Drone Methodologies: Taking Flight in Human and Physical Geography

Introduction

> 'We need, in other words, to invent an art of experiment which can up the methodological ante.' (Thrift, 2011, 8)

Suddenly drones seemed to be everywhere. The buzzing props, blinking lights and tiny cameras were whizzing across remote areas, confusing wildlife. They hovered over urban parks, capturing footage of firework shows and weddings. A window of anarchy ensued as people tested the limits of the new technology: planes were grounded where they flew; citizens strapped guns and spray cans to them; one carried irradiated sand onto the roof of the Japanese Prime Minister's office. Only then did politicians respond publicly, citing need for greater regulation. Regulators themselves meanwhile were busy grappling with corporations jockeying to carve out lanes of airspace, amid journalists' desires to be able deploy them for investigations. Meanwhile, geographers watched from the sidelines, bemused, as a familiar research tool and topic morphed into a ubiquitous object of incredible promise and suspicion. In a blink, 'the drone exists, taking to the skies above our heads everyday' (Rothstein, 2015, ix).

Fuelled by a longstanding 'human curiosity to take to the skies' (Miah, 2017) there is now a lightweight drone on every continent on Earth. Almost 2 million drones were sold in 2016 (doubling sales in 2015) and the US Federal Aviation Administration (FAA) predicts that 4.3 million consumer drones will be sold by 2020 (Schuessler, 2016; Masunaga, 2016). 'In 2016, Price Waterhouse Cooper valued the global market for drones at over $127 billion' (Shaw 2017, 13). With over 1500 different drone designs now in existence, Wallace-Wells (2015) suggests that a new taxonomy that places military and civilian drones in different phyla is required to sidestep the 'doublespeak' of the drone. Yet he also suggests that military and consumer drones inform each other through their potentials for surveillance and control:

> '...drone, an impossible word, is also a perfect one. Each of these machines gives its human operator the same power: it allows us to project our intelligence into the air and to exert our influence over vast expanses of space' (Wallace-Wells, 2015).

This statement is promising and ominous. Drones, like many technologies, have a military origin and must therefore be engaged cautiously and critically. Geographers are particularly sensitive to these issues, and are well-equipped to address them, since drones, like cartography and Geographic Information Systems (GIS) sit within a tradition of critical scholarship on the 'view from above' (e.g. see Harley [1988] for a critique of maps and power and Pickles [1997] for an in-depth critical engagement with GIS). As Graham (2016: 68) suggests, some military drone operators come to 'see their top-down view as one of inherent superiority over the subjugated, less important, and racialised people – or even dehumanised non-people – far beneath the gaze', which connects the view from the drone to a long history of subjugation through spatial visualisation.

And yet, geographic technologies have also been appropriated to socially productive ends, such as counter-mapping practices and open-source or participatory GIS, where control of those technologies is democratised, to a greater or lesser degree. Indeed, in physical geography this democratisation has already occurred, to an extent, through a history of experimentation with airborne instrumentation including helicopters (Milton et al., 1994), and kites (Duffy and Anderson, 2016), and more recently through innovative methodologies with drones where biogeographers have surveyed canopy structure to quantify biomass (Cunliffe et al., 2016), volcanologists have flown into craters to sample gases (McGonigle et al., 2008),[i] and geomorphologists have quantified grain-size distributions on hard-to-reach glacial moraines (Westoby et al., 2015), to mention just a few.

So, whilst 'human geography suddenly seems afloat with airs and winds, fogs and aerial fluids, with volumes, verticals and objects in the air' (Adey, 2015, 55), physical geography is entering 'a new proximal sensing era' with widespread use of drones (Anderson, 2016, 192). This fused future of drone methodologies therefore calls for thinking 'not so much on drones as objects, but as [sociotechnical] assemblages of the vertical' (Crampton, 2016, 2). Drones therefore harbour profound geographic potential deserving of serious critical engagement, and it is in that spirit that we seek to broaden discussion on drone technologies as geographic method. To parse the 'doublespeak' (Wallace-Wells, 2015) of the drone, in this article a 'drone' refers to lightweight consumer-grade drones that can be flown by any person with sufficient skill, usually carrying an imaging payload and piloted for geographic research purposes.

This article has three primary aims. First, we hope to spark a conversation between physical and human geographers about what can and should be a shared methodology. Both physical and human geographers are engaged simultaneously, yet separately, in drone scholarship of some kind, but there is currently little cross-fertilisation between those two fields. For example, physical geographers use consumer-grade drones widely in their research (for examples, see Mancini et al. [2013], Mlambo et al. [2017] and James et al. [2017]), but there is scant evidence that they have discussed the social, legal and experiential implications of their praxes with human geography colleagues, despite their operations regularly coming into contact with organisations or individuals who may be wary of drone operations (Duffy et al., 2017).

Reciprocally, human geographers have critically engaged military drone technologies (Gregory, 2014, Shaw, 2013, Shaw, 2017) and imagery (see Gregory [2011]) and argue that 'the experiences, practices and textures of vertical life' need to be studied (Harris, 2014, 608), but there has been little evidence of human geographers engaging practically with consumer drone technologies – building, flying, crashing repairing and upgrading them – so as to be able to effectively chart a course toward more *critical* drone methodologies. We seek to highlight the common ground that underlies both human and physical geography drone methodologies. In doing so, we hope that new research agendas and directions will emerge where, for example, human geographers could conduct ethnographic work with stakeholders involved in physical geography drone surveys, physical geographers collaborate with human geographers to trace and contemplate landscapes and places, or where both evaluate the impacts of existing and emerging airspace legislation on research operations.

Our second and third intertwined goals in the article are to discuss the extent to which the experience of flying expands potential for thinking about 'visual' and 'volumetric' geographies across the discipline. Gillian Rose has suggested that 'with the exception of anthropology, geography is unique in the social sciences in the way it has relied and continues to rely on certain kinds of visualities and visual images to construct its knowledges' (Rose, 2003, 212). In response, John Thornes (2004, 793) wrote that physical geography had also experienced a 'visual turn' and that 'common techniques and methodologies are required to both critically understand and to create powerful visual images across the whole discipline of geography'. Considering that ongoing conversation that spans our discipline, we seek to respond to Rose's (2003) question of, 'how, exactly, is geography "visual"?' with a follow-up that we will answer through this paper: how, exactly, has visual geography become volumetric?

As we will discuss later in the paper, a large proportion of the data captured by physical geographers from drones are images for use in photogrammetry. On a basic level then, we see the physical geographer's 'raw' and unprocessed data as a wellspring of new visual geographies, but where the scale of observation is different to classic remote sensing (RS) analyses. In a short span of time, we have moved from pixelated static satellite images to extremely high-resolution photo/videographic images. Like GIS, the vantage points enabled by drones take both visual geography and physical geography to places it has never been. In framing geographic drone methodologies through scholarship on verticality and the volumetric, we suggest that if a '"Politics of Verticality" entails the re-visioning of existing cartographic techniques… transform[ing] a two-dimensional surface into a three-dimensional volume' (Weizman, 2002, 2), this takes on different weight when considered from the perspective of piloting where 'verticality [can be understood] as the provisional achievement of (horizontal and vertical) entanglements of people, systems, rules, practices, technologies and things...' (Harris, 2014, 612).

Verticality is always volumetric, since as Urry (2003, 138) writes, all aerial technology is tethered or 'moored' to an infrastructure on the ground; skyscrapers have a very determinate relationship to subterranean space (Garrett et al., 2016), aerial bombing often leads to tunnelling (Graham, 2016), and piloted air traffic is radar-tracked as it travels through designated air corridors. Thus, vertical geographies and their associated methodologies (including those used routinely by physical geographers) become further complicated by consumer drone technologies where *more-than-visual* opportunities and imaginaries are shaped by the methodology.

In offering the geographer vicarious access to fresh spaces and perspectives, drones allow new manoeuvres to be made and new data to be captured. So, in addition to our three aims, we propose that a new categorisation of the proximal airspace above our heads is needed to accommodate the drone: the *Nephosphere*. From the Greek, *nepho* (cloud), and *sphere* (round geometrical three-dimensional [3D] object), the term engenders a volumetric perspective that is, generally, above rooftops and below piloted airplanes, an area of the sky previously looked *at* but rarely *from*, the 'habitat for new animate forms including the drones that buzz above our heads' (Mattern, 2016, np).

This article is an exploration of the epistemological nexus that geographical drone methodologies afford the discipline. In what follows, we cite contemporary examples from our own research and from across the discipline, where drones are transforming geographic methodologies within the volumetric space of the Nephosphere. We argue that drones are reshaping geographic imaginations and will reconfigure future urban, visual, creative and even development geographies in the same way they have already transformed the ways in which physical geographers think about and conduct data capture, specifically for spatial modelling and RS research.

We make our case for a formalisation of *drone methodologies* by outlining how the Nephosphere is being reshaped by drones (Section I), and then situate drones in the history of RS and aerial imagery amidst accounts of post-phenomenological technologies (Section II). Next, we engage recent writing about 'enclosures' of the vertical commons (Section III) whilst considering the spatio-political capacities of subversive droning practices in resisting those enclosures (Section IV). Finally, we offer thoughts on how drone methodologies in the Nephosphere can constitute a fused human/physical nexus for rethinking visual and volumetric geographies (Section V). We hope, in short, to prompt physical geographers to gain insight into how the complex 'sensing' capabilities of drones have social and political dimensions, whilst also inspiring human geographers to gain practical expertise in piloting drones to better understand the socio-political complexities involved in taking to the air for research.

I. The Nephosphere's Volume

> 'We've moved from birding to dronewatching, from natural history to dark ecology.' (Mattern, 2016, np)

There is a diverse field of literature contributing to the complexities of the near-Earth atmospheric volume we call the Nephosphere. Despite its importance for studies of climate and environmental health there is no explicit definition of this space: zonal classifications – such as Balkin's (2013) atmospheric chart – leap from the ground to the troposphere, without considering the volume in between. Whilst there are many stakeholders who may lay claim to the narrow aerial habitat, it also occupies varying positions depending on who is consulted. In meteorology, the turbulent boundary layer is defined as the part of the atmosphere where interactions with the Earth's surface occur and, depending on local spatio-temporal variations, its depth can range from just a few metres to several kilometres. From the perspective of human geography, Shaw suggests that at present 'there is a prima facie grey zone for aircraft flying between 83… and 1000 feet' (Shaw, 2017, 13) that we suggest can be conceptualised as the Nephosphere.

Meanwhile, legal literature defines this airspace as separate 3-dimensional blocks to assist in management of 'a complex invisible infrastructure' (NATS, 2017, np). These blocks may vary in their level of use from one country to another, but include class A (very tightly controlled: reserved for high speed jets and for 'instrument flight rules' aircraft), through to class G (uncontrolled: where aircraft must follow simple rules). If we consider the Nephosphere as largely occupying class G airspace, the UK Civil Aviation Authority (CAA), for instance, states: ‘although operators of drones weighing 7 kg or less are not required to have the permission of Air Traffic Control (even when flying within controlled airspace or within an aerodrome traffic zone), the Air Navigation Order requires that any person in charge of a small drone may only fly the aircraft if reasonably satisfied that the flight can safely be made; and must maintain direct, unaided visual contact with the aircraft’ (CAA, 2017, np). Ultimately, the responsibility ‘lies with the operator to determine if the area he (sic) has chosen to fly in is suitable’ (CAA, 2017, np).

We proffer the Nephosphere as a loosely-defined class G airspace of expanding participation, encompassing the otherwise inaccessible volume that exists above the gravity-defined bounds of human habitation but below strictly defined flight zones, analogous in some ways to the open sea. The Nephosphere is a space previously only experienced from relatively static aerial positions such as balloons and kites, or through architectural vantage points like rooftops. So, though the Nephosphere has played a prominent role in the human imagination, the drone is an agile means with which we can *access* the Nephosphere, making the volume of increasing political importance.

Yet geographical scholarship of the drone to date has framed such methodologies along dichotomous lines that are, we suggest, somewhat blinkered to the potentials and complexities of the technology. ‘Like satellites before them, drones have moved beyond their military uses to reshape our vertical publics’ (McCosker, 2015, 2) and we thus follow Noys’ (2015, 14) suggestion that ‘reading the vertical as a site of pure domination underestimates the complexity and tension in constituting the vertical as a site of power’. An expanded sense of drone methodologies in geography, both critical and astute, will shape imaginations and practices (Figure 1 and Figure 2).

Figure 1 and 2 Here

Levels of control over hardware and data are key components of a more critical perspective. Data from satellite RS platforms have long been the mainstay of spatial analysis in physical geography, but powerful agencies define data acquisition protocols and control access (Rao & Sridhara Murthi, 2006). Furthermore, satellite orbital paths dictate a routine temporality to data availability, and clouds can interfere with optical data affecting end-user control of the quality and timing of RS measurements (Asner, 2001). The 'highly uneven resolution and up-to-dateness' (Graham & Hewitt, 2012, 5) of geospatial data delivered through portals such as *Google Earth* expose the structures of power that limit exploration (Kingsbury & Jones, 2009) for physical and human geographers alike. Hovering quadcopters, in contrast, pull the aerial eye into oblique formations between nadir and horizon under the direct control of the operator.

While still steeped in different loci of control, drone methodologies offer the researcher the combined benefits of detailed observations with a self-service capability that satellites cannot equal. Yet it is that very proximity and agency, along with operational anonymity, that has many social scientists concerned about issues of surveillance and privacy. Writing just before the millenium, Slonecker et al. (1998, 589) commented that future developments in RS technology could deliver data with such detail that would 'violate common societal perceptions of individual privacy', with legal and ethical consequences. In the 21st century, drones are now crux of the same debate (see Figure 1), where everyday citizens can fly and capture data at centimetric resolution with relative freedom. As drone methodologies come to the fore concomitantly with democratic and homebrew satellite technologies in Earth's orbital space, geography is entering a new era of transparency that, like the fine-grained spaceborne imaging missions in the late 1990s, 'governments throughout the world are woefully unprepared for' (Rao & Sridhara Murthi, 2006, 263).

II. The Multisensual Flying Robot

> 'First and foremost, drones change the way we see.' (Rothstein, 2015, 125)

The drone is defined as much as a technology that can see as a technology that flies, yet sight is just one part of how they sense. In this section, we conceptualise the drone as a way of flying and sensing (an epistemological tool) and as a way of knowing and experiencing differently (an ontological orientation). Alexander von Humboldt's theories about the telescope provides a useful analogue, where he suggested it was 'an organ of sensuous contemplation' that forever changed our perception of the cosmos (Von Humboldt, 1997 [1850], 302-303). The telescope, writes John Pickles, 'allowed us to see more and see differently, and as a result transformed our view of the universe and our place in it' (Pickles, 1997, 365). Drones do similar work, since they enable us to extend our perception into new places, they multiply our possible experiences, and they reshape our geographic imaginations. In both cases, the technology is more than a data delivery tool, it enables a 'vision that is practised and touched. It is not simply ocular or visual, but an assembly of practices and materials' (Adey, 2010a, 145).

Whilst we cannot provide a full history of aerial photography and reconnaissance from the Nephosphere, it is useful to highlight that 19th-century aerial photographic pioneers used hot air balloons to get cameras airborne, followed by a period of kite aerial photography with cameras triggered by slow burning fuses (Figure 3). By the 1930s, Robert Goddard experimented with cameras on rockets and drones were being constructed by the US-based Radioplane Company for military applications, incorporating cameras for survey. The name drone stems from the 'unsophisticated, noisy, insect-like flight capabilities' of these early flying machines (Rothstein, 2015, 27).

Figure 3 Here

The first lightweight consumer-grade multirotor – the 'Roswell Flyer' – came onto the market in 1999 (Rothstein, 2015, 37). At $350 this became the *de facto* platform for hobbyists who were quick to modify the frames and components, kickstarting a maker movement of grassroots enthusiasts. DIYDrones.com, for instance, is 'a social network for people experimenting with autonomous aircraft' (Anderson, 2012, np), comprised of thousands of drone hackers. Its founder, Chris Anderson, outlined his vision in the following passage:

> 'Just as the PC emerged from the Homebrew Computer Club and hobbyists eventually overturned mainframe-based corporate computing in the 1980s, I suddenly saw how the same sort of movement would bring robots to the skies.' (Anderson, 2012, np)

Thus, the drone, a device central to the history of aerial survey, has always been at least three things: a tool of military engagement, a research instrument, and a popular platform for experimentation. Within this history of sensing from a proximal birds-eye view, contemporary drones introduce extraordinary mobility (for both platform and sensor) within the Nephosphere, and their assimilation into the aerial assemblage thus requires careful consideration of the changing political and ethical relationships between bodies, spaces, experiences and technologies. We argue (as Von Humboldt did with the telescope), that drone piloting, as an experiential process, changes not just what we think we can do but also *how* we think; in the assemblage 'post-human entanglement of the operator and the drone is riddled with affect' (Feigenbaum, 2015, 283).

If the drone allows us to get into volumes of the Nephosphere in new ways, it also renders volumes differently as an expanded way of 'seeing', from novel perspectives and with increasing visual manoeuvrability. The mobility of the drone, coupled with new data processing approaches such as Structure from Motion (SfM) photogrammetry, has been revolutionary in redefining how topographic surveys are carried out in physical geography, because SfM allows 'rapid 3D point cloud acquisition for minimal expense' (Smith et al., 2015, 248). Coupled drone/SfM methodologies have proliferated in physical geography because the resultant volumetric point cloud data can exceed the quality of data from more expensive laser scanning systems (Zahawi et al., 2015). However, viewing the methodology through this epistemological lens, though exciting, overlooks the broad cross-disciplinary areas that are ripe for mutual human/physical geography exploration.

For instance, SfM was used in a demonstration to build a model of the Christ the Redeemer statue in Rio de Janiero (Pix4D, 2015). Terrestrial laser scanners were not able to measure the top of the statue, whilst sensors on board piloted aircraft and satellites would fail to measure the tall, narrow structure in detail – but by manoeuvring agile quadcopter drones around and over the figure to collect photographic data, a model was produced allowing virtual navigation of the statue in 3D (Figure 4).[ii] Here we see an example of human geography's interest in the vertical and volumetric, using RS techniques that are familiar in physical geography, a demonstration of how drone technology allows us to sense, create, imagine and share, and a practical example of Weizman's (2002, 2) 're-visioning of existing cartographic techniques… transform[ing] a two-dimensional surface into a three-dimensional volume'.

Geographers well know that landscapes are not uniform or static, they are volumetric and dynamic, and so to encounter them, explore them and measure them with more experiential and experimental drone praxes – developing more dynamic and reactive flight-paths that respond to terrain or canopy variance in real-time; and diversifying from 'lawnmower' survey patterns as are common in physical geography research – will likely lead to enhanced understanding across the disciplinary spectrum.

Figure 4 Here

Given that SfM photogrammetry has already been accepted as a useful methodology in physical geography (see Lucieer et al., 2014; Glendell et al., 2017) and for surveying archaeological remains (López et al., 2016), it is not difficult to imagine the benefits of this highly mobile aerial technology in, for instance, surveying heritage sites under threat in war zones or providing rapid situational information to urban or transport geographers. Such methodologies will be brought to bear on a full spectrum of geographical questions and how human geographers will theorise 'visual' geographies from *within* these volumes. Author 1, for instance, recently contributed an SfM model to an exhibition about an Aboriginal Heritage Trail in New South Wales, Australia. Visitors could use a touchscreen to 'swim' through a textured point cloud of the path rendered from 10,000 drone images. Numerous visitors suggested this a visceral sense of being 'in' the landscape and 'on' the trail.

Bringing a human geography sensibility to the technology stimulates consideration of ontological as well as epistemological questions where 'materials, technologies and infrastructures associated with vertical spaces and forms can also shape people's memories, feelings, sensations and emotions' (Harris, 2014, 610). In the words of Shaw (2017, 11), 'these prostheses are unimpeded by terrestrial obstacles and can access subjects from above, reconfiguring the interface between capital, state, and sense. For this reason, aerial prostheses must be considered ontologically'. Clearly, though the drone is tied connotatively to scholarly discourse in RS at present, it harbours potential for more variegated proximate positions. Nephospheric perspectives generate materials that surmount 'the eye's immobility... [through] ...foregrounded "dislocation" and aerial motility' (McCosker, 2015, 7). Therefore, we argue, it behoves geographers (both human and physical) to embrace the drone as a data capture device *and* as a conduit to haptic volumetric experiences. Remote sensing becomes 'proximal sensing' where the 'human operator is surrounded by the machine, is intimate with the machine, becomes the machine…' (Mindell, 2002, 63 cited in Adey, 2010a).

Though some might sense danger in drone methodologies exacerbating the role of technology in supplying 'the dominant basis for an understanding both of the world and ourselves' (Ihde, 1983, 10), methodological participation takes seriously the novel geographic imaginaries already unfolding within the turbulent Nephosphere, allowing us to productively and disruptively shape everything from hardware development to airspace legislation from a more-than-speculative position.

III. Aerial Commons

> 'It has been long established that the sky is public—otherwise each airplane would have to get permission to fly over your property. This is akin to the concept of

> international waters on the ocean. But as with international waters, this public space is becoming increasingly and deliberately enclosed, in what might constitute a modern 'enclosure of the commons'. (Crampton, 2016, 140)

In his potent critique of the overlaps between military and corporate drone technologies, Ian Shaw (following Crampton 2016) has argued that 'the upper atmosphere was an inaccessible frontier' (Shaw, 2017, 12) but that 'corporations of various sizes are seeking to colonize the skies with a robotic armada' of drones orbiting 'the towering skyscrapers of a capsularized elite, materializing a cloud city of secessionary volumes' (Shaw, 2017, 12). Shaw suggests that this new constellation of atmospheric activity amounts to an effective enclosure of vertical common space that echoes 17th and 18th-century land enclosures in England.

Attempts have indeed been made at political and technological enclosure of the Nephosphere, through geo-fencing areas to keep drones out, drone registration requirements (recently introduced in the USA and UK), and more stifling country-wide blanket bans on drone flights in some countries (e.g. Spain where only government-approved pilots are permitted to fly). It is generally illegal to release liquids or objects from drones and flights within 'congested' spaces are deemed illegal according to civil or federal aviation laws in many countries.

Despite legislation, subversive uses of consumer drones has continued, prompting changes in commercial practice. The drone manufacturer DJI, for instance, recently made wholesale changes to their flight control system, imposing a mandatory firmware update that established a geofence around the White House, restricting civilian drone flights over 13% of Washington DC; an irony given that military drone flights are ordered from there all over the world without local permission. Similar geofences exist around major airports or restricted military zones. Yet these invisible 'fences' are only enforced by specific manufacturers and do not apply to open-source drone hardware. This means that if you buy into closed-source drone technology, the 'democratizing' potential of drones is compromised through hardware, firmware or software updates enforced by corporations. Technological barriers to operation (like geofences) are futile in the face of home-brew or open-source drone technology and Bracken-Roche (2016, 168) suggests that 'building your own drone' (something that physical geographers have long experimenting with), is just one of many simple ways to subvert such structures of control. Figure 5 shows how 'hobbyist' expertise has guided some developments within physical geography (see Cunliffe et al. 2016 for research stemming from a self-build example).[iii]

Figure 5 Here

At present the geofences, like so many regulatory and surveillance technologies, are extremely limited in what they do. Their deployment by drone manufacturers, coupled with sustained media campaigns, is rather meant to dissuade governments from passing more legislation whilst convincing the public that the 'wild west moment' in the Nephoshere is over. Any pilot will assure you this is not the case: from our own flying experiences, we know that taking off, landing and manoeuvring the aircraft is a fraught event that provokes a multitude of physical and emotional responses in the body, precisely because the drone is a powerful object. The regulation of drones then, from a pilot's perspective, is more assumed than one might expect. In practice, the drone can access any vantage point not occupied by another material structure without much legal, technological or social impediment, meaning that for human geographers, the 'voids and volumes in-between buildings' or for physical geographers, the complex structures within the tree canopy or the volcanic crater 'become the subject of a new spatial imagination' (Jensen, 2016, 71).

Attempts at enclosure, which have been about as effective as trying to ban piracy on the internet, are reactions to conflicting intentions and ideologies in the Nephospheric commons, where drones have sprayed graffiti on urban billboards, crashed into stadiums full of people, struck power lines, strayed into international airports, and hampered the life-saving activities of firefighting aircraft. These activities can carry heavy penalties – if the pilots can be located. Despite technical and political attempts at enclosure, there remains a lack of clarity around control and ownership of the Nephosphere because the complicated relationship between bodies, machines, interfaces and environments contained within formed faster than social or political understanding of potentials. In terms of the democratisation of the volume, this uncertainty has proved beneficial in permitting a broad spectrum of experimentation by scientists, engineers and hobbyists, including geographers.

Critical to the assimilation of drones into geographical methodologies is consideration of Nephospheric navigation and future access. Looking to different contested environments may prove useful in postulating future aerial territories. Considering shipping, Peters (2014) writes that 'ships are mobile or immobilised through apparatus of national and international control' [and yet]... 'those surveilled also harness legal and material conditions to avoid surveillance'. In the past, the sea was seen as unregulated space and with the creation of national Exclusive Economic Zones, shipping lanes and maritime etiquette, many decried the loss of the 'open sea'. Yet pirates still lurk, internet cables are still ripped asunder by trawling nets, and the seas are still filled with migrant boats, home-brewed flotillas, drug cartel submarines and saildrones.

The FAA is currently trying to establish an 'Unmanned Aerial System Traffic Management' system, partly to create airspace for commercial and government drone flights (see Figure 6): a model that much of the world will likely follow to boost aerial business opportunities (FAA, 2015).[iv] Like the establishment of shipping lanes in the past, the striation of the Nephosphere does not necessarily predicate a cessation, or even constriction, of subversive use, but it does mean technical and legislative knowledge will enable researchers to more effectively participate in, or subvert, those structures. Like public space on urban streets, vertical publics will be negotiated at different scales. Asserting a public right to the Nephosphere assures it remains contested space.

Figure 6 Here

IV. Aerial Subversions

> 'Lost in the concern that the drone is an authoritarian instrument is the possibility that it might simultaneously be a democratizing tool, enlarging not just the capacities of the state but also the reach of the individual.' (Wallace-Wells, 2015, np)

Despite the importance of the concerns lodged by Shaw (2017) in the previous section, he also paints a picture where the only drones being deployed in the Nephosphere are police and commercial drones, harbouring no room for the public deployment of drones, for productive research uses, or for subversive reworkings. In considering the drone as a sensing machine and as a machine that extends our own sensory capacities and affordances as researchers, drones can spark innovative geographic methodologies through subversive redeployment, despite their emergence (like many technologies) from a militaristic milieu. Like all technologies of surveillance ('watching from above'), drones can be *détourned* and wielded as sousveillance ('watching from below') tools.

As we have shown, drones are now routinely used by physical geographers to subvert traditional data supply routes (see Figure 1); but beyond a few limited examples (e.g. Sandbrook, 2015) there is little scholarly material for physical geography audiences that considers the critical, ethical and philosophical implications of aerial practices. Perhaps this is because RS has a long history in physical geography and the analysis of synoptic Earth-view images is now part of a routine geospatial workflow. As Figure 5 evidenced, there are examples of physical geographers having engaged with technological experimentation and hacking (see also Anderson et al. 2016) but the full detail of drone self-builds is rarely found within scientific publications, since the data captured (and their geospatial quality) tend to be the major aim of such research (Duffy et al 2017). And yet human geographers, we argue, could reap much by learning from their physical geography colleagues who are actively experimenting with drone technology, assisting in developing critical potentials for the drone as a political tool.

Outside of academia, other groups have been actively involved in both critical and technically incisive aerial subversions. For example, in the USA, PETA used drones to gather evidence of a large-scale farm in Texas dumping blood into a river (Schuessler, 2016, np), while in California, one man operates a 'flying citizens' patrol', filming police as they pull cars over to curb abuses (Wallace-Wells, 2015). During 2016 protests against the Dakota Access Pipeline (North Dakota), citizen drone pilots captured 'human rights abuses, caught police in lies, and—in the case of the numerous videos that show their drones being shot at by police—have documented law enforcement committing federal crimes' (Koebler, 2016, np). In the UK, social justice collective ImmigrantX (2016) have used drones to disrupt stop and search operations by border forces. Meanwhile, Australia has taken a more nuanced approach to regulation, protecting drone sousveillance where 'the productive, though legally dubious use of drones' has prevented greater crimes from taking place (McCosker, 2015, 10).

Drones have proven their potential to subvert traditional power structures, and deliver benefits in areas considered marginal by the corporations who define the quality of, and control access to, mapping products. The grassroots mapping project 'Re-Map Lima', for instance, utilized drone aerial photography to 'interrogate the exclusionary nature of cartographic representations of marginalised neighbourhoods […] which often play a role in the unjust trajectory of urban change' (Centre for Advanced Spatial Analysis (CASA), 2015, np). Peluso (1995, 386) argues that such activities allow local groups to 'claim power through mapping by using not only what is on a map, but what is not on it' and in Lima this allowed for map-making by local citizens (CASA, 2015). In Indonesia, drones have also been used for participatory counter-mapping to stop land grabs and provide indigenous communities with a means of challenging 'spatial planning from above' (Radjawali & Pye, 2015, 3); capabilities that were hindered by the insufficient spatial and/or temporal resolution of satellite RS data previously.

Patrick Meier's network of digital humanitarian 'UAViators',[v] is a further example of citizens engaging with drone methodologies to provide targeted spatial data for decision making (Meier, 2015). In doing so, these approaches subvert normal data supply chains to fill the data gap when satellites cannot deliver information quickly enough. UAViators have also established evolving codes of conduct in which drone communities work with local people to develop frameworks for 'ethical deployment' in community mapping projects, humanitarian crises and rescue efforts. When engaged effectively by local citizens, drones can therefore be wielded as a positive technology that paves the way for public participation in conflict resolution (Zhang & Fung, 2013). There remains a lack of geographical research addressing the implications of these subversive drone practices and their impacts on society however and development geographers could research the growing importance of drones in these contexts, expanding the imagined remit of drone methodologies (Martini et al., 2016). Researchers should participate in these subversions or, at the very least, engage in ethnographic work with those who do.

Sandbrook (2015, 640) counsels caution over the use of drones in remote areas, where he suggests their presence may provoke 'fear, confusion and hostility' or 'generate conspiracy theories, suspicions and fantasies' and 'trigger a fresh wave of alarm' amongst indigenous people. When practicing drone methodologies closer to home, we can testify that social anxiety about drones can still surface in unexpected places. Recently, during a drone survey at a remote site, Author 2 was stopped by an agitated local resident who repeatedly positioned himself underneath the drone's path, rendering the survey impossible: to do so would have been to breach the rules dictating operations at the site. He argued that drones were disruptive and didn't care what permissions were in place (see Figure 7).

Figure 7 Here

Equally, sousveillance for social causes can boomerang. In Philadelphia, USA, labour unions using drones to monitor their own protest were accused of 'invest[ing] in the most cutting-edge technology available to intimidate people who get in their way' (Wolf, 2016, np). Here we see an example of how the positive uses of drones for geographical research are pitched against a backdrop of social alarm, highlighting the need for work by geographers on exploring the interplay that emerges as drones take to the skies. The double edge of drones is that, like security cameras, they have the capacity to marshal people's behaviours and compel even those in power to act with integrity. Yet surveilled authorities often actively work to subvert the 'protester panopticon' by hiding badge numbers and electronically or physically attacking drones or their operators in a spiral of responses (Waghorn, 2016).

Matthew Power (2013) suggests that drones are 'too easy a placeholder or avatar for all of our technological anxieties—the creeping sense that screens and cameras have taken some piece of our souls, that we've slipped into a dystopia of disconnection.' Part of the 'terror' of the drone is the ascension of sensing bodies into the Nephosphere, subverting existing architectures of control. Proximal aerial mobility has the capacity to render security investment in CCTV, gates, fences and guards farcical and hence drones 'speak back into the all-encompassing ambitions of the security-entertainment complex in unexpected ways from which it is possible to learn new associative open-ends' (Thrift, 2011, 19); 'proof enough of the validity of Walter Benjamin's thesis that technology, today used for deathdealing purposes, may eventually recover its emancipating potential and readopt the playful and aesthetic aspirations that secretly inspire it' (Chamayou, 2015, 78).

Consider, for instance, the ways in which cities are being transformed through 'vertical sprawl' where archipelagos of wealthy 'vertical gated communities' now dominate urban horizons (Graham & Hewitt, 2012, 80). The drone has a role to play here in challenging 'aerial sovereignty' (see also figure 7), offering the ability to match and even exceed the perspectives of these erections (Williams, 2010). Drones also harbour enormous potential for both sanctioned and unsanctioned exploration underground, encased in cages to protect their blades and to mitigate damage to infrastructure and bodies (Figure 8). Such design modifications provide a useful urban exploration proxy for those unable or unwilling to climb heights or plunge depths in the skin they are in, or for surveying complex physical environments (e.g. tree canopies, rocky outcrops) where navigation of the drone would otherwise be risky.

Figure 8 Here

Practices of geographic exploration have been critiqued because of the inevitable (in)ability of bodies to move in 'standard ways' and it has been suggested that a 'multiplicity of subjectivity can help us think productively about both the different ways that people explore, as well as the different bodies who perform the action' (Mott & Roberts, 2013, 8). Drone methodologies multiply subjectivities by facilitating exploration of spaces beyond immediate gravitational, social or physical limitations. Cross (2016), a disabled aircraft modeller, describes using a first-person-view (FPV) drone to explore the upstairs areas of his own house, which he had never been able to visit. Here, the Nephosphere is more localised but the capacity to explore out-of-body locations vicariously is nonetheless of relevance to volumetric, home, and mobilities research, whilst also creating new opportunities for physical geography fieldwork by those who could never access field sites on foot.

Anderson (2012) suggested that drones are 'the first technology where the toy industry and hobbyists are beating the military industrial complex at its own game' and that hobbyists will inevitably 'demilitarize and democratize them so they can find their full potential'. Earlier in Figure 5, we demonstrated how physical geography drone methodologies have been informed by hobbyist approaches, subverting traditional data supply routes (see also Figure 1), allowing geographers to circumvent the need to buy products from commercial companies who restrict dissident deployment. Furthermore, the technical literacy gained from this work also means that geographers are better able to critically understand the drone's specific limitations and potentials.

Of course, home-brew technology may also be appropriated by those in power, further highlighting how military and consumer technologies inform each other. Military technology often takes years to test and develop before it is deemed safe or operational and in some cases consumer drones have outpaced military capabilities. Hsu (2017, np) writes that the military may soon use consumer drones to 'scout high-rise buildings and underground tunnels' for troop threats, whilst Dorrian (2016, 51).

argues that the military actively seeks to promote consumer drones because the domestication of the technology, and the grounding of the drone in a 'pictorial tradition of empathetic machines' dulls public critique of military drone use. Like any technology, geographers should be wary of deploying drones, or sharing what we learn about them, uncritically.

Thus, drones, with their 'unruly trajectories, their multidirectional motility, and their accessibility to ordinary users' (McCosker 2015, 4), are amorphous avatars that reshape geographical possibilities in environments, often faster than they can be regulated. Concerns about where the drone goes, as a roaming eye of an oft-unseen pilot, unnerve people precisely because of their directional freedom that defies fixed vectors, allowing a re-imagining of phenomenology that:

> '...gives objects much more importance than traditional phenomenology since it is so obviously an assemblage that depends upon the articulation of bodies and objects in new combinations for its force...' (Thrift 2011, 21).

We suggest that flying is less a habitation of machine subjectivity and more a melding of human-machine perception which changes what we imagine we might do, including how we move, where we go, and what we might encounter. The exploratory potential of the drone, more than any other technology, triggers this conception, replete with linked apprehensions; regardless of the interface or degree of autonomy, we have begun to comprehend the world through drone sense and sensibilities. The subversive power of the drone 'indicates [both] the threat and the obvious military application, but also the promise of points of resistance or media innovation' (McCosker 2015, 6). In other words, 'drones are power tools with the ability to transform the political and social landscape forever' (Yehya, 2015, 3).

V: Future Drone Geographies

> '…to open thinking spaces for an affective micropolitics of curiosity in which we remain unsure as to what bodies and images might yet become.' (Lorimer, 2010,

252)

Looking to the future of drone methodologies, geographers should consider aerial futures where drone-to-human communication and drone-to-drone cooperation are managed with increasing autonomy, using cues from human and non-human biology. Most consumer drones can already fly autonomously along way-pointed routes, guided by GPS, but the scientific and engineering literature suggests that it will not be long before drones will fly by following different cues, with minimal human input. An aerial future is in sight, replete with microcomputer-powered 'detect-and-avoid' drone systems carrying tiny sensors that allow the aircraft to adjust its flightpath to avoid obstacles independently of pilot control. Pushbroom stereo imaging approaches (Barry & Tedrake, 2015) and super-lightweight (2mg) insect-inspired compound eye cameras (Pericet-Camara et al., 2015) are two such examples that will allow drones to navigate the Nephosphere without human involvement. Indeed, within the timescale of writing and publishing this article, the drones we are flying for our research have evolved to incorporate more intelligent flight capabilities including detect-and-avoid and reliable automatic landing procedures.

Geographers should imagine a future where drone flights are controlled by electro-encephalogram headsets (LaFleur et al. 2013), with research in computer learning underpinning the translation of brain impulses into robotic motion (Kos'myna et al. 2014). Coupled with changes in the hardware that are intended to improve safety (see Figure 8), it is possible that emerging intelligent software capabilities will bring improvements to piloting that reduce risk to people, wildlife and property (see also Figure 2 and section IV), whilst also allowing immobile pilots to enjoy intricate vicarious mobility in the Nephosphere. But what are the post-phenomenological politics of brain-controlled drones? Human geographers have work to do if they are to understand emerging drone capabilities and guide policy decisions and social imaginations using examples of tangible praxes. Equally, physical geographers should experiment with these capabilities to deliver evidence-based understanding of their effectiveness for surveying challenging landscapes, and we suggest, should think through the extent to which the drone has transformed their opportunities and imaginations in and beyond an expanded sense of ethics.

New research prospects in geography will be created by the increasingly immersive experience of flying. Head goggles with FPV allow pilots to fly so that '...what you feel is not displacement but extension' (Wallace-Wells, 2015). Observing a pilot using the goggles, Kirk (2016) writes that, '...his hands were visibly trembling. He quakes, he said, because the experience is so overwhelming.' In vertiginous YouTube videos created through FPV, pilots make clear that the technical capacities of drone technology engender orthogonal subjectivities. This parallels the findings of Vertesi (2012) who investigates the 'body work involved in [robotic] simulation, and the embodied imagination' and suggests that 'scientific seeing requires not only eyes and instruments, but hands and bodies as well', a phenomenology not limited to the human or the biological. As Vertesi's (2012) work suggests, there is a clear benefit to scientific sampling if this embodiment is engaged – for example, there are many places where being 'in' the drone as it flies via FPV will open new possibilities for novel data capture, even as it breaches 'line-of-sight' legislation. [vi] We urge physical geographers to evaluate how FPV flight could enhance manoeuvrability, data capture and spatial accuracy, and human geographers to think seriously about how the drone fits into disciplinary narratives about exploration (Garrett, 2016).

New research is taking place on bio-adapting drone control using insect cognitive processes to enable drones to respond to visual or smell-based cues (Cope et al., 2016). These cyborg drones are the product of social and technological conditions (Dodd, 2014) evidencing the 'porous borders between human, animal and machine' (Whatmore, 2002, 174). Drones then, as extensions of the body, are more than tools and in fact are 'organs, full partners, […] in "infoldings of the flesh"' (Haraway, 2008, 250). New ways of simplifying human-robot interactions (e.g. the drone that flies to meet its waving human controller [Monajjemi et al., 2016]) will allow 'embodied imagination', supporting 'robotic possibilities' of motion, and 'articulating the instrumental action and interaction necessary for seeing' (Vertesi 2012: 396). Soon, vat-grown drones, simultaneously machinic and biological will metamorphose and emerge (Atherton, 2016). Thus, we 'reprogram users' eyes, hands, necks, feet, and sensoria, giving rise to a variety of new gestures and interactions at the human–nonhuman interface' (Woodward et al., 2015, 498). Once biomimetic sensors and algorithms are controlling drones through hybrid intelligence and autonomy, human geographers will have a tangible methodology for entering Weizman's (2002: 2) 'three-dimensional volume' whilst physical geographers and RS researchers will need to understand the ways that they can interface with and explore this new scientific method.

As Feigenbaum (2015) suggests, drone futures will also incorporate swarms. The US Navy recently launched the LOCUST (Low-Cost UAV Swarming Technology) programme, which will enable the firing of drone swarms onto a battlefield. Although disconcerting in the hands of the military, there are civilian projects underway where swarms work co-operatively to 'tie fibers together to create tensile structures' to build infrastructure (Wallace Wells 2015, np). These speculative futures, we re-stress, point towards augmentation and entanglement as much as autonomy. In paying attention to the changing relationship between humans, non-humans and objects in these assemblages, geographers will find themselves in interesting philosophical territory (see Shaw & Meehan, 2013).

Regardless of whether the above speculative narratives crystallise, we suggest that development of drone methodologies is crucial to understanding political and social futures and that these suspicious machines are also creating a '...counter-politics of verticality' (Harris 2015, 608) where 'the aerial subject bounces back. It fights, flees, improves, toughens, and resists the poverty of the imaginations that attempt to govern it' (Adey 2010a, 262). As with GIS, geographers may remain critical of drones' military origins and malicious deployments and still be adept operators. This is facilitated by the rapid acceleration of technical development in tandem with an upswing in 'maker' cultures which has meant that the drone has outstripped the pace of legislation and, to an extent, corporate control. For now. It is up to geographers to engage with this technology and its myriad complexities so that we can have an educated discussion about the promises and threats of drones for science and society.

Conclusions

> 'We think we know our logical and geographical borders, and have a sense of how vulnerable we are to social engineering and insider threats. But drones have the potential to change all of that' (Badman 2014, np; cited in McCosker 2015, 11).

To conclude, we summarise our findings in regard to our initial aims: to explore the transdisciplinary potential of drone methodologies in the context of volumetric and visual geographies.

Firstly, we return to the z-axis, where if 'thinking about power and circulation in terms of volume opens up new ways to think of the geographies of security' (Elden, 2013, 49), then a methodological perspective on drone technology requires experiential reframing of this consideration because 'without knowing what lies above us, we have very little scope for bringing it under democratic control' (Cwerner et al. 2009, x, cited in Adey 2010b, 35). As Crampton (2016, 3) rightly suggests, in the contested Nephosphere, the stakeholders in the surveillance-market-governance assemblage countermand singular narratives. In other words:

> 'We make the drone a singular existence to hide its complications. We make it into something with amazing potential to hide the fact that we don't really know where it is going.' (Rothstein 2015, 57)

So, in interpreting the drone as a geographical methodology we agree that, 'depending on its contexts of use the same piece of technology can perform a very different function' (Jablonowski 2015, 2). This is true within geography presently – physical geographers are taking to the air with a major aim of data capture, whilst human geographers are concerned with a critical evaluation of the technology. The Nephosphere is being legally defined in response to aerial engagements, yet capacities to act and hack that zone can and will continue by geographers, hobbyists and others, regardless of any restructuring that takes place. We are therefore sceptical of claims that the expanding sensing capacities of drones simply lead to monitoring, policing and destruction (Adey 2010a, 113) or that 'the tools of human geography and the sociology of social networks are' simply being 'enlisted in the service of a policy of eradication' (Chamayou 2015, 49). However, we are equally dubious of claims that drones are an apolitical geographic 'tool' (Snitch, 2015) harbouring no socio-political weight or consequences.

In avoiding the uncritical deployment of drones as simple tools for data capture, and refusing to condemn them as simple components of the 'military-industrial complex', off limits to critical researchers (Bracken-Roche, 2016), we suggest that a new nexus for understanding lay in the experiential, where praxis pitches drones as a way of differently experiencing the environments around us. While we agree with Shaw (2016, 3) that 'we are entering an era of complex, aleatory, and risky skyscapes', we suggest that not all of those risks are negative – much of the unfolding complexity creates compound capacities for novel forms of participation. So, drone methodologies are a powerful phenomenological proposition, because they 'immerse' us as researchers in the volume and thus challenge our imaginations of the volumetric.

Drones have a clear role to play in linking surface and subsurface and suprasurface spaces (Graham and Hewitt 2012, 4) through increasing experiences in what we have termed the Nephosphere. Drones, regardless of their degree of autonomy, are always part of a volumetric assemblage intersecting and mutually constructing those domains. Where Adey asks '...are there other ways of thinking about volumes that appear more open, more plural imaginaries that might not only describe but offer alternative volumes to inhabit' (Adey 2013: 52), we respond that physical geographers have been piloting their way through that space for some time now, developing drone methodologies. These practices undermine claims that 'verticalized digital imagery, sensed automatically from afar through machinic prostheses… tend towards ethical thinning and distanciation' (Graham and Hewitt 2013, 85).

Indeed, from a methodological perspective it makes little sense to refer to drone methodologies as purely visual, for they are multi-sensual and multimodal, and piloting is an immersive, embodied endeavour. With drones, geographers can manoeuvre sensors *within* a volcanic crater or train tunnel, fly *through* a tree canopy and *vault* barriers to explore vertical structures, from rooftops to tunnels. So, the drone offers new ways of seeing, sensing and sharing powerful environmental data and audio/visual materials and offers exploration experiences unparalleled by other methodologies. These potentials should be explored through geography research collaborations aimed at socially, politically and legally situating new and emerging RS and drone methodological practices.

The development of drone methodologies will not be without its challenges, but we must be mindful that the contexts in which drones can be used are shaped more by our inability to imagine and create than by social, legal or technological barriers. Deploying drone methodologies will reveal new directions that can inform the volumetric or 'vertical turn' as much as advance 'visual' geographies, empirical geomorphology and RS science, to name just a few. We suggest a richness to the future of drone methodologies in geography in fields such as audio/visual ethnographic studies, critical geography activism, atmospheric gas flux sampling, landscape research, architecture and infrastructure surveying (both formal and informal) and environmental management. We call for physical and human geographers to collaborate, discuss, and fly together, so that these frontiers can be explored in practice as well as theory. We also urge physical geographers to work carefully, and critically, towards integrating the drone into existing RS infrastructure and prompt human geographers to make groundbreaking (or skybreaking) moves toward critical *deployment*. To conclude, to Adey's (2013, 55) question, 'could there even be the possibility of a more democratic volume?' we respond, 'yes, we're in it, come on up.'

References

Adey P 2010a *Aerial Life* Wiley-Blackwell, Oxford
Adey P 2010b Vertical Security in the Megacity *Theory, Culture & Society* 27 51-67
Adey P 2015 Air's affinities: Geopolitics, chemical affect and the force of the elemental *Dialogues in Human Geography* 5 54-75
Anderson C 2012 How I accidentally kickstarted the domestic drone boom (Wired) http://www.wired.com/2012/06/ff_drones/ Accessed 1 March 2016

Anderson K 2016 Integrating multiple scales of remote sensing measurement - from satellites to kites *Progress in Physical Geography* 40 187-195

Anderson K, Griffiths D, DeBell L, Hancock S, Duffy JP, Shutler JD, Reinhardt WJ and Griffiths A 2016 A Grassroots Remote Sensing Toolkit Using Live Coding, Smartphones, Kites and Lightweight Drones *PLOS ONE* 11 e0151564

Asner GP 2001 Cloud cover in Landsat observations of the Brazilian Amazon *International Journal of Remote Sensing* 22 3855-3862

Atherton K 2016 BAE Wants to Grow Drones in Vats on Demand (Popular Science) http://www.popsci.com/bae-wants-to-grow-drones-in-vats-on-demand Accessed 13th August 2016

Badman L 2014 Drones: The Next WLAN Menace (InformationWeek Network Computing) http://www.networkcomputing.com/wirelessinfrastructure/drones-the-next-wlan-menace/a/d-id/1297454 Accessed 1st August 2016

Barry AJ and Tedrake R 2015 Pushbroom stereo for high-speed navigation in cluttered environments 2015 IEEE International Conference on Robotics and Automation (ICRA) http://dx.doi.org/10.1109/icra.2015.7139617 Accessed 23 August 2016

Bracken-Roche C 2016 Domestic drones: the politics of verticality and the surveillance industrial complex *Geographica Helvetica* 71 167-172

CAA 2017 United Kingdom Civil Aviation Authority: Airspace restrictions for unmanned aircraft and drones: information about prohibited areas, restricted areas and danger areas https://www.caa.co.uk/Consumers/Unmanned-aircraft/Our-role/Airspace-restrictions-for-unmanned-aircraft-and-drones/ Accessed 8 August 2017

Centre for Advanced Spatial Analysis (CASA) 2015 Re-Map Lima, CASA: mapping beyond the palimpcest https://www.youtube.com/watch?v=Jm5oKPLXQeY Accessed 1 October 2015

Chamayou G 2015 *Drone theory* Penguin London

Cope AJ, Sabo C, Gurney K, Vasilaki E and Marshall JAR 2016 A Model for an Angular Velocity-Tuned Motion Detector Accounting for Deviations in the Corridor-Centering Response of the Bee *PLOS Computational Biology* 12 e1004887

Crampton JW 2016 Assemblage of the vertical: commercial drones and algorithmic life *Geographica Helvetica* 71 137-146

Cross K 2016 Drones: a beginners guide *British Model Flying Association Magazine* BMFA London

Cunliffe AM, Brazier RE and Anderson K 2016 Ultra-fine grain landscape-scale quantification of dryland vegetation structure with drone-acquired structure-from-motion photogrammetry *Remote Sensing of Environment* 183 129-143

Cwerner SB, Kesselring S and Urry J 2009 *Aeromobilities* Routledge London

Daughtry CST, Vanderbilt VC and Pollara VJ 1982 Variability of Reflectance Measurements with Sensor Altitude and Canopy Type *Agronomy Journal* 74 744

Dodd A 2014 The Trouble with Insect Cyborgs *Society & Animals* 22 153-173

Dorrian M 2016 Drone Semiosis *Cabinet: A Quarterly of Art and Culture* 54 48-56

Duffy JP, Cunliffe AM, DeBell L, Sandbrook C, Wich SA, Shutler JD, Myers-Smith IH, Varela MR and Anderson K 2017 Location, location, location: considerations when using lightweight drones in challenging environments. *Remote Sensing in Ecology and Conservation*. 10.1002/rse2.58

Duffy JP and Anderson K 2016 A 21st-century renaissance of kites as platforms for proximal sensing *Progress in Physical Geography* 40 352-361

Elden S 2013 Secure the volume: Vertical geopolitics and the depth of power *Political Geography* 34 35-51

FAA 2015 USA Federal Aviation Authority: DOT and FAA Finalize Rules for Small Unmanned Aircraft Systems https://www.faa.gov/news/press_releases/news_story.cfm?newsId=20515 Accessed 12 August 2016

Feigenbaum A 2015 From cyborg feminism to drone feminism: Remembering women's anti-nuclear

activisms *Feminist Theory* 16 265-288
Garrett BL 2016 Exploration in Richardson D, Castree N, Goodchild M, Kobayashi A, Liu W and Marston D eds *Wiley-AAG International Encyclopedia of Geography,* Wiley-Blackwell and the Association of American Geographers, London, UK
Garrett BL, Moss A and Cadman S 2016 *London Rising: Illicit Photos from the City's Heights* Prestel/Random House London
Glendell M, McShane G, Farrow L, James MR, Quinton J, Anderson K, Evans M, Benaud P, Rawlins B and Morgan D 2017 Testing the utility of structure-from-motion photogrammetry reconstructions using small unmanned aerial vehicles and ground photography to estimate the extent of upland soil erosion *Earth Surface Processes and Landforms*
Graham S 2016 *Vertical: looking at the city from above and below* Verso Books London
Graham S and Hewitt L 2012 Getting off the ground: On the politics of urban verticality *Progress in Human Geography* 37 72-92
Gregory D 2011 From a View to a Kill *Theory, Culture & Society* 28 188-215
Gregory D 2014 Drone geographies *Radical philosophy* 183 7-19
Haraway D 2008 *When Species Meet* University of Minnesota Press Minnesota
Harley JB 1988 Maps, Knowledge and Power in Cosgrove D and Daniels S eds *The Iconography of the Landscape,* Cambridge University Press, Cambridge, UK 277-312
Harris A 2014 Vertical urbanisms: Opening up geographies of the three-dimensional city *Progress in Human Geography* 39 601-620
Hsu J 2017 The Military May Soon Buy the Same Drones You Do *Wired* Conde Nast New York
Ihde D 1983 *Existential Technics* State University of New York Press Albany
ImmigrantX 2016 Drones for social justice http://www.immigrantx.org/drones-for-social-justice-iv/ Accessed 2 August 2016
James MR, Robson S, d'Oleire-Oltmanns S and Niethammer U 2017 Optimising UAV topographic surveys processed with structure-from-motion: Ground control quality, quantity and bundle adjustment *Geomorphology* 280 51-66
Jensen OB 2016 Drone city – power, design and aerial mobility in the age of "smart cities" *Geographica Helvetica* 71 67-75
Kingsbury P and Jones JP 2009 Walter Benjamin's Dionysian Adventures on Google Earth *Geoforum* 40 502-513
Kirk J 2016 Killer Bunny in the Sky. A drone war begins between vegans and hunters http://harpers.org/archive/2016/03/killer-bunny-in-the-sky/5/ Accessed 2 August 2016
Koebler J 2016 The Government Is Using a No Fly Zone to Suppress Journalism At Standing Rock *Motherboard* Vice London https://motherboard.vice.com/en_us/article/yp3kak/the-government-is-using-a-no-fly-zone-to-suppress-journalism-at-standing-rock Accessed 21 October 2017
Koh LP and Wich SA 2012 Dawn of Drone Ecology: Low-Cost Autonomous Aerial Vehicles for Conservation *Tropical Conservation Science* 5 121-132
Kos'myna N, Tarpin-Bernard F and Rivet B 2014 Bidirectional feedback in motor imagery BCIs *Proceedings of the extended abstracts of the 32nd annual ACM conference on Human factors in computing systems - CHI EA '14*
LaFleur K, Cassady K, Doud A, Shades K, Rogin E and He B 2013 Quadcopter control in three-dimensional space using a noninvasive motor imagery-based brain–computer interface *Journal of Neural Engineering* 10 046003
López JAB, Jiménez GA, Romero MS, García EA, Martín SF, Medina AL and Guerrero JAE 2016 3D modelling in archaeology: The application of Structure from Motion methods to the study of the megalithic necropolis of Panoria (Granada, Spain) *Journal of Archaeological Science: Reports* **10** 495-506
Lorimer J 2010 Moving image methodologies for more-than-human geographies *Cultural*

Geographies 17 237-258
Lucieer A, Jong SMd and Turner D 2014 Mapping landslide displacements using Structure from Motion (SfM) and image correlation of multi-temporal UAV photography *Progress in Physical Geography* 38 97-116
Mancini F, Dubbini M, Gattelli M, Stecchi F, Fabbri S and Gabbianelli G 2013 Using Unmanned Aerial Vehicles (UAV) for High-Resolution Reconstruction of Topography: The Structure from Motion Approach on Coastal Environments *Remote Sensing* 5 68-80
Martini T, Lynch M, Weaver A and van Vuuren T 2016 *The Humanitarian Use of Drones as an Emerging Technology for Emerging Needs* in The Future of Drone Use edited by Bart Custers Springer London
Masunaga S 2016 FAA predicts that 4.3 million hobbyist drones will be sold by 2020 http://www.latimes.com/business/la-fi-drone-forecast-20160325-htmlstory.html Accessed 1 February 2017
Mattern S 2016 Cloud and Field *Places Journal* https://placesjournal.org/article/cloud-and-field Accessed 19 Oct 2017
McCosker A 2015 Drone media: unruly systems, radical empiricism and camera consciousness *Culture machine* 16 1-21
McGonigle AJS, Aiuppa A, Giudice G, Tamburello G, Hodson AJ and Gurrieri S 2008 Unmanned aerial vehicle measurements of volcanic carbon dioxide fluxes *Geophysical Research Letters* 35 1-4
Meier P 2015 *Digital humanitarians: how big data is changing the face of humanitarian response* Taylor and Francis, London
Miah A 2017 How the drone went from the latest must have tech toy to a billion-dollar cultural phenomenon http://theconversation.com/how-the-drone-went-from-the-latest-must-have-tech-toy-to-a-billion-dollar-cultural-phenomenon-71773 Accessed 3 February 2017
Milton EJ, Blackburn GA, Rollin EM and Danson FM 1994 Measurement of the spectral directional reflectance of forest canopies: A review of methods and a practical application *Remote Sensing Reviews* 10 285-308
Mindell D 2002 *Between human and machine: feedback, computing and control before cybernetics* Johns Hopkins University Press Baltimore
Mlambo R, Woodhouse HI, Gerard F and Anderson K 2017 Structure from Motion (SfM) Photogrammetry with Drone Data: A Low Cost Method for Monitoring Greenhouse Gas Emissions from Forests in Developing Countries *Forests* 8 68, doi:10.3390/f8030068
Monajjemi M, Mohaimenianpour S and Vaughan R 2016 UAV, come to me: End-to-end, multi-scale situated HRI with an uninstrumented human and a distant UAV Volume IEEE 4410-4417
Mott C and Roberts SM 2013 Not Everyone Has (the) Balls: Urban Exploration and the Persistence of Masculinist Geography *Antipode* 46 229-245
NATS 2017 National Air Traffic Services: Introduction to airspace http://www.nats.aero/ae-home/introduction-to-airspace/ Accessed 8 August 2017
Noys B 2015 Drone Metaphysics *Culture Machine* 16 1-22
Peluso NL 1995 Whose woods are these? Counter-mapping forest territories in Kalimantan, Indonesia *Antipode* 27 383-406
Pericet-Camara R, Dobrzynski MK, Juston R, Viollet S, Leitel R, Mallot HA and Floreano D 2015 An artificial elementary eye with optic flow detection and compositional properties *Journal of The Royal Society Interface* 12 109
Peters K 2014 Tracking (Im)mobilities at Sea: Ships, Boats and Surveillance Strategies *Mobilities* 9 414-431
Pickles J 1997 Tool or Science? GIS, Technoscience, and the Theoretical Turn *Annals of the Association of American Geographers* 87 363-372
Pix4D 2015 Projeto Redentor White Paper, Aeryon Labs Inc. 22pp. https://pix4d.com/wp-

content/uploads/2013/04/Projeto_Redentor_Pix4D_AeryonLabs_Whitepaper_2015.pdf Accessed 1 March 2016.
Power M 2013 Confessions of a Drone Warrior *GQ Magazine* October 2013
Radjawali I and Pye O 2015 Counter-mapping Land Grabs with Community Drones in Indonesia (conference paper 80). International conference on land grabbing, conflict and agrarian-environmental transformations. Thailand, 5-6 June 2015 http://www.iss.nl/fileadmin/ASSETS/iss/Research_and_projects/Research_networks/LDPI/CMCP_80-Radjawali_and_Pye.pdf Accessed 5 September 2016
Rao M and Sridhara Murthi KR 2006 Keeping up with remote sensing and GI advances—Policy and legal perspectives *Space Policy* 22 262-273
Rose G 2003 On the Need to Ask How, Exactly, Is Geography "Visual"? *Antipode* 35 212-221
Rothstein A 2015 *Object lessons: Drone* Bloomsbury London
Sandbrook C 2015 The social implications of using drones for biodiversity conservation *Ambio* 44 636-647
Schuessler R 2016 How a Philadelphia union turned drone technology into a key tool for protest *The Guardian https://www.theguardian.com/technology/2016/feb/19/philadelphia-union-strike-international-brotherhood-of-electrical-workers-private-drones-activism* Accessed 19 Oct 2017
Shaw IGR 2013 Predator Empire: The Geopolitics of US Drone Warfare *Geopolitics* 18 536-559
Shaw IGR 2017 The Great War of Enclosure: Securing the Skies *Antipode* 49 4 883-906
Shaw IGR and Meehan K 2013 Force-full: power, politics and object-oriented philosophy *Antipode* 45 216–222
Slonecker ET, Shaw DM and Lillesand TM 1998 Emerging legal and ethical issues in advanced remote sensing technology *Photogrammetric engineering and remote sensing* 64 589-595
Smith MW, Carrivick JL and Quincey DJ 2015 Structure from motion photogrammetry in physical geography *Progress in Physical Geography* 40 247-275
Snitch T 2015 How drones can deliver tangible benefits to ordinary people in Africa http://theconversation.com/how-drones-can-deliver-tangible-benefits-to-ordinary-people-in-africa-44941 Accessed 1 September 2016
Thornes JE 2004 The Visual Turn and Geography (Response to Rose 2003 Intervention) *Antipode* 36 787-794
Thrift N 2011 Lifeworld Inc—and what to do about it *Environment and Planning D: Society and Space* 29 5-26
Urry J 2003 *Global complexity* Polity Press Cambridge UK
Vertesi J 2012 Seeing like a Rover: Visualization, embodiment, and interaction on the Mars Exploration Rover Mission *Social Studies of Science* 42 393-414
Von Humboldt A 1997 [1850] *Cosmos: a sketch of a physical description of the universe (Vol. 2)* Johns Hopkins University Press Baltimore
Waghorn NJ 2016 Watching the watchmen: resisting drones and the "protester panopticon" *Geographica Helvetica* 71 99-108
Wallace-Wells B 2015 Drones and everything after - the flying, spying, killing machines that are turning humans into superheroes *New Yorker Magazine* New York, USA 5 October 2014
Weizman E 2002 *Hollow Land: Israel's Architecture of Occupation* Verso Books London
Westoby MJ, Dunning SA, Woodward J, Hein AS, Marrero SM, Winter K and Sugden DE 2015 Sedimentological characterization of Antarctic moraines using UAVs and Structure-from-Motion photogrammetry *Journal of Glaciology* 61 1088-1102
Whatmore S 2002 *Hybrid Geographies: Natures Cultures Spaces* SAGE London
Williams AJ 2010 A crisis in aerial sovereignty? Considering the implications of recent military violations of national airspace *Area* 42 51-59
Wolf C 2016 Union Allegedly Uses Drone to Intimidate Construction Workers in Editor

http://dailycaller.com/2016/05/16/union-allegedly-uses-drone-to-intimidates-construction-workers/ Accessed 19 October 2017

Woodward K, Jones JP, Vigdor L, Marston SA, Hawkins H and Dixon DP 2015 One Sinister Hurricane: Simondon and Collaborative Visualization *Annals of the Association of American Geographers* 105 496-511

Yehya N 2015 The Drone: God's Eye, Death Machine, Cultural Puzzle *Culture Machine* 16 1-3

Zahawi RA, Dandois JP, Holl KD, Nadwodny D, Reid JL and Ellis EC 2015 Using lightweight unmanned aerial vehicles to monitor tropical forest recovery *Biological Conservation* 186 287-295

Zhang Y and Fung T 2013 A model of conflict resolution in public participation GIS for land-use planning *Environment and Planning B: Planning and Design* 40 550-568

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[i] And flown into places human bodies cannot go. Here, *National Geographic* destroys two drones making the first 3D map from inside a spewing volcanic crater: https://www.youtube.com/watch?v=zFIWWM0Iv-U (Last accessed: 9th August 2017).

[ii] With 80% overlap in photography, producing a 134.4-million-point cloud (Pix4D, 2015).

[iii] Though we suggest that the label 'hobbyist' acts to undermine the considerable expertise that exists within non-research user communities (see Duffy et al 2017), since communities such as DIYdrones.com have provided critical support to the development of physical geography drone methodologies (and in other disciplines like ecology, Koh & Wich, 2012).

[iv] Aimed at generating $82 billion and creating over 100,000 jobs in the next decade (FAA, 2015).

[v] UAViators is a network of 2000 vetted pilots in 120 countries who work to promote the co-ordinated use of drones in humanitarian settings.

[vi] There has been government pressure on commercial operators like Amazon (now testing drone deliveries in Cambridgeshire) to prove that losing direct line-of-sight can be safe, propelling research on autonomous systems.