the anticipated spatial and temporal scales of the mapping project, and the types of data required.

Limitations of UAVs

Although UAVs represent a new source of data for epidemiological investigations, there remain significant potential limitations in their use. Similarly to light aircraft, small UAVs cannot fly in all weather conditions. The ability to withstand certain weather conditions is determined by the size and specifications of the UAV used. The model we chose could not be used during rain or with wind speeds over 45 km/h (12 m/s). We also found that high temperatures at our study sites (frequently in excess of 35°C) could cause the UAV to overheat after multiple continuous flights. While not as much of an issue as with satellite data, low cloud cover can also limit the visibility of data collected at certain times of day or in areas with poor visibility. The variability of weather conditions can make it difficult to plan exact flight times ahead of time and even when conditions appear suitable, areas frequently need to be remapped to obtain sufficient data. Some land types, such as forest, are more difficult to map due to the difficulty of matching overlapping images and may need to be mapped repeatedly or at higher resolutions.

Additionally, mapping exercises using an UAV require adequate resourcing. While small areas can be mapped quickly, mapping larger areas can require significant amounts of field personnel time. The amount of time needed to map an area is highly dependent on local weather conditions and the image resolution required. If higher resolutions of data are needed, UAVs need to be flown at lower heights and can cover shorter distances per flight. The number of flights conducted per day may also be constrained by the availability of electricity and ability to recharge the UAV's batteries. High levels of usage can necessitate the purchase of additional equipment and spare parts as well as lead to higher maintenance costs. Further, processing and analysis of UAV data can be computationally intensive, requiring computers with high specifications that may not always be available in the field. While data can be processed at a later date, immediate processing of collected images allows rapid assessment of data quality and better planning of further fieldwork. UAVs have also been limited by the lack of multispectral data, although recently UAVs have been modified to record other data of interest; for example, UAVs have been fitted with near-IR (NIR) cameras to measure the biomass of forest areas [46,47]. Currently, the spectral resolution of most UAVs is limited compared with available satellite data; however, this is a rapidly developing technology and may change in the near future.

Challenges can also be encountered while applying for official permission for conducting UAV mapping. As the use of UAVs is relatively uncommon, there is often no clear regulatory framework for applying for permission. For our research, we were required to apply for permissions from multiple agencies, ranging from ministries of defence and civil aviation authorities to conservation and development councils and land-use-planning authorities. While guidelines are in place for traditional aerial surveys, these guidelines were not always appropriate for relatively short, low-altitude UAV flights. For example, some regulations required the submission of detailed flight plans to allow redirection of other aircraft within the area, despite the differences in flight heights between a small UAV and larger planes. It is also worth noting that insurance associated with the use of UAVs is potentially restrictive. Although we encountered no safety issues with using an UAV, all project staff needed to be instructed on the safe handling of equipment.

Concluding remarks and future perspectives

Detailed investigations of environmental factors influencing the transmission of infectious diseases are vital to effectively target surveillance and control programmes. UAVs present a new opportunity to obtain high-resolution, georeferenced data in real time. These data can be used to better understand how land-use changes affect the emergence and spread of infectious diseases by monitoring the distribution of human populations and changes to the habitats of disease vectors and wildlife reservoirs. We demonstrated the utility of this method by using an UAV to obtain environmental data for an epidemiological investigation of risk factors for zoonotic malaria.

The use of UAVs is most appropriate when detailed maps of relatively small geographical areas are needed in areas where high-resolution satellite data are not readily available. UAVs may be inappropriate for large-scale data collection due to the time and resources required to operate them. Also, despite the modification of some UAVs to record data at different wavelengths, UAVs do not have the spectral resolution of most satellite data. Within smaller areas, UAVs can be used to generate high-resolution data on land cover, vegetation, and elevation and can be used to monitor changes in habitats of vectors and wildlife reservoirs on a fine spatial scale. Additionally, UAVs can provide a valuable alternative to other data sources when data are needed either in real time or at very frequent time points.

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