Parasites, ghosts and mutualists: a relational geography of microbes for global health

Jamie Lorimer

Scientific research on the microbiome offers an ecological model of the human, comprised of myriad forms of microbial life. The composition and dynamics of this human microbiome are increasingly implicated in discussions of health. Attention has focused on missing microbes and their links to a range of inflammatory and autoimmune diseases. Pathological dysbiosis is understood to result from both the excessive presence and the absence of microbes. Microbial declines have been indexed to modern hygiene and healthcare practices and there is a growing interest in the therapeutic use of beneficial microbes. This reappraisal of the salutary potential of microbes challenges the negative associations prevalent in health geography and the field of global health. This paper develops relational and multispecies approaches to health geography to examine situations of microbial excess, absence and controlled reintroduction. The analysis focuses on human relations with hookworms. Hookworms are animal members of the microbiome. They co-evolved with humans, live in us and are understood to manage the human microbiome to enable immunological tolerance. Both the excessive presence and the absence of hookworms can be pathological. They are currently the subjects of concurrent, but spatially discrete, programmes to deworm and reworm a variegated world. Focusing on this seeming spatial paradox, the analysis examines three types of human–hookworm relation: the parasite, the ghost and the mutualist. The conclusion reflects on the implications of this analysis for the human and nonhuman subjects of global health and the microbiopolitics of prevalent forms of antibiotic and probiotic healthcare.

**Key words** microbiome; health geography; hookworm; global health; dysbiosis; biopolitics

School of Geography and the Environment, University of Oxford, Oxford OX1 3QY
Email: jamie.lorimer@ouce.ox.ac.uk

Revised manuscript received 23 February 2017

**Homo microbis**

Recent developments in gene sequencing have helped identify the vast diversity of microbial life in, on and around the human body. Scientists interested in this microbiome offer a figure of the human as *Homo microbis* (Helmreich 2015), comprised of bacteria, viruses, fungi, archaea and even a few animals invisible to the naked eye. The composition and dynamics of the human microbiome are increasingly implicated in discussions of human health (Relman 2015). We are learning more about the causes of infectious diseases, but we also increasingly hear about beneficial microbes and the consequences of their decline or absence.

‘Missing microbes’ (Blaser 2014) have been associated with a range of metabolic, immunological and mental health conditions – including allergy, obesity, inflammatory bowel disease and depression. These ‘epidemics of absence’ (Velasquez-Manoff 2012) have been tied to situations of microbial imbalance or ‘dysbiosis’ (Logan et al. 2016). While causal links are not yet clear, and these claims are contested, a widespread reappraisal is underway in modern medicine of the salutary potential of the microbiome and the therapeutic use of microbes.

This medical microbiology of missing and beneficial microbes departs from the germ theory of disease, in which a specific malady is linked to a specific microbe. Instead it is founded on an ecological or configurational model. Here no microbe is inherently pathogenic (Méthot and Alizon 2014): context and relations matter. Disease is presented as the emergent outcome of complex, spatio-temporal interactions between the host immune system and the internal and external microbial environment (Hinchliffe et al. 2016).

These developments in microbiology have some profound implications for the geography of health and disease. While there is a long history of relational and ecological work on health in geography and anthropology, this has largely been premised on a negative understanding of microbes. Spatial patterns of microbial presence and abundance have been taken as an index of socio-economic development: fewer microbes = better places. This ‘antimicrobial’ geography
informed the history of public health and is also true for global health, the ‘area for study, research, and practice that places a priority on improving health and achieving equity in health for all people worldwide’ (Koplan et al. 2009, 1995; see also Brown and Moon 2012; Herrick and Reubi 2017). Global health describes a diverse range of programmes. But they are united by an antimicrobial concern with the control and/or eradication of infectious diseases. There is currently little room in geography or in global health for understanding health and disease as configured by missing or beneficial microbes.

To address this gap, this paper develops a relational geography of microbes and the diseases of microbial dysbiosis. To do so it builds from recent relational approaches at the interface of more-than-human geography and political ecology. These examine health and disease as multispecies conditions configured by specific socio-ecological ‘situations’ (Hinchcliffe et al. 2016). The concept of a disease situation foregrounds the political and ecological relations that shape the ‘intensities’ of human–animal–microbial interaction that might lead to pathogenesis – or the emergence of disease.

The analysis in this paper develops the prevalent concerns in this literature with infectious diseases associated with microbial excess. Here microbes are parasites, benefiting at the expense of their hosts. It then turns to disease situations marked by missing microbes. Here microbes figure as ghosts whose absent presence causes dysbiosis. The paper then attends to disease situations that are addressed through proactive microbial introduction and management. Here microbes become mutualists performing relations with the host of reciprocal benefit. The human–microbial relations captured by the three figures of the parasite, ghost and mutualist are those of upmost concern to medical scientists engaging with the microbiome. The three labels that describe these relations are taken from the microbiology literature.

In identifying these three figures and tracing their political ecologies, the paper aims to offer geographers a more expansive conception of human microbial relations and the forms of ‘microbiopolitics’ (Paxson 2008) that might underpin contemporary approaches to global health. It supplements long-standing concerns with antimicrobial or ‘Pasteurian’ approaches to healthcare, that are focused on the microbial parasite, with an attention to probiotic or ‘post-Pasteurian’ (Paxson 2008) alternatives. These seek to manage and modulate human infection intensities to channel the mutualistic potential of microbes.

**Hookworms**

The analysis in this paper focuses on human relations with hookworms (*Necator americanus*; Figure 1). Hookworms are helminths and comprise one of the few animal components of the human microbiome. They are microscopic in their larval stage, during which they live outside of the human body. Hookworms are biologically very different to the bacteria that have become the main foci of microbiome research. Some microbiologists might even contest their inclusion in the microbiome. But, as I hope to show in this analysis, the bifurcated geographies of hookworm disease situations, and an emerging understanding of the worms’ role in configuring the human microbiome, make them ideal subjects for a relational geography of microbes.

Hookworms live in our guts and feed on our blood. They reproduce by laying their eggs in our faeces. Larvae hatch in warm, moist, shity soil and seek to re-enter human bodies through the skin. Subsequent stages in the life cycle (Figure 2) see the larvae migrate to the heart, from where they eat their way into the lung. They are coughed up and swallowed, returning to the gut. Hookworms co-evolved with people and each worm can live in the host for several years. ‘Colonies’ tend to develop fairly slowly and a modest ‘wormload’ can be tolerated without symptoms.

Hookworms can become pathogenic in different socio-ecological situations. Excessive hookworm infection causes significant morbidity to more than 500 million people in rural areas of low-income countries (CDC 2016) (Figure 3). Hookworms are the second most significant parasitic infection after malaria (Hotez 2013), and are the subject of global health initiatives to ‘deworm the world’ (Evidence Action 2016). Hookworms were eradicated from North America and Europe at the start of the 20th century through the development of antimicrobial drugs and improvements in sanitation (Ettling 2013). The absence of hookworms has been implicated in the rise of dysbiosis. The demise of these ‘old friends’ (Rook 2009a) is understood to imbalance the immune system, turning it against the...
self and generating a range of autoimmune, allergic and inflammatory disease. Clinical trials are underway to test the potential of helminthic therapy (Wammes et al. 2014). These trials have been overtaken by the ‘hookworm underground’ (Velasquez-Manoff 2012): an international network of patients who breed worms at home and distribute them through the Internet. There is growing industry interest in replicating hookworm’s immunosuppression in pill form (Ditgen et al. 2014).

This seeming spatial paradox, of concurrent programmes to ‘deworm’ and ‘reworm’ the world, provides a compelling rationale for a relational geography of microbes and of dysbiosis. Hookworms are not inherently pathological. They become so because of shifts in the intensities of their socio-ecological relations. These shifts give rise to disease situations marked by both excessive presence and by recent absence. Too many or too few hookworms can cause dysbiosis. The paper details three contrasting human–hookworm relations, which are described by the political-ecological figures of the parasite, ghost and mutualist that were introduced above. It critically examines their multispecies character, and prevalent political-economic and microbiopolitical relations. The conclusion reflects on the implications of this analysis for the geographies of health and disease, and for the practices of global health. It assesses the contributions the figure of Homo microbis could make to developing more-than-human approaches to the geographies of health. It suggests a need to recognise multiple forms of microbial humans by mapping the patchiness of situations in which people can live well with and without hookworms. It links these geographies to prevalent patterns of inequality. It advocates for forms of healthcare better calibrated to the pathological potential of microbial excess and absence, and the mutualistic possibilities of living with microbes. These alternatives challenge the antimicrobial orthodoxy, essentialist models of the microbial pathogen and the magic bullet solutions to disease ascendant in global health.

Relational geographies of microbes

Medical geographers and anthropologists have long been concerned with microbes in their studies of disease ecology (Mayer 2010). This work resonates (in often underexplored ways) with more recent ethnographic research on health in more-than-human and multispecies studies (for a review see Nading 2013). While these health literatures have yet to engage explicitly with the ecological ontologies of the microbiome, attention has been paid to exchanges between a wide range of viruses, bacteria and animals and human immune systems across a growing diversity of interspecies contact zones (e.g. Beisel and Boëte 2013; Bull 2016; Greenhough 2012; Lowe 2010). We can situate this multispecies turn within a wider shift towards relational understandings of disease in medicine and the social sciences (Anderson and Mackay 2014).

Steve Hinchliffe and his co-authors (2013 2016) develop this work in their analysis of the geographies of...
biosecurity. They take issue with conventional ‘Cartesian’ mappings of disease as the outcome of universally pathogenic microbes crossing borders and infecting discrete territories. They note the importance of the extensive networks of globalisation in enacting and distributing ‘socio-technical diseases’ (see also Ali and Keil 2011), but suggest that it is more informative to think of disease in terms of topologies of intensive relations. In their reading, topology refers to the complex spatio-temporal relations and intra-actions (after Karen Barad) that configure the ‘intensities’ of any socio-ecological situation. Bodies become ecologies entangled and enfolded within a geography of more or less pathogenic landscapes. These are marked by potential disease ‘tipping points’ (Hinchliffe et al. 2013, 538). Here infectious disease does not come from an outside, but is ‘ecosyndemic’ (Singer 2010): immanent from particular political ecological ‘situations’ whose shifting microbiologies create conditions of dysbiosis. Pathogenicity, they argue, is best conceived ‘as a process, rather than a fixed object’ (Hinchliffe et al. 2016, 25).

Work in this vein has tended to focus on the topologies of viral ‘hotspots’ (Brown and Kelly 2014), ‘clouds’ (Lowe 2010) and ‘epidemic space’ (van Loon 2005). A common concern lies with the intensified socio-ecological relations of contemporary agriculture, urbanisation and globalisation, which are understood to generate ‘blowback’ (Wallace and Wallace 2015), or the excessive presence of undesired microbes (Shukin 2009; Porter 2013; Wallace 2009). Here microbial dysbiosis takes the form of ‘crowd infections’ (Wolfe et al. 2007) and emergent infectious and zoonotic disease. To date, there has been little work exploring the topologies of dysbiotic situations generated by microbial absence, or of the proactive efforts to tip bodily ecologies out of dysbiotic relations that we will encounter in the hookworm story. Indeed, there has been remarkably little research in geography or anthropology on allergy and the inflammatory and autoimmune diseases that are currently being associated with missing microbes (though see Mitman 2008).

The critical impulse that shapes this relational, microbial turn is inspired by theories of the biopolitics of immunity, as well as more established concerns with political economy. For example, Hinchliffe and his co-authors are critical of the security practices – or what they term ‘disease diagrams’ (2016, 25) – of modern intensive agriculture and associated programmes for One Health (Hinchliffe 2015). These, they argue, are premised on the separation and purification of animal bodies and ecologies and the denigration of vernacular and non-Western forms of expertise. They suggest that these generate ‘autoimmune’ tendencies, in which bodily (and by extension social) ecologies tip into a disease state when the immune system turns again itself in the absence of a co-evolved antagonist (Hinchliffe and Ward 2014; see also Mutsaers 2015; Brown and Nettleton 2017).

Drawing on the writings of Roberto Esposito and Jacques Derrida, they illustrate more communitarian approaches to ‘immunology management’ on the farm (Hinchliffe and Ward 2014). These are premised on the affirmative potential of encounters with social and microbial difference (in this case pig shit and the vernacular knowledge of the farmers who make it available; see also Law and Mol 2008). They suggest that this strategic ‘mucking up’ enables tolerance, hospitality and mutual flourishing. We can find resonances of these communitarian approaches to immunology management in the shift from Pasteurian to post-Pasteurian forms of microbiopolitics that

Figure 3 Global distribution of *Necator americanus* in 2003
*Source*: Republished with permission from de Silva et al. (2003)
Heather Paxson (2008–2014) has identified in her work on raw milk cheese production in North America. Post-Pasteurian approaches do not reject Pasteurisation, but involve more targeted means of managing microbial life, encouraging or living with some microbes to secure desired systemic properties. There is a nascent interest here in finding ethical means – however ‘awkward’ (Ginn et al. 2014) – of living well with microbes and their insect vectors.

These relational understandings of pathogenicity could be better linked to established writings in anthropology and political ecology on the structural violence and ‘pathologies of power’ (Farmer 2004) associated with colonial and capitalist forms of public health and biomedicine. There are important differences between work in this older, Marxist tradition and the new relational approaches (for discussion see Braun 2015; Brown and Kelly 2014; Guthman and Mansfield 2013). There is scope for a more systematic synthesis than can be offered here, but for the purposes of the analysis that follows I will identify one common concern and point of conceptual convergence. Hinchliffe et al. (2016) give a ‘topological twist’ to established approaches to political economy in their analysis of campylobacter as a ‘just-in-time’ disease. They argue that campylobacter was a ‘traditional’ disease. In working bacterial and viral agencies into theories of capitalism, they link the intensification of agriculture and its endemic dysbiosis to post-Fordist relations of labour precarity, commercial pressure and regulatory inefficacy. Their argument is that we can only understand the pathological intensification of human–microbial relations by tracing the globalising logics, practices and assemblages of contemporary capitalism. In the analysis that follows, I develop this conceptual framework by attending to the pathologies of power associated with the parasites of plantation capitalism, the inequalities among those facing microbial absence and the emerging political ecologies of microbial reintroduction.

**Human–hookworm relations**

This account is structured to explore three types of human–hookworm relation, which are described by the ecological figures of the parasite, ghost and mutualist. This account is informed by a close reading of scientific literatures on hookworms and interviews with a range of clinical practitioners and patients engaged with de- and reworming. It is not exhaustive of human–hookworm relations past, present or hypothetical. Instead it offers a heuristic for developing a relational geography of microbes.

**Parasite**

Parasite is a polysemous word. Recent work in the social sciences (oft inspired by Serres 2007) has developed transgressive, or even affirmative, figures of the parasite (Bull 2016; Kelly 2012; Lezaun 2011). I touch on these in the discussion of other relational figures below. But in the interests of specificity, I take a rather narrow and negative biological definition of a parasite as ‘an organism that obtains nutrients at the expense of the host organism, which it may directly or indirectly harm’ (OED 2016).

Mortality as a direct result of ‘hookworm disease’ (Necatoriasis) is rare. But hookworms can become parasitic and thus pathogenic in particular political-ecological situations. Necatoriasis hotspots are characterised by high and protracted levels of infection intensity, where bare skin frequently comes into contact with the soil and a dysbiotic worm colony accumulates. High wormloads lead to protein deficiency and anaemia. They can affect cognitive function and development, especially in children (Brooker et al. 2004). We can find examples of such relations in critical histories of public health. These illustrate how the political-ecological intensities of colonial capitalism created the perfect conditions for hookworms to become parasitic. Steven Palmer argues that hookworm disease was a sickness of ecological, economic, and cultural displacement and recombination; its virulent appearance along these teeming trenchworks of modernity went hand in hand with the increasing density and speed of the globe’s road, rail, and ocean connections. A close relative of nineteenth-century capital, the hookworm parasite thrived in heated frontier regions where vulnerable bodies were amassed for hard labor, and it became potent through accumulation. (2009, 679)

Colonial mines, tunnels, railroad beds and plantations (in India, Africa and the Americas) were ideal ‘hotspots’ (Brown and Kelly 2014) for the genesis of hookworm disease, as were the settlements of indigenous peoples forcibly confined to reserves (e.g. in Australia). Hotspots were comprised of rapidly growing concentrations of displaced and poorly nourished people, suffering from high levels of reinfection as a result of bad sanitation and suitable soil (Couacaud 2014).

Palmer suggests that in the 19th century hookworms were ‘simmering among rural peoples around the world’. They ‘boiled over’ because of the ‘intense ecosocial disruptions’ (2009, 708) of world capitalist expansion. The amplified intensities of these situations tipped hookworms over a threshold, shifting them from a microbial old friend (more below) to a parasitic ‘crowd infection’. Necatoriasis briefly became an ‘industrial epidemic’ (Jahiel and Babor 2007) – a pre-Fordist precursor to the contemporary just-in-time diseases we encountered above. As various authors have argued, the ‘macroparasitic’ (i.e. asymmetrical and exploitative) character of plantation colonial capitalism exacerbated the ‘microparasitic’ depredations of the hookworm (see Brown 1987).
During the early 20th century, hookworms became known as the ‘germ of laziness’ because of their effects on labour productivity (Ettling 2013; Anderson 2006). Subsequent scientific research and public health programmes (largely funded by the Rockefeller Foundation) sought to modulate infection intensities to control Necatoriasis (Palmer 2010; Farley 2003). In the South of the USA, sanitation, footwear, drugs and education disentangled agricultural workers from the vectors for infection. Many people left hookworm hotspots for cities, and gradual improvements in nutrition helped boost host tolerance. Worms and other microbes were killed off in large numbers. Such programmes for hookworm control have all the hallmarks of the modern, antibiotic modes of microbiopolitics documented by Latour (1988) and other, more celebratory, historians of public health (e.g. Farley 2003). They involve systematic efforts to lock down and rationalise the circulation of microbial life, separating human bodies from the environment and purifying them of their component microbes.

The application of such antibiotic approaches is globally patchy and the biogeography of hookworm prevalence and infection intensity conforms to familiar maps of uneven development – to the extent that public health experts have devised a ‘worm index’ of human development (Hotez and Herricks 2015). Some helminth infections are still common among minority populations living in poverty in North America and the EU (Hotez 2009). But hookworms are now extinct in the ‘wild’ in these regions and their prevalence and infection intensity are on the wane across much of the urban Global South (Pullan and Brooker 2012).

Parasitic relations with hookworms persist amid rural populations in low-income countries, especially in Africa and South Asia. Highest infection intensities are often found in children (Hotez et al. 2005). Sanitation projects have fallen out of favour as strategies for hookworm control and World Health Organization attention and Gates Foundation funding is now focused on the regular distribution of deworming drugs to schoolchildren (WHO 2016). The efficacy of school-based deworming is fiercely contested (Evans 2015), especially in areas with poor sanitation and high reinfection risk. Hookworms have also developed resistance to deworming drugs and there has been limited investment in alternatives, as more affluent Northern markets have shrunk (Hotez et al. 2013).

This brief, topological analysis of hookworms-becoming-parasitical on crossing a threshold suggests that Necatoriasis is not necessarily a disease of underdevelopment resulting from the spread of a specific pathogen. Hookworms are not inherently pathological. They can be endemic and asymptomatic, but become pathogenic because of an increased intensity of exploitative, unequal or abandoned socio-ecological relations. In these situations, pathology is indexed to excessive presence and bodily dysbiosis is the outcome of the crossing of a disease threshold. Historians link the amplification of infection intensities to the pathologies of power associated with colonial capitalism, but they also caution against reading off hookworm disease as a universal outcome of systemic structural violence. The materialities of co-infection, host genetics and epigenetics, soil type, working conditions, defecation practices and sanitation investments all shape the differential emergence of infection intensities (Couacaud 2014).

**Ghost**

A growing collection of immunological theory, scientific evidence and vernacular experience questions the desirability of wholesale hookworm eradication. There is a concern that the absence of hookworms and other microbes could be as pathological as their excessive presence. Epidemiologists have noted that general declines in microbial infection are associated with an increase in susceptibility to autoimmune and allergic diseases (Bach 2002). In 1989 David Strachan offered a ‘hygiene hypothesis’ to account for these trends (Strachan 1989). This theory was refined by work that seeks to differentiate the salutary effects of different microbial infections. Immunologists like Graham Rook (Rook et al. 2014) encourage a separation between harmful crowd infections (which evolved recently because of urbanisation) and the microbial old friends with which humans co-evolved.

Rook suggests that radical recent changes in the composition of the human microbiome have led to the loss of the ‘old friends mechanism’ (Rook 2009b) through which resident microbiota enable and calibrate vital bodily processes like metabolism, immunity and cognition. The same service is not provided by crowd infections, which either kill the host, or to which the host develops immunity. While scientific and public health attention remains focused on ‘targeted hygiene’ and the control of crowd infections (Bloomfield et al. 2016), the salutary effects of the absent venerable human microbiome is emerging as a hot topic in the life sciences.

Hookworms have been identified as one such old friend. The absence of hookworms and other human helminths is currently being afforded significant attention in explaining microbial dysbiosis and its effects on human health. Epidemiological research suggests that allergic diseases are rare in areas with high helminth parasite exposure and common where helminth exposure is lacking or significantly reduced, such as urban areas of developing countries and industrialized nations. (Flohr et al. 2009, 20)

A long-term observation study of patients with multiple sclerosis infected with different helminths
showed that disease activity improved during infection and regressed when infection was treated (Correale and Farez 2011). Comparable, but by no means clear-cut, patterns have also been observed for the effects of helminths on diabetes, inflammatory bowel disease (IBD) and metabolic disease (for a review see Wammes et al. 2014).

Immunologists seeking to explain these trends suggest that hookworms produce an entirely different ‘immune response profile’ to bacterial and viral pathogens (Allen and Maizels 2011). They argue that because of a long history of human co-evolution, ‘helminths have evolved to dampen, rather than disable, the immune system of their hosts’ (2011, 384). Recent work in immunology identifies a ‘helminth-induced immune regulatory environment’ (Helmy 2009, 122) through which worms enter into a ‘continuing dialogue’ (Allen and Maizels 2011, 385) with the human immune system to enable permanent residence. This work also suggests that in the absence of worms and other components of the microbiome, the immune system becomes poorly calibrated, is unable to differentiate harmful materials, becomes oversensitive and ultimately turns against itself, resulting in elevated levels of allergy and inflammation (Fleming and Weinstock 2015).

Microbiologists use mouse models to trace the interactions between the host immune system, helminths and resident bacteria. They suggest that helminths can manipulate the microbial population for their own ends, in ways that explain immune modulation (Reynolds et al. 2015; Zaiss et al. 2015). One set of immunologists has drawn on concepts from conservation biology to explain helminths’ calibrating potential (Bilbo et al. 2011). They suggest that hookworms figure as missing ‘keystone species’: ‘species that play a disproportionately large role in the prevalence and population levels of other species within their ecosystem or community’ (Wagner 2010, 51). The past presence of hookworm is sensed as a contemporary absence made manifest in forms of ecosystem dysfunction and ‘ecological anchronism’ (Barlow 2013). The concept of ghost keystone species was first developed to explain the ‘trophic cascades’ caused by the absence of apex predators like the wolf (Eisenberg 2010). The absence of these species is understood to tip ecologies into new states characterised by reduced diversity, functionality and resilience. Advocates of helminthic therapy speak of ‘Darwinian medicine’ (Rook 2009a) that would address analogous ‘evolutionary mismatches’ between the ecological composition of human bodies, the immune systems they have trained and the external environments to which they are exposed (Parker and Ollerton 2013).

These discussions of the demise of old friends and the causes of the current epidemics of absence implicate practices that are central to the modern, antibiotic approaches to managing microbes that were encountered above (see Table I).

Interventions like flush toilets, antibiotics and C-sections, which have been central to Western narratives of civilisation and development, have been recast as potentially pathological. We are told that in becoming modern the human microbiome is in danger of unravelling. Immunologists and microbiologists have extended this discussion to pathologise Western urban and post-industrial life. They draw attention to undesirable processes of microbial colonisation and the resulting forms of microbiome composition (Hanski et al. 2012; Rook et al. 2014). The story here is of health and safety going too far. An excessive desire to minimise risk and modulate microbial infection intensity creates a model of biosecurity that is prone to autoimmunity: ‘a self-protective syndrome whose attempts to exclude difference are ultimately self-destructive’ (Hinchliffe and Ward 2014, 143).

Early accounts of inflammatory and autoimmune conditions suggested that these are ‘Western diseases’ or ‘diseases of affluence’ (Pollard 2008), associated with populations that have passed through a spatial epidemiological transition. But there are stark disparities in the socio-economic status of those who currently experience hookworms as a ghost in urban areas around the world (Rook et al. 2014). Coping with autoimmune disease may require regimes of immunosuppressant drugs, whose availability is patchy and dependent on an ability to pay. Autoimmune diseases may well be exacerbated by the socio-ecological intensities of urban poverty that generate a perfect microbial storm of absent old friends and amplified exposure to urban crowd infections. The chances of living well without hookworms and other old friends are as strongly configured by entrenched pathologies of power as the situations in which people can live well with worms.

A figure of hookworms as ghost helps extend Hinchliffe et al.’s (2016) topological understanding of pathogenicity to explore situations in which microbial absences shift ecological intensities to create dysbiosis. Many of the microbial excesses associated with the emergent infectious diseases of agriculture and urban life may stem from the absence of regulating microbes. But there has been little explicit attention given in medical geography to the topologies of such absences and their effects on autoimmunity. Understanding the immune system legacies of microbial absences requires a more protracted conception of the microbial geographies of health, where the focus is less on the intensities and immediate spatio-temporalities of outbreak (cf. Dixon and Jones 2015), and more on intergenerational microbial inheritance, the accumulation of microbial exposure and immunomodulation over the life course,
Table I  Modern practices understood to negatively affect the human microbiome

<table>
<thead>
<tr>
<th>Socio-ecological change</th>
<th>Microbial consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean water</td>
<td>Reduced faecal transmission</td>
</tr>
<tr>
<td>Increase in C-sections</td>
<td>Reduced vaginal transmission</td>
</tr>
<tr>
<td>Reduced breastfeeding</td>
<td>Reduced skin-to-skin transmission and a changed gut flora</td>
</tr>
<tr>
<td>Smaller family size</td>
<td>Reduced early life transmission</td>
</tr>
<tr>
<td>Widespread antibiotic use</td>
<td>Reduced vaginal transmission and selection for a changing composition</td>
</tr>
<tr>
<td>Changing diet and cooking practices</td>
<td>Alterations in gut flora</td>
</tr>
<tr>
<td>Diminished contact with soil and farm animals</td>
<td>Reduced early life transmission</td>
</tr>
<tr>
<td>Increased bathing, showering</td>
<td>Selection for a changing composition</td>
</tr>
<tr>
<td>and use of antibacterial soaps</td>
<td>Infectious disease</td>
</tr>
<tr>
<td>Increased exposure to ‘crowd infections’</td>
<td></td>
</tr>
</tbody>
</table>

Sources: Blaser and Falkow (2009), Bono-Lunn et al. (2016) and Rook et al. (2014)

and the cascading effects of microbial absences. Emerging relational geographies of pathogenicity must also attend to the protracted and discordant temporalities of microbial colonisation and immune system calibration.

Mutualist

Anxieties about missing microbes have informed a wide range of laboratory research manipulating the microbiomes of animal models. Experiments and pre-clinical trials with mouse models and murine helminths, comparable to those of humans, try to simulate the effects of de- and reworming and trace their links with the incidence of allergic and autoimmune disease. Wammes et al. argue that these experiments in murine helminthic therapy ‘provide strong evidence that helminths can not only downregulate parasite-specific immune responses, but also modulate autoimmunity and allergic inflammatory responses and improve metabolic homoeostasis’ (2014, 1150).

Human clinical trials of helminthic therapy are now underway. A recent review identifies 28 trials focused on ten different autoimmune diseases, including Crohn’s, multiple sclerosis (MS) and autism (Fleming and Weinstock 2015). The USA Food and Drug Administration has granted a licence to use the ova (eggs) of the pig whipworm Trichuris suis as an investigational medicinal product (Elliott and Weinstock 2009) and the Danish company Parasite Technologies has patented a production process. In the UK, the Medicines and Healthcare Regulatory Authority has licensed the use of Necator americanus (Pritchard 2011). Trials have demonstrated that it is safe to introduce these two species into human patients. But evidence of the efficacy of helminthic therapy has been mixed and inconclusive. Fleming and Weinstock note that ‘some phase 2 studies have not achieved positive results for their primary outcome measures’ and argue that ‘the jury is out as to the efficacy of helminth treatment’ (2015, 289) as many studies are in progress, and several were poorly designed. New trials are underway and many more are planned.

In parallel with these clinical developments, and in part in frustration at their slow progress, a variety of expert patients have been reworming. In 2016, there were at least five commercial providers of hookworms and other helminths, all run by people with experience of self-treatment (see Cheng et al. 2015). Hookworm therapy has been driven by social media, which links a global community of patients that are largely independent of scientific researchers and commercial providers. Empowered by the resources they find online and their own experiments, some users have learnt to raise their own worms. They use animals purchased from commercial providers or sourced from their involvement in clinical trials. Some work with commonplace technologies to make their own domestic laboratories. Detailed protocols circulate explaining how to incubate and nurture worms. Users harvest and isolate new stock from their faeces and make use of cheap microscopes and library images to count larvae before self-infecting (for more information see Lorimer 2016).

A recent survey identified up to 7000 ‘self-treaters’, using four different helminth species (Cheng et al. 2015). Allergies, IBD and MS were the most common reported conditions. The cost of helminth therapy varies from US$10 000 to US$1000 per annum, depending on the species used, the dose required and the degree of support provided. This is a marginal economic activity, whose legality is currently unclear. In the main, this hookworm underground involves non-profit, communitarian relations and zealous advocacy. Fellow sufferers and users gift or exchange worms at cost. They share experience to ensure reserve supplies and to build capacity. The shared aim of these ‘biological citizens’ (Rose and Novas 2008) is to enhance the legitimacy and availability of helminth therapy (cf. Epstein 1996 on patient activism and HIV).

Here hookworms come to figure as ‘symbionts’ (Biome Restoration 2016), ‘mutualists’ (Pritchard and Brown 2001) or ‘mutualistic symbionts’ (Autoimmune Therapies 2016). Patients talk affectionately of their ‘gut buddies’ or ‘colon comrades’ (Lorimer 2016). Mutualism and symbiosis were once synonymous in ecology, but the latter is increasingly used to describe a wider range of relations, including parasitism. Mutualism is more specific and describes a ‘relationship existing between two organisms of different species which contribute mutually to each other’s well-being’.
(OED 2016). In accounting for the mutualistic agencies of hookworms, scientists draw on the accounts of an interspecies dialogue between old friends outlined above. Helminth providers use similar metaphors. They argue that worms initially serve to ‘calibrate’ a child’s immune system before ‘exercising’ adults’ immunity (Biome Restoration 2016). Worms are understood to ‘restore nature’s balance’ (Autoimmune Therapies 2016) and enable ‘symbiotic immunomodulation’ (Symmbio 2016). They are to be enrolled in a wider project of ‘biome restoration’ (Biome Restoration 2016).

We can position this DIY reworming within a broader probiotic turn that is taking place in the management of health in certain Western contexts (Lorimer 2017). Efforts to translate the science of the human microbiome have converged with a reappraisal and reinvention of the microbial dimensions of a range of vernacular cooking and hygiene practices. The result is a range of experiments, interventions and regulations designed to reverse the trends outlined in Table I (see Table II). Examples would include: the proliferation of pro- and pre-biotic diets and supplements designed to work on the gut microbiome (e.g. Sonnenburg and Sonnenburg 2015), and private sequencing services to monitor their effects (e.g. uBiome.com); probiotic hygiene products that colonise the body or the built environment with good bacteria (e.g. motherdirt.com); and the use of faecal transplants to treat antibiotic-resistant infections (Gough et al. 2011) and swabbing to replicate microbial birth canal colonisation in babies born by C-section (Dominguez-Bello et al. 2016).

In these situations, we see hookworms (and other microbes) becoming subject to Paxson’s (2008) post-Pasteurian forms of microbiopolitics. Even the most fulsome advocates of microbial ‘rewilding’ (e.g. Leach 2015) are post-, rather than ‘anti-Pasteurian’ (Paxson 2014). Post-Pasteurian reworming is similar to the practices of biosecurity as ‘immunity management’ documented by Hinchliffe and Ward (2014) in their writings on how pig farmers ‘muck-up’ sterile animals with earth and faeces to boost their immune systems. But here hookworms are used strategically as a known keystone species to manage the ecological intensities of the bodies into which they are deliberately introduced. Hookworms are deployed to tip dysbiotic bodily ecologies back over the threshold, which triggered autoimmune disease. Like wolves reintroduced to riddle nature reserves, hookworms are enrolled to modulate the intensities of a target ecology and secure desired systemic properties. Hookworms restore immunomodulation and enhance the resilience of Homo microbis to prevent degenerative change (see Lorimer 2017).

The discovery of hookworms’ salutary properties has prompted a range of speculation and research and development on the future of helminth therapy. While advocates speak of restoration and rewilding, there is a growing (and not necessarily incommensurable) desire to gain more control over hookworms and their mutualistic potential. Prominent advocates of helminthic therapy want to persevere with the use of whole organisms. They seek to refine their choice of species and speculate about modifying the helminths currently in use (Elliott et al. 2007; Parker et al. 2012). A very different future is currently being imagined for

**Table II** Post-Pasteurian responses to modern anxieties about microbial dysbiosis

<table>
<thead>
<tr>
<th>Socio-ecological change</th>
<th>Microbial consequence</th>
<th>Post-Pasteurian management of microbial intensities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean water</td>
<td>Reduced faecal transmission</td>
<td>Probiotic drinks, like Kombucha</td>
</tr>
<tr>
<td>Increase in C-sections</td>
<td>Reduced vaginal transmission</td>
<td>Discouragement of C-sections</td>
</tr>
<tr>
<td>Reduced breastfeeding</td>
<td>Reduced skin-to-skin transmission and a changed gut flora</td>
<td>Swabbing to replicate the microbial colonisation associated with vaginal delivery</td>
</tr>
<tr>
<td>Smaller family size</td>
<td>Reduced early life transmission</td>
<td>Breastfeeding promotion</td>
</tr>
<tr>
<td>Widespread antibiotic use</td>
<td>Reduced vaginal transmission and selection for a changing composition</td>
<td>New types of probiotic and prebiotic formula</td>
</tr>
<tr>
<td>Changing diet and cooking practices</td>
<td>Alterations in gut flora</td>
<td>Pox parties to spread diseases like measles and chicken pox*</td>
</tr>
<tr>
<td>Diminished contact with soil and farm animals</td>
<td>Reduced early life transmission</td>
<td>Ban on some antimicrobial cleaning products</td>
</tr>
<tr>
<td>Increased bathing, showering and use of antibacterial soaps</td>
<td>Selection for a changing composition</td>
<td>Discouraging use of antibiotics</td>
</tr>
<tr>
<td>Increased exposure to ‘crowd infections’</td>
<td>Infectious disease</td>
<td>Promotion of probiotics</td>
</tr>
</tbody>
</table>

*Some of these practices shade towards the anti-Pasteurian (Paxson 2014), for example with pox parties organised by anti-vaccination movements.
hookworms by figures in the pharmaceutical industry. Scientists who were involved in decoding the hookworm genome express hopes for a 'veritable pharmacopoeia' of synthetic molecules that will become available for new rounds of drug development (Navarro et al. 2013).

On the one hand, there is excitement about new 'drugs from bugs' that will replicate hookworms’ abilities to train and calibrate the human immune system (Ditgen et al. 2014). The hope is that the agencies of the hookworm might be simulated in pill form to secure the type of profitable returns currently associated with chronic dependency on immunosuppressant drugs. In this guise the ghostly hookworms return in molecular form to function as the immunological equivalent of a scarecrow: a pared-down simulation that mimics a keystone’s calibrating agencies.

At the same time, information provided by the hookworm genome and conceptions of helminths in dialogue with microbes inform a new round of deworming drug and vaccine development. New pharmaceuticals might target the bacteria that make the body hospitable to parasitic helminths, reconfiguring the gut microbiome to make it harder for worms to take up residence. Comparable and well-established global health programmes to develop a hookworm vaccine (Hotz et al. 2016) are focused on identifying antigens to chemicals secreted at key stages in the hookworm lifecycle. These pharmacological and vaccinological interventions turn the dialogical character of the hookworm, and the embodied history of its human conversation, against the organism (cf. Beisel 2017 on the malaria vaccine). Drugs would exclude hookworms’ microbial ‘messmates’ (Haraway 2008) and increase its antagonists, while vaccines teach the body to attack on first encounter.

These proposals have been criticised by scientists who point to the cost and the difficulties of recapitulating the ecological agencies of an entire animal in molecular form (Bilbo et al. 2011). They do not believe that a keystone species can be simulated and note that worms will continue to develop drug resistance (Hawdon 2014). Others have expressed concerns that a successful hookworm vaccine would permanently deprive immunised populations of the immunomodulation benefits of mutualistic infection and increase the risk of dysbiosis among already precarious groups (Wammes et al. 2014).

More broadly, critics note the differences between a drug that is designed to treat a specific illness and a live organism that acts preventatively on a bodily ecology to confer health (Bono-Lunn et al. 2016). They suggest that a focus on drugs from bugs ignores the systemic drivers of dysbiosis (Logan et al. 2016). Members of the hookworm underground contest the proprietary tendencies implicit within these developments. They are concerned that profit-centred efforts to privatise the hookworm secretome and eradicate worms may undermine the patient-centred benefits already emerging from helminthic therapy. From the perspective of the hookworm, these pharmacological futures can no longer be described as mutualistic. Benefits flow only one way, and the human has become the parasite. Some even hope that new vaccines might enable hookworm eradication.

These post-Pasteurian relations of deliberate re-entanglement with hookworms or their molecular surrogates have quite specific geographies, which are currently under explored. Clinical trials in helminthic therapy are focused on populations living near a small number of North American and UK hospitals. The geography of the online hookworm underground is harder to establish. The gatekeepers and most active members of this network on social media, who were contacted in the conduct of this research, are concentrated in North America, Western Europe and Australia. It is likely that mutualistic human–hookworm relations map on to the more affluent regions in which hookworms currently figure as ghosts.

**Geography, dysbiosis and global health**

This paper has developed a relational geography of the microbiome and of dysbiosis through a focus on disease situations associated with human hookworms. It argues that no microbe is essentially pathogenic; pathogenesis is the outcome of political and ecological relations. The paper adds to existing work on disease situations marked by microbial excesses and offers an analysis of disease situations of microbial absence and proactive restoration. In so doing, it identifies three types of human–microbial relation, which are described by the ecological figures of the parasite, ghost and mutualist. The paper maps the global occurrence of each type of relation, their multispecies composition and their prevalent modes of political economy and forms of microbiopolitics. These are summarised in Table III.

In conclusion, I will briefly reflect on the implications of this analysis for the geographies of health and for the field of global health. But, before doing so, it is worth reiterating the limitations posed by a focus on hookworms. There are risks in taking hookworms as illustrative of the great diversity of the human microbiome. Hookworms are obligatory animals (i.e. they only reside in humans) that cannot reproduce inside their host. Unlike the bacteria that have been the main focus of recent scientific work on the microbiome, they reproduce slowly and cannot engage in lateral gene transfer. Hookworms’ sociability with bacteria and their keystone mutualistic agencies are likely relatively rare.
There are plenty of other helminths, let alone viruses and bacteria, with which such mutualistic relations are improbable (e.g. Moran-Thomas 2013). There are plenty of microbes we might not miss.

 Nonetheless, there are three broad contributions offered by this analysis of human–hookworm relations. First, thinking with hookworms helps open up the radical implications of an ontology of Homo microbis for conceiving the human and human health. These are early days in the development of this science, and much of what is outlined above may well be revised as microbiologists gain more traction on the ecological and immunological dynamics of the human microbiome. But here we are presented with a porous and ecological figure of the human whose life course microbial exposures come to configure identity, subjectivity and health outcomes (cf. Meloni 2015 on epigenetics). Only some of our microbes are inherited and the microbial self is thus open to deliberate or inadvertent modification. This relational ontology of the microbial human challenges how medical geography might conceive space-time. Analysis must focus on life course microbial colonisation, and infection hotspots and vectors. But it must also acknowledge absences and their latent ecological effects (cf. Anaya et al. 2016). The human as Homo microbis is an unstable and nonlinear accumulation, marked by disease tipping points with differing degrees of reversibility.

 Influential commentators like Donna Haraway (2016) celebrate the ways in which the science of the microbiome and microbial symbiosis offer a post-foundational ontology for more-than-human theory and politics that further undermines humanist dreams of the bounded individual (see also Hird 2009). Other sociologists of science are more cautious about the new materialisms emerging from the ‘microbiomania’ (Paxson and Helmreich 2014) of the contemporary biosciences. Drawing together their disparate research on astrobiology and raw milk cheese, Paxson and Helmreich note the ways in which communities of microbes are coming to figure as ‘model ecosystems’ for a range of hopeful political and ecological projects. They are wary of taking Homo microbis too literally and await its encoding by established power geometries of gendered, racialised and capitalist biotechnology (cf. Guthman and Mansfield 2013 on the coding of environmental epigenetics). While the post-genomic, vital materialism offered by microbiome science can be aligned with the political projects of more-than-human geography, we should be aware of the historical, political and economic conditions that shape its emergence (see Sangodeyi 2014). The differentiation of microbiome science as it increasingly proliferates across the domains of big science, biotechnology, citizen science, art-science and DIY biology will be important subjects for future research.

 The analysis in this paper begins to lay the foundations for this type of critical work. By identifying the geographies that come to configure the human microbiome, it pluralises Homo microbis, identifying different sub-species of Homo microbi. Tracing how hookworms make and unmake different humans adds to existing criticisms of germ theory and its essentialist understanding of disease as caused by a specific pathogen. Instead this analysis has demonstrated how hookworms, like any other microbe, take on radically different roles in different political-ecological

### Table III Key characteristics of the three types of human–microbial relation identified

<table>
<thead>
<tr>
<th>Parasite</th>
<th>Ghost</th>
<th>Mutalist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global occurrence</td>
<td>Tropical areas in the rural Global South (Figure 3)</td>
<td>Global North and urban Global South, especially areas from which hookworm have recently been removed</td>
</tr>
<tr>
<td>Multispecies composition</td>
<td>Excessive worms, repeated infection, co-infection with other parasites, poor nutrition, compromised immune system</td>
<td>Absent worms; dysbiotic microbiome; overactive immune system</td>
</tr>
<tr>
<td>Political ecology</td>
<td>Poor sanitation and healthcare, intensive plantation agriculture, poverty and inequality, limited access to effective deworming drugs</td>
<td>Common access to sanitation, footwear, deworming drugs and basic healthcare. Variable access to immune-suppressant drugs</td>
</tr>
<tr>
<td>Microbiopolitics</td>
<td>Pre-Pasteurian, patchy Pasteurian based on ‘magic bullet’ drugs and vaccines</td>
<td>Antimicrobial. Involving toilets, sanitation and national deworming programmes</td>
</tr>
</tbody>
</table>

© 2017 Royal Geographical Society (with the Institute of British Geographers)
situations. These situations are patterned and patchy (cf. Tsing 2015 2016). They map on to historical and contemporary geographies of colonialism, development, trade, property and urbanisation, to draw out just a few of the processes identified in this story. Hookworms become pathological as parasites in situations of agricultural and industrial intensification and/or political abandonment. The shifting intensities of these situations are familiar from existing work on the emergent diseases of colonialism, agriculture and urbanisation. What this analysis adds is an attention to the pathological potential of microbial absence and the dysbiosis it generates. While the causes of autoimmune and inflammatory disease are multivariate and still unclear, their apparent microbial signature suggests the need for a relational geography of missing microbes. The degree to which the diseases of microbial absence are pathologies of power that can be linked to the structural violence of the unequal provision of healthcare is now an open question. Autoimmune and inflammatory diseases are neglected in medical and health geography and require further research.

Thinking with hookworms helps us begin to answer this question and in so doing to identify some of the implications of the rise of the microbiome for global health. While we are some way off knowing what a healthy microbiome looks like – and the answer is unlikely to be singular – there is a growing interest in cultivating the microbiome as a route to individual and public health. Thinking global health in terms of the microbiome requires a continued attention to situations of excessive microbial presence, coupled with a new concern for beneficial microbial colonisation and the risks of microbial absence and dysbiosis. Such thinking further complicates linear models of a modern epidemiological transition, in which development can be indexed to microbial absence. It suggests a need to recalibrate the discourses inherent (if not explicit) in global health that developed countries are healthier because they are cleaner and more devoid of pathogens and microbes, whereas the Global South is the geographic Mecca for bad microbes, dirt and lack of sanitation. If the pursuit of sterility can be pathological, then global health will need to rethink its ontological foundations.3

Hookworm control will remain a clear public health priority in many rural areas of the Global South. But it appears that too comprehensive a shift to antibiotic relations with hookworms can instigate autoimmune and inflammatory conditions in populations ill equipped to manage without them. Urban populations with ghostly worms, living in situations with poor sanitation and exposed to pre-Pasteurian relations with urban crowd infections and novel infectious diseases, are particularly vulnerable to dysbiosis. A concern with contemporary dysbiosis does not necessarily imply an anti-Pasteurian return to an ‘Eden’ of universal symbiosis. Pasteurian forms of microbiopolitics have made life better, and their geography is still all too patchy.

Attention turns to a post-Pasteurian recalibration of hygiene that would secure the mutualistic presence of old friends and calculate and manage the intensities of microbial ecologies. This might involve intervening through the strategic use of keystone species to maintain biological diversity and ecosystem functionality. As the story of hookworms makes clear, any panoptic aspiration for a global post-Pasteurian microbiopolitics is confounded by established geographies of underdevelopment. Hookworms illustrate the rarity of situations in which such forms of microbiome management can be achieved. The provision of sanitation, drugs and living organisms is distinctly uneven (cf. Braun 2007). The current focus in global health on deworming through vaccination and drug delivery fails to address the socio-ecological drivers of infection intensity. If these programmes were successful, they risk driving future epidemics of autoimmune disease. In short, the rise of the microbiome raises some profound challenges to the geographies of global health whose import is only just becoming sensible.

Acknowledgements

Versions of this paper were presented to audiences at the Rachel Carson Centre in Munich, the Department of Geography at King’s College London, and workshops in Durham and Montebello, Quebec. I am grateful for the comments and criticisms received. Thanks to Adrian Bailey for ensuring a smooth and speedy publication process and to three anonymous referees for their incisive comments.

Notes

3. I am grateful to an anonymous reviewer of this paper for the wording of this paragraph.

References

Allen J and Maizels R 2011 Diversity and dialogue in immunity to helminths Nature Reviews Immunology 116 375–88
Nading A 2013 Humans, animals, and health: from ecology to entanglement Environment and Society: Advances in Research 4 60–78
Navarro S, Ferreira I and Loukas A 2013 The hookworm pharmacopoeia for inflammatory diseases International Journal for Parasitology 43 225–31
Palmer S 2009 Migrant clinics and hookworm science: peripheral origins of international health, 1840–1920 Bulletin of the History of Medicine 83 676–709
Palmer S 2010 Launching global health: the Caribbean odyssey of the Rockefeller Foundation University of Michigan Press, Ann Arbor MI
Parker W and Ollerton J 2013 Evolutionary biology and anthropology suggest biome reconstitution as a necessary approach toward dealing with immune disorders Evolution, Medicine, and Public Health 2013 89–103
Parker W, Perkins S E, Harker M and Muehlenbein M P 2012 A prescription for clinical immunology: the pills are available and ready for testing: a review Current Medical Research and Opinion 28 1193–202
Paxson H 2008 Post-Pasteurian cultures: the microbiopolitics of raw-milk cheese in the United States Cultural Anthropology 23 15–47
Paxson H 2014 Microbiopolitics in Kirksey E ed The multispecies salon Duke University Press, Durham NC 115–21
Paxson H and Helmeisch S 2014 The perils and promises of microbial abundance: novel natures and model ecosystems, from artisanal cheese to alien seas Social Studies of Science 44 165–93
Pollard T M 2008 Western diseases: an evolutionary perspective Cambridge University Press, Cambridge
Pritchard D 2011 Worm therapy: for or against? Journal of Helminthology 85 225–7
Pullan R L and Brooker S J 2012 The global limits and population at risk of soil-transmitted helminth infections in 2010 Parasites and Vectors 5 81
Relman D A 2015 The human microbiome and the future practice of medicine JAMA 314 1127–8
Rook G 2009a The hygiene hypothesis and Darwinian medicine Birkhäuser, Basel
Rook G 2009b Review series on helminths, immune modulation and the hygiene hypothesis: the broader implications of the hygiene hypothesis Immunology 126 3–11
Rook G A W, Raison C L and Lowry C A 2014 Microbial ‘old friends’, immunoregulation and socioeconomic status Clinical and Experimental Immunology 177 1–12
Rose N and Novas C 2008 Biological citizenship global assemblages Blackwell, Oxford 439–63
Sangodeyi F I 2014 The making of the microbial body, 1900s–2012 Doctoral dissertation Harvard, Cambridge MA
Serres M 2007 The parasite University of Minnesota Press, Minneapolis MN
Shukin N 2009 Animal capital: rendering life in biopolitical times University of Minnesota Press, Minneapolis MN
Strachan D 1989 Hay fever, hygiene, and household size BMJ 299 1259–60
Symmbio 2016 About us (http://www.symmbio.com/about-us/)
Tsing A L 2015 The mushroom at the end of the world: on the possibility of life in capitalist ruins Princeton University Press, Princeton NJ
Tsing A 2016 Earth stalked by man The Cambridge Journal of Anthropology 34 2–16
van Loon J 2005 Epidemic space Critical Public Health 15 39–52
Velasquez-Manoff M 2012 An epidemic of absence: a new way of understanding allergies and autoimmune diseases Scribner, New York NY
Wagner S 2010 Keystone species Nature Education Knowledge 3 51
Wallace R G 2009 Breeding influenza: the political virology of offshore farming Antipode 41 916–51
Wallace R and Wallace R G 2015 Blowback: new formal perspectives on agriculturally driven pathogen evolution and spread Epidemiology and Infection 143 2068–80
Wamases L, Mapirwe H, Elliott A and Yazdanbakhsh M 2014 Helminth therapy or elimination: epidemiological, immunological, and clinical considerations The Lancet Infectious Diseases 14 1150–62
WHO 2016 Intestinal worms: strategy (http://www.who.int/intestinal_worms/strategy/en/)