7. Mapping patchy malaria: the role of drone technologies in depicting particular environments and contingent risk

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Running header: Mapping patchy malaria

Abstract

This chapter is based on an anthropological study of a global, multidisciplinary network of researchers (MACONDO) that use drone technologies to support malaria vector control programmes. The purpose of this study was to investigate the ways in which drone technology for malaria control is deployed by various researchers and the implications the different applications had for the way malaria was conceived of and dealt with. It reports two key findings. First, that drone technologies reflected and mediated a shift towards thinking about malaria as multiple and emergent within heterogenous landscapes. Second, that in the hands of various researchers, malaria 'environments' were rendered 'partial' and 'particular' and risk equally fragmented. As a result, we highlight the 'patchy' character of malaria landscapes that drone technologies mediate and the challenge this poses to global health narratives based on 'concrete' and 'neutral' scientific ways of knowing.

Background

Malaria is a life-threatening vector-borne disease caused by parasites and spread to humans through the bites of infected female *Anopheles* mosquitoes (WHO 2021). While there are over 400 different species of *Anopheles* mosquito that can transmit the disease to humans, around 30 are characterised as malaria vectors of major importance (ibid.). Five species of *Plasmodium* parasite are thought to cause illness in humans (*Plasmodium falciparum, Plasmodium vivax, Plasmodium ovale, Plasmodium malariae* and *Plasmodium knowlesi*) and people who contract malaria may experience a range of symptoms including fever, headache, muscle aches and tiredness (CDC 2021). Infection can also lead to severe illness and death if not treated (WHO 2021). Although malaria is treatable and preventable there were an estimated 229 million cases and 409,000 deaths in 2019, of which children under five accounted for 67% (ibid.). Malaria is found mostly in poor, tropical and subtropical areas of the world and is heavily concentrated in the African region which recorded 94% of global deaths in 2019 (CDC 2021). The disease is considered both a consequence and driver of poverty, with an estimated economic impact of US$ 12 billion per year (ibid.).

While these numbers indicate the epidemic proportions of the disease, they also obscure its multiplicity (Kelly and Beisel 2012). Malaria is a complex phenomenon that cannot be understood separately from the diverse contexts across which it is differentially situated and enacted. Not only is this term a 'simplification of several parasite-mosquito constellations that vary both locally and seasonally' (Eckl 2017, 424), it also captures 'a range of clinical manifestations, vector pathways and biological entities' (Kelly and Beisel 2012, 72). Due to the contingent and relational character of the disease, circulating across human, mosquito and host species, it is highly sensitive to social and ecological changes at the landscape level ranging from deforestation to armed conflict (Fornace *et al*. 2021, Ruckstuhl *et al*. 2017). For this reason, recent anthropological scholarship (e.g. Chandler and Beisel 2017; Hausmann-Muela and Eckl 2015) has pushed back against the assumption that malaria is a fixed natural entity and called for attention to 'malaria multiple' (Chandler and Beisel 2017, 413). Such a move entails a focus not simply on how malaria is variably represented or interpreted across different cultures or academic disciplines, but on the myriad ontological enactments of disease (Mol

2002). This chapter will explore practices of malaria making in the MACONDO network and the varied constructions of landscape and risk that come to the surface as a result.

On a global policy level, efforts to combat malaria are largely focused on prevention, case detection and treatment. Many prevention strategies are centred around indoor-based interventions which target the mosquitoes that transmit disease through insecticide treated nets (ITNs) and indoor residual spraying (IRS) (WHO 2020). Although there has long been recognition that environmental conditions (e.g. climatic conditions such as temperature and rainfall, as well as macroenvironmental factors such as local topography, human land-use and management) play an important role in malaria transmission (Randell *et al.* 2010), following the Second World War, environmental management strategies such as maintaining drains, removing pools of stagnant water, managing vegetation, irrigating intermittently, altering rivers to create faster flowing water and improving housing (Randell *et al.* 2010; Okumu 2020) 'fell off the malaria control agenda' (Lindsay *et al.* 2004:2). As Lindsay *et al.* (2004) explain, the perceived promise of Dichlorodiphenyltrichloroethane (DDT) for house spraying as the main tool for the World Health Organisation's (WHO) malaria eradication programme from 1956-67 spurred a neglect of wider environmental management techniques and coincided with a move towards vertical programmes lodged firmly in the health sector. Alongside the increased use of insecticide on bed nets and jungle hammocks that became widely available in the mid-1980's (Okumu 2020), the use of insecticides and chemicals in IRS has been a major feature of vector control strategies over the last three decades (Najera *et al*. 2011). Together with targeting parasites directly through drugs and more recently vaccines, these interventions have had a significant impact. According to the WHO World Malaria Report 2020, 7.6 million malaria related deaths have been averted since 2000 (WHO 2020). However, more recently, the WHO's progress towards malaria elimination has reached a plateau with 2020 targets for reduction in disease and death missed by 37% and 22% respectively (ibid.).

The introduction of drones to malaria research is largely motivated by a growing awareness of the need for additional environmentally-focused approaches and tools to complement existing efforts, namely indoor-based interventions for vector management (Hardy *et al*. 2017). In recent years, worrying trends of insecticide resistance have weakened the impact of IRS and ITNs, contributing to a recent slowing of progress in controlling malaria (Okumu 2020). Furthermore, these interventions have proved ineffective in areas where transmission is driven by exophagic mosquito species that bite outdoors (Fornace *et al*. 2021; Hardy *et al*. 2017). One complimentary control strategy being employed to combat this is larval source management (LSM). LSM refers to the targeted management of mosquito breeding sites, with the objective of reducing the number of mosquito larvae and pupae as they mature in aquatic habitats in the environment (WHO 2013; Tusting *et al*. 2013). LSM includes prevention strategies such as habitat modification (e.g. permanent land reclamation), habitat manipulation (e.g. flushing of streams, the shading or exposure of habitats), larviciding (e.g. the regular application of a biological or chemical insecticide to water bodies), and biological control (e.g. introducing natural predators into water bodies) (WHO 2013).

The effectiveness of LSM is determined largely by the capacity to map and identify aquatic mosquito habitats (Hardy *et al*. 2017). As such, drones have been advocated by some as a valuable asset to LSM campaigns in particular because they provide precise, high resolution spatial data in real-time that can be used to support this mapping process (Fornace *et al*. 2014). Drones also offer insights into the landscape (its classification and use) more broadly. The notion that 'malaria eradication will be the indirect outcome of a combination of targeted malaria control on the one hand and broader social and environmental change on the other hand' (Eckl 2017, 431) is evidenced by the historical success in areas such as Italy where the disease was eliminated through large scale hydrological and agricultural modifications (Fornace *et al*. 2021). Now, with factors such as climate change, population growth and deforestation driving accelerated environmental change, some scholars are asking whether we need to return to the pre-war focus on landscape and expand the present paradigm of vector control (ibid.; Tusting *et al*. 2013) While the labour intensive character of environmental management strategies (stream clearing, cutting branches, that shade larval habitats etc.) has in the past placed a burden on communities and control programme staff, drone imagery opens up new opportunities for more precise and analytically driven interventions in malarial landscapes. As Lindsay *et al.* (2004. 2) suggest 'Environmental management needs to be considered a central pillar of malaria control that all other activities are linked to in an integrated fashion, informed by accurate ecosystem analyses' (ibid., 2).

Introduction

MACONDO was a multidisciplinary research network which used drone technology to support malaria vector control programmes. The network was brought together in 2019 through a Global Grand Challenges Research Fund for an 'International collaborative network for the Integration, Standardization and Assessment of the use of drones in malaria vector control strategies' (GGCRF 2019, 1). It was led jointly by the London School of Hygiene and Tropical Medicine, UK (LSHTM) and Universidad Peruana Cayetano Heredia, Peru (UPCH) and its remit was to assemble researchers from Southeast Asia, Sub-Saharan Africa and South America employing drones for malaria control and risk mapping. It aimed to elaborate guidelines for integrating drone technology into malaria control for use by researchers, ministries of health and national malaria control programmes. Specifically, the network intended to produce guidance on technical requirements, analysis methods and the usability of data; frameworks for assessing community engagement with drones; and guidance on technical and institutional limitations for incorporating drones into malaria control programmes. It comprised 29 researchers ranging from entomologists and epidemiologists to electronic engineers, and remote sensing specialists operating in multiple sites including Peru, Côte d'Ivoire, Burkina Faso, Tanzania, Zanzibar, the Philippines, and Malaysian Borneo (MACONDO 2021). The data presented in this chapter was collected as part of a masters project conducted by Jacob Brockmann (supervised by Dalia Iskander) in 2021. Jacob conducted semi-structured interviews with 10 MACONDO researchers and participated in two online webinars in order to elucidate the way in which they incorporated drones into their work and the implications of how malaria was conceived of and dealt with by each of them. Interviewees also pointed Jacob towards news and academic journal articles that had been published about their work, which provided more detailed insight into methodology and findings. A thematic analysis was applied to data to inductively identify themes that arose from the data. The study received ethics approval from UCL, LSHTM and UPCH. All participants were asked for their written, free, informed and prior consent to be interviewed and were provided with a written information and consent form to sign prior to data collection. Anonymity was optional for this research and pseudonyms used only when participants requested this. This was because there was a strong chance that participants would be identifiable due to the fact the network is relatively small and the nature of their work is quite specific.

Section 1 – Malaria as emergent within patchy landscapes

In the context of the aforementioned shift towards environmental management in malaria control, we argue that MACONDO researchers employed drones to effectively visualise some of the links between malaria and landscape and in doing so, revealed the heterogenous nature of such 'hotspots' (Brown and Kelly, 2014). As Brown and Kelly (2014) suggest, this heuristic, borrowed from epidemiology, refers to the potential spatial and temporal sites where different kinds of human-animal-nonhuman entanglements may facilitate the exchange of pathogens and particularly speaks to the micro and macro interactions that create such 'conditions of pathogenic possibility' (ibid.: 282). Due to the different disciplinary perspectives adopted by various researchers, as they each zoomed out and in on different dimensions, features and relations within landscapes, they rendered them fluid, layered, dynamic and animated in nature at times as much as they rendered them static, flattened, immobile and inert. As such, we argue that the use of drones by multidisciplinary teams rather than reveal neutral and unmediated 'views from nowhere' (Haraway 1998), actively constructed 'particular' views from 'somewhere' (Haraway 1998), that were altogether 'patchy' (Tsing *et al.* 2019) in nature, challenging notions of 'neutral' and 'objective' and transmission dynamics that are sometimes presented in scientific accounts of malaria.

###Kop3###Drones and heterogenous malaria landscapes

As mentioned in the introduction, the use of drones for malaria research is closely related to a renewed interest in environmental management strategies such as LSM.. Such interventions entail a shift away from a biomedical focus on mechanisms of pathogenic transfer towards a broader outlook on how multispecies encounters across temporally and spatially heterogenous landscapes give rise to varying patterns of malaria transmission. In interviews with MACONDO members, it was clear drone technology mediated a shift towards thinking about malaria as emergent within local landscapes. Many stressed that the 'visually striking character' of drone imagery, as Andy, a lecturer in Remote Sensing put it, offered a new perspective on how uneven interactions in the landscape shape patterns of disease transmission. Researchers such as Kim (a Spatial Statistician and Epidemiologist) articulated the significance of getting people 'quite excited about landscapes' that was felt to be instrumental for effective malaria management. As a result, drones facilitated researchers to explore a broad range of questions that they felt were important such as: how animal host habitats were impacted by land use change; how mosquito abundance related to different land types; and how human movement patterns intersected with vector biting behaviours. With their capacity to generate high resolution imagery at 'user-defined time points', drones offered 'new opportunities' to explore these relationships and better 'understand the habitats in which diseases circulate' ~~(Fornace and Iskander in press, 6)~~. Through a focus on the mechanism of pathogenic transfer, dominant biomedical renderings of malaria tend to reify a singular version of the disease which obscures the multiple malaria realities that emerge across diverse social, historical and environmental contexts (Iskander 2015). Instead, through the gaze of the drone, malaria was transformed into a thoroughly visual, spatial, temporal and dynamic phenomenon that could be traced across particular 'hotspots' of interaction.

###Kop3###Zooming out – macro-level features of the landscape

As Brown and Kelly (2014) articulate, a great conceptual challenge is to do justice to the characteristics of the hotspot that defy scalar logics including social, economic and political drivers of environmental transformation. On a macro level, drones gave access to views of landscapes as they changed in space and time as well as the factors mediating such change. For example, in Kim's work with the MONKEYBAR project, she used drones to map the spatial epidemiology of *Plasmodium knowlesi* in Malaysian Borneo and the Philippines (Fornace *et al.* 2014). *Plasmodium knowlesi* is a primate malaria that afflicts long-tailed and pig-tailed macaques but also has the potential to infect humans (William *et al.* 2013). The purpose of the MONKEYBAR project was to explore the hypothesis that changes in the landscape, particularly exacerbated by deforestation, were driving an increase in *Plasmodium knowlesi* transmission by bringing human, mosquito and macaque habitats into closer proximity. In a public webinar, Kim explained that 'to test this hypothesis and really explore these dynamics, we needed to actually map land cover change [over time]' ~~(Fornace 2021)~~. Drones were invaluable in this sense because they 'really gave the ability to monitor land cover and change at these very . . . fine spatial and temporal resolutions' ~~(ibid.)~~. To illustrate this, Kim showed two images of the same geographical area in February 2014 and May 2014. The first displayed a densely forested area, the second showed a scarred landscape that had been cleared for a rubber plantation. By integrating this spatial data with GPS information from collared macaques, Kim and her colleagues were able to create maps illustrating how deforestation had directly influenced macaque behaviour. Kim explained in her webinar that from these maps, the MONKEYBAR team were able to depict the increasing unpredictability of macaque habitats in deforested areas that was being ~~'~~driven by agricultural expansion of irrigated rice paddies as well as plantation industries such as palm oil, pulpwood, timber and rubber and illegal logging~~' (Iskander and Fornace, in press, 3)~~. Consequently, as macaques moved closer to villages, the risk of *Plasmodium knowlesi* transmission to human inhabitants increased particularly in increased forest edges. By using drones to specifically look for the movement of landscapes over time, in their analysis, malaria was not depicted as a static entity, but instead conceived of as a fluid process (Latour, 1988; Law, 2008) that unfolded unevenly across transforming patchworks making up the landscape.

As well as display the fluid nature of landscapes, drones were also used to highlight their layered and dynamic nature across multiple scales. Under the umbrella of the same MONKEYBAR project that Kim worked on, a Research Assistant in Vector Biology, Emma investigated factors that were associated with larval sites at different spatial scales in Malaysian Borneo. Using drone and satellite imagery, she extracted data about the land cover of 11 different areas at 50 to 500m intervals surrounding multiple larval collection points (water bodies). Consequently, she was able to assess whether high amounts of particular land classes at specific distances from water bodies influenced the statistical probability that mosquito larvae were present at specific locales. Explaining her methodology, Emma said, 'I think it's really important…to take [account of] the environment surrounding the water body and not just the exact pinpointed spot of the water body when you're looking at why mosquitoes choose breeding sites'. She explained that this was because different actors involved in malaria transmission such as monkeys, humans and mosquitoes operated and interacted across different sites and at different scales. For example, Emma found that being 'near to rubber plantations but not inside rubber plantations was a risk factor for *Anopheles* mosquitoes'. She hypothesized that, while insecticides might make water bodies within the plantation unsuitable habitats for mosquitoes to lay their eggs, the insects could breed nearby and travel to the plantation in search of a bloodmeal from a human or monkey. In this account, the landscape was constructed not as a flat and inert surface, but as a layered and mobile space where species interacted across multiple sites and scales. Together, Kim and Emma's work highlighted 'morphological patterns in which humans and non-humans [were] arranged' (Tsing *et al.* 2019, 188). In this rendering, malaria emerged out of a dynamic set of processes that intersected, yet extended beyond, the specific 'relevant' moments of pathogenic transfer.

###Kop3###Zooming in – micro level features of the landscape

At a micro level, drones provided new information on the fine-grained interactions of vectors, animal hosts and human populations which researchers linked to epidemiological heterogeneity in specific contexts. As described in the introduction, the interest in using drones reflected a shift in malaria control techniques towards broader environmental management. In line with this, Andy explained that from his perspective, the use of drones was motivated by a growing awareness of the need for new methods to supplement conventional indoor based interventions which were becoming ineffective against resistant strains of mosquitoes that have evolved to bite outdoors (Hardy *et al*. 2017). Working with the Zanzibar Malaria Elimination Campaign (ZAMEP), Andy used drones to support larval source management (LSM) campaigns on the ground, identifying potential mosquito breeding sites for precision larviciding. Compared to

Kim's research, this project had a very fine-grained local applicability as the aim was to direct attention to real-time, micro-level features of specific places rather than highlight broad changes over time. The imagery captured by drones was shared with fieldworkers via a mobile application called Zzap which created a map of water bodies and access routes. This enabled users to treat potential mosquito habitats with larvicide and track their progress as they did so. Andy explained that 'when the fieldworkers are walking around, what they're seeing (on the app) is a big bunch of potential breeding sites that they need to go and visit and tick them off and say, 'I visited it''. Additionally, if the fieldworkers encountered any water bodies that the drone did not pick up, for example those under the canopy cover, they could take a photo and add it to the map. As the fieldworkers visited each of these sites, Andy explained that their manager could track this progress via an 'online dashboard' which showed 'hundreds if not 1000s' of these points and the percentage of them that had been treated with larvicide.
This precision focus on water bodies represents a much more focal view on malaria than the macro level processes of land use change that were observed in Kim's work. In their paper on neglected malarias in urban Dar es Salaam, Kelly and Beisel (2011, 73) contrast the Gates Foundation's approach to malaria as a 'global enemy' with the small-scale maps that fieldworkers produce of water bodies in the back streets of Tanzania's capital. They argue that global malaria control strategies often fail to recognise how malaria is 'multiply implicated in the environments we inhabit' (ibid., 71) and tend to leave out the malaria that 'begins where the pavement ends' (ibid., 73) which fieldworkers locate in blocked drains and discarded plastic cups. This 'discrepancy between malaria control as an arduous everyday practice and the targeting of malaria as a global enemy' (ibid.,73) is also visible within the MACONDO network. Whereas Kim's project focused on macro level environmental processes that shaped malaria distribution across large scales and time periods, the fieldworkers in Andy's study, as well as those who Kelly and Beisel (2011) observed in Tanzania, attended to the gritty, fine-scale, real-time details of the specific places (water bodies) from which malaria emerges. In contrast to Kim's work which emphasised landscape dynamism, this focal view of malaria rendered the landscape momentarily static. By virtue of the drone's ability to provide imagery in real time, the fieldworker was presented with a snapshot of the quite literally 'fluid' distribution of water bodies across the terrain. The shifting landscape was immobilised as a map of water bodies that could be visited, treated and then checked off on an online dashboard. In this way the complex landscape from which malaria emerges was briefly contained as a stable object of scientific knowledge and intervention as researchers 'necessarily simplify and provisionally freeze what entities they will notice and count' (Tsing *et al.* 2019, 190). In the hands of different researchers, malaria landscapes were thus constructed as variably dynamic and static across different spatial and temporal scales. The drone images MACONDO's members produced both elucidated large-scale dynamics shifting environments over time and froze the landscape on a small scale to render it an object of knowledge and intervention.

###Kop3###Bringing mosquito behaviour into view – animating the landscape

When analysing drone imagery, some MACONDO researchers animated certain areas of the landscapes by integrating the movements of mosquitoes into analyses. This was evidenced in the work of Marta (a Research Fellow in Vector Biology) and Gabriel (Associate Researcher in Epidemiology). Paying specific attention to vector behaviour, they attempted to define a distinctive spectral signature for water bodies that were favoured by *Nyssorynchus darlingi* mosquitoes - the main malaria vector in the Peruvian Amazon (Carrasco-Escobar *et al*. 2019). This project differed from Andy's work in that it was motivated by the aim of mapping not just *potential* breeding sites, but ones that were also *positive* for mosquito larvae. Marta explained to me that one of the challenges of larval source management 'is to find not only the aquatic habitats, but where the mosquitoes [actually] breed, because they use some [very] specific places'. Elaborating on the implications of this, she said that in places such as the Amazon rainforest where 'the water reservoir is huge', it is not possible to treat all water bodies with larvicide. For this reason, 'the idea is to identify *only* the ones that we want to target that are going to produce mosquitoes'. Similarly, to Kim and Andy's studies, this project was closely tied to an interest in vector ecology. Gabriel explained that the project was motivated in part by a desire to learn more about the behaviour of *Nyssorhynchus darlingi*, a vector that is 'behaviourally very plastic' and can select suitable breeding sites according to visual and olfactory cues. Through integrating drone imagery of aquatic habitats with entomological data from the same locations, Gabriel and Marta attempted to map these behaviours. In the process, they transformed the landscape from a patchwork of potential breeding spaces into a mosaic of risky places, animated by the agency of insects. This focus on the vector as an actor (Latour 2005), rather than a passive object of scientific knowledge, facilitated a more animated view of malaria transmission.

###Kop3###Obscuring the complexities of mosquito behaviour – flattening the landscape
While such attention to the behavioural choices of the vector enlivened the landscape, other researchers intentionally obscured certain complexities rendering it flattened. As Edwards (2010, 15), points out, models are data infrastructures which both 'enable and deaden observation'. This point was exemplified in Edgar's (an environmental engineering student) research, which was supported by Marta and Gabriel under the umbrella of the same project, coordinated by the International Centres of Excellence for Malaria Research (ICEMR) in the Loreto department of Peru. Edgar's work investigated the abundance and distribution of *Nyssorynhcus darlingi* across different land cover types. He explained that previous studies in this region had discovered that there were more *Nyssorynhcus darlingi* located outside household structures than inside. Building on this information, he was interested in how far away from the household area mosquito presence extended. Edgar noted that, surrounding the village there were many different land types including crops, secondary forest and more densely forested areas. Consequently, he wanted to explore 'what types of landscapes or what types of vegetation we find more or less mosquitoes'. To do this, he adopted a 'stratified sampling strategy'. Using drone and Sentinel 2 satellite imagery and a 'clustering' algorithm, he constructed a regular hexagonal grid which classified the landscape into five land cover categories: households, forest, crops, degraded patches and flooded areas. In this way, the 500m study area around Santa Rita village was broken down into what looked like a honeycomb mosaic of hexagonal landscape clusters. Each month, 20 of these hexagons were sampled at random, allowing Edgar to determine the relative abundance and distribution of *Nyssorynhcus darlingi* across the different land types.
When asked why he chose this hexagonal sampling strategy, Edgar explained that it was related to the 'human landing catch' method where researchers sit in a single location and count the mosquitoes that land on them over a given time period. The hexagonal sampling grid was well suited to this method because it created a 'symmetrical area of influence' around each catchment point, thus providing 'a way to simplify the landscape'. This classificatory scheme rendered the drone and satellite imagery intelligible to researchers and amenable to sampling, but it also arguably entailed applying a reductive violence. Edgar alluded to this when he said, 'these artificial boundaries tell us information about the general behaviour inside that area, but we have to understand that it is a continuous surface [between them]'. While the clusters were useful to his study purposes, he stressed that 'there are no [actual] boundaries between them that you cannot trespass'. In other words, while drone use animated specific aspects of the landscape for the purposes of research (such as mosquito preferences for breeding sites), it also dulled others (such as their presence and movement across different land cover types). In seeking to determine the distribution of *Nyssorynhcus Darlingi*, Edgar rendered the mosquito

visible by simplifying the complex terrain it inhabited according to a classificatory scheme. This model simultaneously illuminated certain features of the landscape and excluded other ways of seeing. ~~Such models 'both illuminate what is in the world [whilst] exclud[ing] other ways of seeing' (Mathews 2017).~~ The hexagonal grid of land type clusters that he presented was at once a recognition and denial of the landscape's complexity and was another example of the 'partial' and 'particular' landscapes that were constructed as a result of intentional choices made in the use of drone technology.

###Kop3###Patchy landscapes

The landscapes that MACONDO members constructed through drones were therefore fluid, layered, dynamic and animated as well as static, flattened, immobile and inert. Somewhat ironically, given science's preference for the objective and panoptic view from above or 'conquering gaze from nowhere' (Haraway 1998, 581), it is precisely through the very 'patchiness' created that researchers were able to comprehend the 'whole'. The pictures captured by the drone were so rich and multifaceted that only by drawing attention to specific features, by painting an incomplete picture so to speak, could MACONDO researchers generate knowledge that was 'useful' to malaria research and control. This idea was expressed well in Maz's (Senior Research Officer in Primatology) work with the MONKEYBAR project in which she used a drone with a thermal camera to conduct rapid estimates of macaque populations (Jumail *et al*. 2020) to inform understanding of zoonotic malaria transmission. Maz explained that in the conditions of high canopy cover in Sabah's Lower Kinabatangan Wildlife Sanctuary, standard drone imagery and traditional visual counting methods along the riverbank were ineffective for primate censuses. In this context, the advantage of the thermal camera was that it could identify animals by the body heat that they emitted in the form of infrared rays (Jumail *et al*. 2020). Interestingly, Maz noted that this technique worked best at night-time or early morning when the contrast between the macaques' body heat and the surrounding environment was highest. In other words, this process of mapping landscapes involved cutting through the visual 'noise' of the drone image to highlight a specific aspect of it that was relevant to malaria transmission. Instead of offering a transparent and unmediated 'view from nowhere' (Haraway 1998), Maz's complex visual work with the drone generated a partial perspective on the landscape that suited her needs. As Haraway (1998, 590) points out, 'the only way to find a larger vision is to be somewhere in particular'. Although Maz aspired to see the full picture of malaria transmission, it was only by accentuating the incomplete and 'patchy' nature of her imagery that she was able to comprehend it.

###Kop3###Summary

Thus far in this chapter, we have argued that MACONDO researchers employed drones to elucidate links between malaria and landscape in different ways. In the process of mapping these interactions in partial and particular ways, 'patchy' landscapes emerged in the resultant drone images that were used to guide malaria control . However, rather than present an obstacle to the pursuit of scientific knowledge, this patchiness was a necessary feature of it, rendering complex contexts 'visible', 'comprehendible' and therefore arguably more 'manageable.'

Section 2 – The patchy character of risk

In the remainder of this chapter, we argue that the patchy character of malaria landscapes trickled down to frame equally fragmented and incomplete accounts of disease risk and manifested in many different ways. First, it was clear that drones could only map small areas of the landscape at a time, requiring researchers to make calculated choices about where to conduct surveys and consequently where they 'looked' for risk. Second, in classifying and categorizing features of drone images, researchers engaged in a process of compartmentalisation denying the 'blurriness' of the landscape where malaria risk was arguably highest. Third, MACONDO members presented a simplified notion of risk as they encountered many difficulties in analysing the relationships and connections between different factors. Fourth, multiple dimensions of incertitude influenced the 'accuracy' of risk assessments. Lastly, we describe how the multidisciplinary character of the MACONDO network evoked multiple constructions of malaria. Pushing back against the notion that scientific risk assessment is distinctively comprehensive and robust, we argue that just as malaria landscapes are 'patchy', risk as a consequence and the way malaria is advised to be dealt with is equally 'patchy'. This patchiness is not random but emerges from a series of strategic and political manoeuvres made by researchers.

###Kop3###Deciding where to map

The images that drones capture of malaria landscapes are limited in scope, meaning that researchers had to make deliberate choices about where to conduct drone surveys and by implication, where they located risk. Due to battery limitations, drones have limited flight times. While these vary according to the model, Andy's research using a standard DGI Phantom Drone was able to image a 600 x 600m area, flying for 13 minutes on a single battery. For fieldworkers, this was a significant amount of spatial information, but it paled in comparison to the global scope of the coarser satellite data that researchers were familiar working with. This punctual character of the drone gaze compelled researchers to target their studies in specific areas because as Andy pointed out 'we can't fly drones everywhere'. In this sense, while drones are closely associated with military usage and logics of surveillance (Wall and Monahan 2011) the visibilities they produce are not systematic or all-encompassing, but rather result in 'highly variable spatial logics and articulations' (Pauschinger and Klauser 2010, 443). To conclude his webinar on precision larvidicing in Zanzibar, Andy suggested 'broad scale mapping' as a method for planning future drone surveys ~~(Hardy 2021)~~. He explained that he had been involved in the development of a tropical wetland mapping tool 'TropWet' which used LANDSAT data to characterise the landscape according to percentage coverage of water and vegetation (Hardy, Oakes and Ettritch 2020). Because this data stretches back to the 1980's, Andy explained that TropWet allowed for the mapping of seasonal inundation patterns and the 'targeting of public health resources to tackle water-borne disease' (ibid., 18). This use of historical data to predict malaria hotspots was only one of the methods used to decide where to fly the drone. As Marta pointed out to me, the choice as to where to conduct a drone survey 'depend[ed] on what you want to know' and MACONDO members all had variable interests. While some were interested in mapping the impacts of land use change on human and host movement patterns, others were focused on mapping water bodies or understanding the behaviour of mosquito vectors. In other words, there is nothing given or definitive about the decision over where and what to map with the drone. The drone gaze was not so much panoptic as 'patchy' in character and, as Brighenti (2010, 187) points out, 'the decision as to who, where, when, and what is made visible [was] never of a neutral nature'. These choices were the first of many in a series of manoeuvres by researchers that gave rise to a patchy account of malaria risk.

###Kop3###Compartmentalisation of landscape and risk variables

The analysis of drone imagery involved a process of categorization and compartmentalisation that sought to locate and isolate 'risky' malaria places. According to Leach and Scoones (2013) the development of new technologies, such as drones, tends to favour the gaze from space or databases rather than the ground. This 'view from above' is associated with the 'ascendancy of quantitative modelling' (ibid, 15) that invokes the authority of 'evidence-based decision making' (Nutley *et al.* 2007, 23). In this discourse, 'sound scientific' risk assessment methods reduce the complex dimensions of the problem at hand to quantitative parameters of 'outcomes' and ‘probabilities’ that yield ‘a single ostensibly definitive picture of risk’ (Stirling and Scoones 2009, 1). In the context of malaria transmission, this segmentation of risk into scientific variables ‘relies on the compartmentalism of human, parasite, insect and environmental realms’ (Chandler and Beisel 2017, 415). Although my interviewees all expressed a desire to explore interactions between these categories, their analyses tended to achieve complexity by fragmenting components down further in each of their own niches rather than exploring *relations* between them. As a result, malaria risk was broken down into interrelated, but separate components and located in specific places of interaction.

For example, many MACONDO projects segmented the landscape in an effort to locate malaria risk, but these were not ‘natural’ categories found ‘out there’. As Haraway (1988, 595) points out, ‘boundaries are drawn by mapping practices; ‘objects’ do not pre-exist as such’. In another project, Fedra and Gabriel J’s trained machine learning algorithms to classify drone images according to land cover classes. Fedra (an electronic engineer) explained that by working with training images which had been manually pre-labelled according to the land classes they wanted to use, the neural network could ‘learn those patterns and recognise further images in order to classify them’. Importantly, these ‘risky’ land types were not self-evident but defined after careful discussion. Gabriel J (an electronic engineer) explained that when he first joined the MACONDO network, he had to meet weekly with the entomologists conducting the drone surveys and larval sampling to decide what categories they wanted to use to classify the landscape. In these meetings, there was a slight disconnect between the categories the engineers could train the network to recognise and the ‘categories most critical for [the entomologists’] analysis’. For example, Gabriel J explained that while researchers wanted to know about mosquito presence in vegetated versus non-vegetated water bodies, he was unable to teach the algorithm to recognise this difference. Eventually, they shifted from 6-7 ‘very detailed land classes’ down to a smaller number of simpler categories including rice, bare soil, households and forested areas. As such, classificatory systems ‘are imagined holisms through which structures fit together’ (Ton and Bubandt 2010, 17). The land classes used by Gabriel J and Fedra were not ‘natural’ but emerged from a series of deliberate manoeuvres shaped by a combination of research aims and objectives and technical limitations.

In compartmentalising the landscape into areas of supposed ‘risk’, researchers drew straight lines along blurred edges. Key to larval source management campaigns which target malaria breeding sites is the question ‘What constitutes a water body?’. The answer to this is far from straightforward. When describing their efforts to classify water, researchers spoke of its slippery character, noting that water bodies can be natural or artificial, temporary or permanent, static or flowing and positive or negative for mosquito larvae. They also pointed to their varying scale (small containers, puddles, lakes, rivers) and biochemical composition (pH, level of vegetation, temperature, salinity, level of shade). During Andy’s webinar on his work in Zanzibar, he showed an image from the field that illustrated the challenges of capturing this dynamic character of water. In the picture, which showed a 600 x 600 m area in rural Zanzibar, a range of land classes were visible including tilled soil, canopy cover and emergent vegetation. When this photo was digitally stitched together with other images to form a larger ‘orthomosaic’, yet more land cover categories were made visible, such as buildings, tracks, roads, open water and dense canopy cover. The water bodies visible in these images were heavy with sediment and similar in colour to surrounding soil. Furthermore, they had overflown into areas of vegetation at variable depths that were impossible to gauge accurately from the image. To the human eye, this liquid landscape was clearly difficult to arrange into distinct categories and, as Andy explained, it was even more difficult to train the computer to do this. The algorithm struggled to distinguish silted water from crops, shadows and inundated vegetation, and accuracy (compared to the manual classification) was only 57.9% due to the large number of false positives. Crucially, however, this blurriness between land categories was more than an obstacle to identifying water bodies and pinpointing malaria risk. Landscape 'blurriness' matters because it is often in the 'ecotones' (Lambin *et al*. 2010, 6) or transitional spaces between households and forests, water bodies and plantations where malaria transmission occurs ~~(Iskander and Fornace, in press)~~. While MACONDO members compartmentalised the heterogenous landscape in an effort to locate malaria risk and target interventions, these land types did not exist 'out there'. Instead, researchers 'reify[ed] categories for the sake of the analysis' (Tsing *et al.* 2019, 190), often at their blurry edges where malaria risk is arguably highest.

###Kop3###Indeterminate relationships between components of risk

When MACONDO members broke risk down into component parts, there was often a lack of clarity about how these elements were connected, perpetuating overly simplistic or vague notions of dynamics. Stirling and Scoones (2009, 4) argue that conventional 'reductional-aggregative techniques' of risk assessment often fail to acknowledge the uncertainty entailed in establishing relationships between different indicators or components of risk. They define uncertainty as the state in which 'the available empirical information or analytical models simply do not present a definitive basis for assigning probabilities [to specific outcomes]' (ibid., 10). This was evident in Marta's comment that when you conduct larval surveys to assess where mosquitoes are breeding 'You kind of measure all these things, but there is not really a correlation or association with a specific measure or factor'. She continued, 'For example, it's not that if the pH is above or below seven, the mosquitoes are not going to be there. It is really variable and it depends on the species, it depends on the season, it depends on many other things.' This complexity was important to Marta's study because it prevented her from establishing a causal relationship between certain environmental variables and mosquito presence. Interestingly, however, Marta's awareness that mosquito behaviour could not be comprehensively captured as a sum of environmental variables did not deter her from attempting to locate areas of malaria risk. In fact, her study sought to identify a distinctive spectral signature for water bodies that were positive for mosquito larvae. While the correlation established between the mosquito habitats and a specific wavelength did not explain *why* the mosquitoes selected that aquatic habitat to breed in, Marta said this information was nonetheless useful for targeting the efforts of fieldworkers. MACONDO members understood that the connections between different environmental variables and risk factors were 'patchy' and riddled with uncertainty. Despite this, they made strategic choices to move forward with malaria control interventions. As Leach and Scoones (2013, 10) point out, disease models do not 'inform policy in a linear manner' but instead have 'social and political lives' that shape their development and application in public health projects. Although scientific methods make claims to 'rigour' and 'robustness' (Stirling and Scoones 2009, 13), what emerges from this study of mosquito behaviour was not a definitive picture of malaria risk, but rather an incomplete patchwork of component parts that did not fit together neatly.

###Kop3###Uncertainty and ignorance

Another important point to note about the mosaic of malaria risk articulated by MACONDO members is that while it included patches of 'precise' findings, these did not necessarily form a comprehensive account of malaria risk. This was reflected in the practice of ground-truthing which was shared across the network. Marta explained to me that ground-truthing is 'basically trying to match the satellite (or drone) image with what you're seeing on the ground'. For many of the researchers, this involved visiting areas that the drone had imaged to confirm the presence of a specific land type or water body. In Marta's study it also included larval sampling to establish a correlation between the spectral signature of the drone and the presence of anopheline larvae. This process of comparing the drone image with the 'reality' on the ground produced a narrow mathematical definition of accuracy. Marta's research, for example, concluded that 'high-resolution multispectral imagery can discriminate a profile of water bodies where *Ny. darlingi* is most likely to breed… with an overall accuracy of 86.73%- 96.98%' (Carrasco-Escobar et al 2019, 1). While there was nothing factually incorrect about these findings, it is important to acknowledge that they were very narrow and assessed according to metrics that the researchers selected. Stirling and Scoones (2009, 15) argue that such quantitative analyses of risk often lead the policy makers who favour them to a fallacious conflation of 'accuracy and precision'. In the context of MACONDO's work, this means that although their findings were 'precise', they did not necessarily capture an 'accurate' picture of the full phenomenon of malaria transmission.

Another form of incertitude that pockmarked the character of malaria risk assessment in the MACONDO network was 'ignorance' (Stirling and Scoones 2009, 1). Simply put, this term encapsulates the 'unknown unknowns' of risk assessment or 'things we don't know we don't know' (ibid, 6). By definition, analyses based on probability 'cannot address possibilities that have not been defined or even anticipated' (Smithson 1989, 54). This is particularly relevant to complex phenomena such as malaria transmission where researchers cannot be confident that they are aware of all causal factors contributing to disease spread. For example, Kim noted in her webinar that *Plasmodium knowlesi* was only diagnosed in 2004, revealing the previously 'unknown' role of macaques in malaria transmission. It is also worth noting that for over 2500 years, the idea persisted that malaria arose from miasmas rising from swamps (Cox 2010) and the origins of the word 'mal-aria' ('bad air') (Kelly and Beisel 2012, 74) suggests an association with those who worked in marshes, fought in the trenches of slept without a roof over their heads. It was not until the late 19th century that the role of parasites and mosquito vectors in malaria transmission was discovered (Cox 2010). More recently, the pace at which parasites and vector species are evolving has confounded efforts at disease prevention and control (Kelly and Beisel 2012). Many MACONDO members were racing to learn more about the behaviour of mosquitoes that have developed resistance to insecticides and are exhibiting new biting behaviours which evaded current control methods such as mosquito nets and indoor residual spraying. Going forward it was anticipated that processes of climate change, deforestation and biodiversity loss will have indeterminate impacts on malaria transmission both locally and globally (Fornace *et al.* 2021, Lambin *et al*. 2010). These 'unknown unknowns' (Stirling and Scoones 2009, 6) are an inevitable feature of malaria risk assessment. Consequently, the accounts of malaria risk offered by MACONDO members are understandably incomplete, with patches of 'precise' findings bordered by spaces of ignorance lurking somewhere in the shadows of the scientific gaze. Drawing attention to the 'multiple dimensions of incertitude' (ibid, 8) which checker scientific or evidence-based risk assessment methods is important because it questions the extent to which they can capture the indeterminate landscape interactions which shape malaria transmission and thus 'determine which interventions cause particular outcomes' (Adams Sandbrook 2013, 331).

###Kop3###Multidisciplinarity and malaria multiple

Finally, it is important to note that the accounts of malaria risk sketched by MACONDO members were stitched together using a range of disciplinary practices. The MACONDO network was deliberately composed of researchers from varying academic backgrounds including entomology, epidemiology, remote sensing and anthropology. One important driver behind this interdisciplinary collaboration was that many MACONDO researchers worked in residual transmission settings, where malaria elimination could not be achieved with conventional tools such as bednets and spraying. Edgar stressed to me that, in order to accomplish elimination, we need to 'broaden the tools that we have available.' He continued, 'it's not only, let's say epidemiology or entomology that are going to solve the problem, you have to have a multidisciplinary team'. Kim expressed a similar sentiment and stressed the value of 'people coming from different perspectives and backgrounds and looking at the same problem in different ways'.

This description of malaria as a stable problem that could be approached from different perspectives was certainly shared by other members of the network. However, recent relational theories in anthropology have argued that knowledge production is 'not only and epistemological act, but also a *doing* – a practice that involves creating worlds and that shapes ontologies' (Chandler and Beisel 2007, 415). In this sense, disease-making can be construed as a 'material-semiotic process' (Law 2004, 3) which conjures different articulations of malaria and enables certain practices of treatment and control (Langwick 2007). For example, when I asked Kallista to talk about how drone imagery was analysed, she said 'honestly I'm more of a mosquito person…I am more familiar with catching mosquitoes than using drones to take images of the environment'. As discussed in the introduction, this unitary focus on the vector has historically facilitated a focus on insecticides which has reshaped the biology of mosquitoes and parasites. On the other hand, Fedra (an electronic engineer) told me 'I am familiar with the images, but not with the process of being in the field, or taking images with drones. I mainly work with the images they acquire'. As mentioned above, this view of malaria as a visual and spatial phenomenon is linked to a shift towards environmental management strategies. The point to be drawn from this comparison is that different framings of malaria enable different intervention strategies which in turn shape the biology of the vector, the composition of the landscape, the behaviour of local populations and the focus of future studies. In other words, 'the fight against malaria can be understood as an ontological project' (Kelly and Beisel 2012, 72) which is constantly remaking the disease through its attempts to study and control it. The patchwork of malaria risk assessment is not simply comprised of different disciplinary viewpoints on a singular problem but rather constructs malaria as multiple and emergent from different disciplinary practices and geographical contexts.

###Kop3###Summary

In this section, we argued that just as the landscape imaged by drones was 'patchy', so too were the assessments of risk made by members of the MACONDO network. Pushing back against the idea that the scientific 'view from above' offers a comprehensive overview of malaria risk, we have argued instead that the picture of risk that emerged from drone use was distinctively incomplete. Due to their limited flying times, drones were only able to map small 'patches'of the landscape, requiring researchers to make deliberate choices about where to conduct their surveys. In the process of analysing their images, the landscape was separated into component parts which blurred together. Rather than offering an 'accurate' rendering of the 'full' picture of malaria risk, MACONDO researchers created small pockets of 'precise' findings which were bordered by spaces of uncertainty and ignorance, lurking somewhere in the shadows of the scientific gaze. This patchiness was also reflected in the multidisciplinary character of the network which entailed multiple malaria ontologies 'rubbing up against each other' (Tsing *et al.* 2019, 187) as researchers strove to generate knowledge that was useful for malaria control programmes.

Discussion – why patchiness matters?

In this chapter, we have argued that the MACONDO network's engagement with landscapes and risk was distinctively 'patchy'. Section 1 explored how drones facilitated a shift to thinking about malaria as emergent within heterogenous landscapes and constructed these as variably dynamic and static across macro and micro scales. In the process, specific landscape features were animated and flattened to produce an incomplete, but intelligible picture of multispecies processes relevant to malaria transmission. Section 2 explored how this 'patchy' character of the landscape was also reflected in MACONDO's engagement with risk. Contesting the notion that scientific methods of risk assessment are definitive and comprehensive, we pointed instead to their incomplete character. Due to their limited flying times, drones produced a punctual rather than panoptic view of malaria risk. Attempts to isolate 'risky' malaria places by compartmentalising the landscape were limited by the blurry and indeterminate relationships between environmental and spatial variables. MACONDO's quantitative and cartographic models did not capture the 'full' phenomenon of malaria risk, but instead offered patches of 'precise' findings, blemished by pockets of uncertainty and ignorance.

Why does patchiness matter? In short, because it leads us to question many of the received certainties upon which global health is predicated. Highlighting how malaria is emergent from 'patchy' landscapes, as MACONDO researchers inexplicitly do, questions the logic of biotechnical interventions that reify malaria as a stable natural entity that can be tackled with the same tools regardless of context (Iskander 2015). By pointing to the complex visual practice entailed in directing the drones punctual gaze on the landscape we additionally show that visualising technologies are never neutral or apolitical. Instead, we open the way for further discussion about how power is implicated in choices about what aspects of landscape, disease and community should be rendered visible.

Acknowledging the 'patchy' character of drone technology will be essential if drones are to become a more widespread and effective tool for malaria control intervention going forwards. This chapter has argued that making more effective use of drones is not simply a question of technical progress. While there will no doubt be improvements to flight times, photo quality and image processing as more training data is gathered and new drone hardware is released, we have cautioned against the pursuit of a 'perfect picture'. No matter how high resolution the image, researchers will continue to make choices about where to fly, what land type categories to use and how to present their findings. The 'patchy' character of drone imagery and its analysis will endure. If researchers want to improve and enrich their future studies, they need to be cognisant of the patchiness of their own work and be more deliberate in the way they engage with it. One way of doing this would be intertwining their scientific analyses of drone imagery with other ways of knowing. While many researchers acknowledge the importance of local communities to their work, there was little mention of these people's lived experiences of malaria. If researchers are to take seriously the idea that their imagery and analysis is 'patchy' then they should engage with these stories, not as lesser or more 'subjective' forms of knowledge, but rather as equally patchy, situated and powerful perspectives on malaria landscapes.

Patchiness also offers new incitements to anthropological theory and possibilities for multidisciplinary dialogue. Both anthropology and natural science have an interest in how disease emerges from multispecies landscapes, but this tends to be discussed in different registers. Science privileges scalable knowledge about the 'natural world' that can be applied across contexts, such as entomological data about the biting behaviours of specific vectors, or drone imagery that can be used to train classification algorithms. Anthropology, on the other hand, foregrounds the 'social' and presents lived experiences of space, place and disease which do not nest or translate easily. In the era of the Anthropocene, in which imbricated social and environmental processes are shaping new patterns of disease transmission, there is a growing need to bridge this divide between 'social' and 'natural' science. For anthropology, this means expanding the notion of the social to encompass more-than-human relationships (Tsing 2013). For science, this requires attention to the messy ways in which the social is enmeshed in 'natural' phenomena such as malaria and acknowledging how power is implicated in their models. This study has made small steps towards bridging this disciplinary divide by investigating how malaria emerges within 'patchy' multispecies landscapes. We have shown that disease and landscape are not exclusively 'natural' or 'social' concepts. Instead, they are co-constructed by researchers writing classification algorithms, mosquitoes searching rubber plantations for bloodmeals, parasites developing resistance against insecticides, timber-workers travelling along the riverbank, and macaques migrating into new habitats. Patchiness was a valuable analytical tool in this process because it encouraged attention to the uneven interactions of the 'natural' and the 'social' which public health discourse tends to flatten, but the intimate gaze of the drone on malaria landscapes cannot deny.

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