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journals.sagepub.com/home/ene**Richie Nimmo** 

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Abstract

This article undertakes a critical examination of emergent technologies involving the use of robots to carry out crop pollination in the context of declining populations of bees and other insect pollinators. It grasps robotic pollination research and development as a future-making practice, which imagines and partially materialises one possible future by inscribing a specific ontology in the present which is geared to enact that future. Unpacking this, the article traces how artificial pollination reframes pollination ecology around a productivist ontology and inscribes a web of meanings around nature, technology and economy which point to a future where insect pollinators are largely absent or extinct. It argues that this effectively backgrounds alternative futures in which structural transformations of agriculture and the world food system are able to mitigate and avert pollinator decline and biodiversity loss, and also reveals the deep rationale of artificial pollination. While invoking notions of sustainability and food security, robotic pollination defines these in highly anthropocentric, economic and self-referential terms, as a matter of enabling the reproduction of agro-industrial capital accumulation. Drawing upon the political ecology of Jason W Moore, the article situates robotic pollination as a future-making project in relation to capitalist strategies of accumulation through the appropriation of ‘Cheap Nature’, to show how the automation of pollination would enact a shift in the composition of agro-industrial capital, with systemic consequences inimical to both ecological sustainability and sustained accumulation. In this respect, robotic pollination is a case study in the propensity of capital to invest in the making of sustainable futures only insofar as sustainability equates to the reproduction of capital within the web of life.

Keywords

Robotic pollination, political ecology, farming, futures, capitalism

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It has become easier to imagine the end of the world than the end of capitalism. (Jameson, 1994: xii)

Perhaps the forthcoming ecological crises, far from undermining capitalism, will serve as its greatest boost. (Zizek, 2011: 329)

Introduction

It was with the emergence of what became known as ‘Colony Collapse Disorder’ in 2006–2007 (Cox-Foster et al., 2007; VanEngelsdorp et al., 2008), referring to the phenomenon of rapid large-scale disappearances of honey bee colonies, that the longer term trend of declining honey bee populations began to receive sustained attention. The number of managed honey bee colonies in the US more than halved between 1947 and 2008, with the bulk of that decline occurring after 1980 (National Research Council, 2007), while Europe saw a 16% reduction in colony numbers and a 31% reduction in beekeeper numbers between 1985 and 2005 (Potts et al., 2010: 18). This trend has serious implications for commercial agriculture given that a significant and growing proportion of world food production depends upon pollination by managed honey bee colonies (Gallai et al., 2009; Klein et al., 2007). Although honey bee decline has increasingly been understood as a regional rather than truly global phenomenon, with the numbers of colonies worldwide actually increasing, driven by increasing demand for commercial apiculture, this increase is not keeping pace with the growth of apiculture-reliant agriculture (Aizen and Harder, 2009). Moreover, Colony Collapse of managed honey bees in the US and Europe is situated within a worldwide decline of multiple species of wild insect pollinators, connected not only with large-scale use of pesticides and systemic insecticides in industrial agriculture (Goulson, 2013; Goulson et al., 2015; Maxim and van der Sluijs, 2013), but with an assemblage of anthropogenic changes including climate change, rising air and water pollution, and habitat destruction through the changing land use associated with intensive farming and urban development (Beismeyer et al., 2006; Cardoso et al., 2020; Gonzalez-Varo et al., 2013; Memmott et al., 2007).

Research in micro-robotics has begun to address itself to this ‘pollination problem’. Recent developments have seen the emergence of various prototype pollination robots from wheeled machines to micro-scale drones, designed to mimic in different ways the pollination functions of bees (Coppola et al., 2020; De Croon et al., 2016). This article critically examines these emergent technologies of artificial pollination and traces the materialities of their design together with the discourses which frame their rationale. Methodologically, the research is grounded in textual discourse analysis of a purposive sample of documentary sources comprising: scientific publications by several research teams, institutes and companies involved in developing robotic pollination technologies; their websites and promotional materials; media coverage of such projects; and scientific literatures on pollination ecology. The analysis of these texts is informed by sociological thinking around the politics of futures and future-making (Adam and Groves, 2007; Urry, 2016), and robotic pollination technologies are thus understood as partly materialised imaginings of possible futures – entanglements of matter and meaning which work to enact particular futures and to circumscribe others (Brown and Michael, 2003; Michael, 2017; Tutton, 2017).

By examining how robotic pollination reframes pollination ecology, I trace how it brings together socio-ecological fatalism with technological hubris, the former subsumed under

and partially concealed by the latter, in a kind of eco-apocalyptic techno-optimism. Although it is presented in terms of the language of sustainability and food security, I argue that robotic pollination does not fundamentally seek to avert or mitigate ecological or food-system crisis, but rather to valorise the economic opportunities these crises could afford for certain sectors of industrial agribusiness. Robotic pollination is therefore not a ‘techno-fix’ (Huesemann and Huesemann, 2011) in the sense of inscribing technology as an ecological saviour, since the future it imagines and partly materialises is one in which the only sustainability that matters is the sustainability of agro-industrial capital accumulation. Drawing upon the posthumanist political ecology of Jason W Moore (2015, 2016, 2018), I grasp this in the context of ‘the end of cheap nature’, by situating the future-making project of artificial pollination within the political ecology of capitalism in its more-than-human dynamics of accumulation. In this way, I attempt to show how, even on its own terms, robotic pollination is a self-negating technology which cannot insulate agro-industrial capital from its own ecology.

Enter RoboBee: Technologies of artificial pollination

A pink and white lily with three large flowers occupies centre-screen, against the backdrop of a sterile-looking white room with an indistinct piece of technical equipment in the background. After a few seconds, something red and white drops rapidly from above and crashes into one of the flowers, before speeding immediately out of view to the left, leaving the flower wobbling from the impact. After an editing cut, a very similar process then occurs again, this time with the flower in the immediate foreground and occupying more of the screen as it is dive-bombed by the flying object. The flying object is a micro-scale drone, resembling a tiny model helicopter. It has been modified in such a way to enable it to absorb and deposit grains of pollen, and the video recreates the key moments in a test of whether this ‘materially engineered artificial pollinator’ is able to effectively pollinate a flower (Science Magazine, 2017; Science News, 2017). The research team who designed the device claim that in the foreseeable future this kind of technology could potentially be used alongside or even replace pollinating insects such as bees, flies and moths. In this way, they suggest that robotic pollinators could be key to the sustainability of global agriculture and to fertilisation of the large variety of crops which currently depend upon insect pollination (Chechetka et al., 2017).

Much of the media attention given to artificial pollinators centres on the arresting idea of ‘robot bees’ (Boffey, 2018; Klein, 2017; Ponti, 2017). In juxtaposing two entities replete with cultural associations, the hybrid ‘robot bee’ seems perfectly engineered to capture our collective imagination as well as our collective anxiety in the era increasingly referred to as the Anthropocene,¹ said among other things to be characterised by a blurring of the distinctions between the machinic and organic, the natural and the artificial, and the biological and technological (Lorimer, 2016; Nimmo, 2020).² However, the key innovation of the research on ‘materially engineered artificial pollinators’ at Japan’s National Institute of Advanced Industrial Science and Technology is not the ‘robot bees’ themselves, which are simply very small commercially available drones, but the materials used to enable them to mimic the pollination function of some insects by absorbing and transferring pollen. This was accomplished by the use of material from the body of another animal, attaching a tiny strip of horse hair bristles to the bottom of the drone in order to mimic the fuzzy bodies of bees with their electrostatic properties and capacity to efficiently gather pollen. The horse hair was coated in an ionic liquid gel with an adhesive quality, initially developed for use in electrochemical applications. Repurposed for artificial pollination, the gel was firstly tested for

toxicity on cells from mice as well as on live ants, and then tested for pollination efficacy by placing a number of ants in a box of tulips, with one sub-set coated in the gel and another untouched, wherein it was observed that the ants coated in the sticky gel collected pollen from the tulips. All that remained was to put these elements together – horse hair bristles, ionic gel and drone – to create a ‘functional hybrid’ (Amador and Hu, 2017; Chechetka et al., 2017).

This ‘materially engineered artificial pollinator’ can absorb and transfer pollen, but in other respects the device hardly resembles bees or flying insect pollinators. The drones use four propellers to achieve and sustain flight and must incorporate an adequate on-board power source for these, making them significantly larger than most pollinating insects, and thus rendering them unsuitable for the fertilisation of many crops and flowers as well as potentially dangerous to the delicate bodies of any living pollinators in close proximity. Moreover, unlike bees, which perform pollination autonomously, a pollinating drone must be remote-controlled by a human operator by means of radio waves (Chechetka et al., 2017). These are significant drawbacks when it comes to the practical viability of such devices as replacements for animal pollinators. For them to be contemplated as viable, it must be possible to imagine artificial pollinators being inexpensively mass-produced and operating autonomously, at scale, in the context of diverse farming environments and crops.

One approach has been to focus on the problem of autonomy by sacrificing both micro-scale and aerial design, instead developing larger robots which can move around on wheels to perform pollination functions rather than attempting to create a tiny robotic pollinator on the model of a flying insect. Unhindered by the technical problems involved in scaling complex technologies down to the size of insects, larger devices are able to deploy state-of-the-art spatial sensing and mapping technologies together with sophisticated heuristics programming in order to identify and map the positions of flowers and their reproductive organs before calculating the most efficient route of pollen collection and transfer. The BrambleBee, developed by researchers at West Virginia University, is a wheeled ground vehicle equipped with a robotic arm and multiple on-board cameras, which operates autonomously by running numerous sophisticated algorithms and does not require a human controller (Ohi et al., 2018; Strader et al., 2019).

Reminiscent of the three gardening robots in Douglas Trumbull’s 1972 science fiction film *Silent Running*, which amble around the spaceship’s botanical garden tending to the needs of its plants, BrambleBee moves around the work area and performs an initial ‘inspection pass’ which maps the approximate locations of clusters of flowers using the on-board depth camera (West Virginia University Interactive Robotics Laboratory, 2018). It then determines an optimal route around these clusters, before carrying out a more detailed spatial analysis of the precise positioning and angle of each flower once in position, which it then uses to perform pollination with the robotic arm and attached ‘end-effector’ mechanism (Ohi et al., 2018; Strader et al., 2019). Although the BrambleBee can avoid obstacles and avoid damaging flowers in the context of the relatively controlled environment of a greenhouse, it is currently incapable of navigating the greater complexities of the outdoor field environments that predominate in agriculture, with their many variables such as uneven ground and varying weather and winds. Moreover, though this is not foregrounded in the research papers, BrambleBee is currently designed only to carry out the pollination of self-pollinating plants rather than the significantly more complex operations of cross-pollination (Ohi et al., 2018: 3; Strader et al., 2019).

Another approach is based on the notion that evolution has already produced the optimal ‘design’, and that the solutions to artificial pollination therefore lie in making the robots more like insects, rather than more like existing industrial robots. Bio-inspired

micro-robotics treats the problems of micro-scale as a challenge to innovation and seeks to approximate the complex flight mechanics of winged insects, rather than relying upon relatively larger and heavier propeller-based drones or turning towards much larger machines for automated pollination.³ For example, the DelFly project underway since 2005 at the Micro Air Vehicle Laboratory (MAVLab) of Delft University of Technology has constructed a series of MAVs based upon fruit flies and other flapping-wing insects, including the DelFly Micro in 2008, the DelFly Explorer in 2013 and the DelFly Nimble in 2018 (Delft University of Technology Micro Air Vehicles Laboratory, 2020). Each iteration has incorporated a greater range of flying and manoeuvring abilities, albeit achieved at the cost of progressively larger size, with the fully manoeuvrable Nimble having a wingspan of no less than 33 cm, compared with 10 cm for the far less controllable and agile Micro. The key problems in this field cluster around how to combine an adequate on-board power source and navigational controls with micro-scale and weight (De Croon et al., 2016).

Harvard Microrobotics Laboratory's parallel RoboBee project claims to be the first to achieve 'sustained untethered flight of an insect-sized flapping-wing micro-scale aerial vehicle' with its 'RoboBee X-Wing' (Jafferis et al., 2019). The approach was to use tiny solar panels rather than a battery as an energy source, as well as two sets of wings, enabling the X-Wing to be significantly smaller and lighter than any of the DelFly devices, with a 3.5 cm wingspan and weighing less than a gram, and yet still achieve sufficient thrust-to-weight ratio to enable flight (Harvard, 2019). But what is described as 'sustained flight' is in fact just a few seconds, and the RoboBee does not incorporate basic navigational controls, let alone the kind of on-board sensing, mapping and processing capacities that are required to enable larger robots like the BrambleBee to perform pollination activities. Moreover, at such a tiny scale the laws of aerodynamics that apply to larger flying vehicles do not operate predictably, with unsteady and chaotic aerodynamic effects playing a larger role in what are referred to as low Reynolds conditions (Liu et al., 2016; Tanaka et al., 2012). This is magnified for ornithopter designs with flapping wings modelled on insects rather than helicopter-like propellers. Truly micro MAVs like the RoboBee have therefore tended to behave erratically during their brief periods of flight, leading to calls for further research in order to better understand the chaotic physics of their flight dynamics.

Micro-robotics has proceeded alongside research in 'artificial swarm intelligence', which is often invoked as a promising source of potential solutions to the challenges facing artificial pollination by micro-scale aerial devices (Coppola et al., 2020; Wagner, 2008: 128–129). Inverting older cultural tropes of the swarm as a mindless collective, swarm robotics tackles the question of how to enable autonomous drones or robots to be capable of effective self-organisation as part of a multiplicity of similar devices, and of operating in a coordinated way through constant inter-communication (Czech Technical University in Prague Multi Robot Systems Group, 2020). The aim is to create drones able to navigate and interact with the environment and each other in order to achieve collective goals, in a manner analogous to the swarm behaviour of honey bees, ants and other social insects (Garnier et al., 2007). The principle of swarm intelligence is that each individual robot should be as simple as possible, with an emphasis on minimising costs and maximising scalability, so that very large numbers of robots are feasible. In this way, scale is to be turned into a key advantage by enabling the swarm to accomplish tasks or solve problems in a manner that would be beyond the capabilities of the individual robots comprising the swarm.⁴ One of the largest such swarms yet assembled was the 1000 robot swarm constructed in 2014 in a laboratory at the Wyss Institute for Biologically Inspired Engineering at Harvard (Harvard University, 2014). Despite the relative simplicity of each individual 'Kilobot', the swarm was able to use basic infra-red sensors fitted to each

robot together with a ‘smart algorithm’ to successfully assemble itself into a series of human-directed shapes and letters, even self-correcting errors in the process, in a demonstration of the potential of collective artificial intelligence (Rubenstein et al., 2014).

When recent developments in these interconnected research fields are considered together – materially engineered artificial pollination, insect-inspired aerial micro-robotics and autonomous swarm intelligence systems – the direction of travel is clear. The aspiration is to reach the stage where it is feasible to mass-produce large autonomous swarms of robotic drones of insect size or smaller, with on-board sensors and information processing, capable of navigating their environment and coordinating their actions in order to carry out tasks such as pollination at scale. Indeed ‘bio-inspired robots’ and ‘robot swarms’ are regularly judged to be among the ‘grand challenges’ for robotics science during the next decade (Yang et al., 2018). While it is currently a growing but still somewhat fringe interest, rather than a large-scale or mainstream development, the significance of robotic pollination research as a future-making practice should not be underestimated. We should not expect to see robotic pollinators deployed at scale in the near future. But all agricultural technologies were fringe developments at one point in time (see Nimmo, 2017), and those who have discerned the trajectories embodied by these emergent technologies have sought to position themselves accordingly, the better to shape this emergent future. In this respect, it is telling that on 8 March 2018, Walmart filed a broad patent for autonomous robotic pollinators or ‘systems and methods for pollinating crops via unmanned vehicles’.⁵ Robotic pollination can also be understood as a particular development within the larger phenomenon of ‘precision agriculture’, which aims to deploy robotics, artificial intelligence and autonomous systems to increase agricultural productivity and farming efficiency, by boosting yields, reducing waste and pollution, and lowering labour costs. Hailed as ‘sustainable intensification’, this is positioned as a favourable solution to food security and sustainability challenges in the future-making discourses, policies and investments of multiple governments, multinational organisations, and research and investment networks (Astill et al., 2020; Chuchra, 2016; ECHORD, 2019; Hopkins, 2016; Saiz-Rubiro and Rovira-Más, 2020; UKRI, 2020). The following section examines the discourses and materialities of artificial pollination more closely, in order to unearth what vision of the future these technologies involve and trace the framings of ecology, economy and technology they inscribe as part of that future-making ontology.

Reframing pollination ecology

The manner in which robotic pollinators are introduced, framed, situated and discussed manifests a recurring discursive structure across media reports, websites and academic articles on artificial pollination research. Typically, an initial brief sketch of the problem of pollinator decline sets the stage for the postulation of robotic pollination as a potential solution. For example:

Pollinating insects such as honeybees play a critical role in maintaining the natural environment. The decline in honeybee populations is a global issue with significant repercussions with respect to the pollination of plants [...] materially engineered artificial plant pollinators should lead to the development of high-performance robotics that can help counter the decline in honeybee populations. (Chechetka et al., 2017: 224)

This notably involves backgrounding the wider ecological implications of pollinator decline, insect decline and declining biodiversity more widely, which go well beyond the impacts on

agriculture and commercial food production and point to loss of biodiversity, degradation of the biosphere and the breakdown of earth's living systems (Cardoso et al., 2020; Marshman et al., 2019). Rather than situating the pollination problem as part of this wider ecological crisis, instead it is framed principally as a problem of agro-economics, with bees inscribed not as vital nodes in ecosystems so much as technologies of agricultural production. In a research article on BrambleBee, this is spelled out explicitly:

An urgent issue faced by the agricultural sector today is the decline of natural pollinators, particularly honey bees, which threatens crop production. Many farmers cannot rely solely on natural pollinators in their local environments to effectively pollinate crops. Farmers often rent bees and have them shipped in from other locations for providing pollination services. [...] the declining bee population is increasing the cost to farmers who must rent them. Therefore, in parallel to addressing the cause of natural pollinator population decline (i.e. colony collapse disorder), there is a need to develop alternative pollination techniques to keep up with the increasing demands of the growing human population. One of these potential techniques is robotic precision pollination. (Ohi et al., 2018: 1)

In short, the decline of bee populations is pushing up prices for those farmers who must rent bees in order to pollinate their intensively produced monoculture crops, the pollination demands of which outstrip the capacities of dwindling natural pollinators. Wild pollinators are a marginal presence here, while the main emphasis is on honey bees and their agro-economic importance, which is reinforced by the conflation of natural pollinator decline with Colony Collapse Disorder.

Yet, notwithstanding the global proliferation of commercial honey bee apiculture in step with the spread of industrial monocrop agriculture, a significant proportion of the world's food crops are fertilised by wild pollinators rather than by commercial honey bees, particularly outside of the US (Breeze et al., 2011; Klein et al., 2007). The variety of plants requiring pollination have co-evolved alongside diverse insect pollinators within ecological webs of life which have mutually shaped both parties (Barth, 1991; Buchmann and Nabham, 1997; Mitchell et al., 2009). Plants have diverse reproductive anatomies that have emerged from co-evolutionary relations with particular insects; indeed the term 'coevolution' was first used by Charles Darwin (1859), with reference to what he called 'the reciprocally adaptive relationship between plants and their pollinators' (Marshman et al., 2019: 2). Hence, particular plants can be much more effectively pollinated, or in some cases only pollinated, by particular insects (Mitchell et al., 2009; Real, 1983; Waser and Ollerton, 2006). Although *Apis mellifera* (hereafter the 'European honey bee' or simply 'honey bee') is a notably prolific and industrious pollinator as well as the only pollinating insect to have been semi-domesticated on a large scale, it does not constitute a *universal* pollinator. Honey bees cannot perform sonication or 'buzz pollination' for example, making them rather poor pollinators of blueberries, cranberries, kiwis, chili peppers, eggplants and tomatoes, in comparison with some wild bee species (Marshman et al., 2019: 3). Yet honey bees tend to be positioned as universal pollinators in the framings of pollination ecology found in discourses of artificial pollination, giving rise to the following logic: replace honey bees, and you replace the only natural pollinator that matters in agriculture, and thus solve the pollination problem. By reducing pollination ecology to agricultural productivity in this way, the pollinator crisis is inscribed as a delimited economic problem of markets, prices, labour and production, rather than a sprawling socio-environmental problem of collapsing biodiversity. This in turn paves the way for the notion that a techno-managerial solution is appropriate, as follows: since honey bees are becoming scarcer, less reliable and more

expensive, a technological replacement could offer a means to reduce costs, restore reliability, and increase productivity and profitability.

The notion that artificial pollination technologies may eventually be cheaper than hiring honey bees, however, is only plausible in the event of an almost complete collapse of insect pollinators. In any other scenario, bees will continue to be significantly cheaper than any robotic pollinators one could imagine, even in the context of intensive monocrop production. As one group of experts in pollination ecology and biodiversity argue:

There are many billions of individual bees and other pollinators across the planet already doing an effective job of crop pollination. Given some of them are declining, the most cost efficient strategy to secure production is to safeguard the pollinators we already have and sustainably manage landscapes to increase their numbers further. Trying to replace this existing pollination service with fleets of robots is economically inviable [...] Even at a modest \$10 per bee for example, the total cost would be many 100s of billions of dollars to pollinate the area of insect-pollinated crops that is currently grown over the world. Further, there are the costs of hardware repair and maintenance, command and control infrastructure. (Potts et al., 2018: 666)

This arithmetic helps to explain why the economic case for replacing animal pollination with robots tends to be shrouded in notions of ‘bio-assistance’ where robotic pollination is imagined as ‘filling the gap’ or being one part of a solution ‘in parallel to addressing the cause of natural pollinator population decline’ (Ohi et al., 2018: 1). For example, a researcher at Japan’s National Institute for Advanced Industrial Science and Technology states that ‘We hope this will help to counter the problem of bee declines’, before adding, ‘But importantly, bees and drones should be used together’ (Klein, 2017). This is no doubt intended to soften the bolder claims of replaceability which tend to frame initial presentations of artificial pollination technologies, and which are very difficult to sustain. In reality, the two solutions are mutually exclusive; if insect pollinator decline is addressed and mitigated then robotic pollinators will never be economically viable, and if robotic pollinators become economically viable that can only be because insect pollinator decline was not addressed until it was too late.

The logic of artificial pollination research, then, assumes a future in which honey bees and other pollinators will eventually dwindle to very low numbers or become extinct, a scenario that is not implausible on current trends but which would be catastrophic in its ecological implications. In this respect, the underlying rationale for micro-robotic pollinators is not quite what is usually suggested – to directly replace honey bees, but rather to replace what will be the only remaining alternative in a future in which insect pollinators no longer exist in sufficient numbers to satisfy the pollination requirements of agriculture. Talk of robotic pollinators working alongside bees or replacing bees is therefore misleading; it is only in the context of human labour that the deeper rationale for artificial pollination emerges, which is to automate hand pollination. The model for this future already exists, in several counties in Sichuan Province, China, where pears and apples have been painstakingly pollinated by hand in an enormously labour-intensive process since the 1980s, after habitat clearance for monocrop fruit farming and years of insecticide overuse led to a dramatic decline in natural pollinators compounded by the refusal of many beekeepers to lend their hives (Partap and Tang, 2012; Tang et al., 2003). From the perspective of artificial pollination research, Hanyuan County and Maoxian County are the future, not just a warning of a possible future to be avoided. As human labour may not always and everywhere be as cheap as it is in Sichuan, machines offer an alternative. This underlines how robotic pollination projects – notwithstanding their adoption of the language of sustainability, bio-inspiration and bio-assistance – are undergirded by an often unstated ecological fatalism.

This finds its counterpart in pronounced optimism concerning the potential of robotics to solve or mitigate the pollination problem; the trend of pollinator decline may be unstoppable, and the modern farming systems driving this immutable, but technology has the capacity to address the undesirable consequences of these, sufficiently at least to sustain agricultural production. This is not quite an image of technology as ecological saviour, of the kind so trenchantly critiqued by Eileen Crist (2019) and Huesemann and Huesemann (2011) amongst others, but rather a notion of technology as ecological substitute, a means to replace and overcome the economic function of collapsing elements of ecosystems, in a kind of eco-apocalyptic techno-optimism. Some sleight of hand is required in framing the current state of the art of artificial pollination technologies and their future prospects in order to sustain this. In particular, the array of severe limitations afflicting robotic pollinators and daunting technical obstacles yet to be overcome are off-set by assumptions of rapid progress and imminent breakthroughs. For example, the inability of any current untethered insect-scale drones to fly for sustained periods, or to incorporate either an on-board power source or adequate navigational controls, are presented as eminently surmountable technical challenges. So too is the current inability of any robotic pollinator to effectively pollinate multiple varieties of plants or to operate autonomously in outdoor field environments (Yang et al., 2018).

A critical assessment might acknowledge, on the contrary, that there remain near-insuperable technical obstacles to robotic pollinators ever becoming feasible direct replacements for insect pollinators, except perhaps on a limited scale in some greenhouse monoculture operations. As pollination ecologist Simon Potts elegantly puts it:

While technology is moving in the direction of unmanned flying robots able to make complex decisions, they are still extraordinarily clumsy and unsophisticated compared to real bees [...]. There are more than 350,000 species of flowering plants on the planet and they all interact in very unique ways with animals as pollen vectors to bring about sexual reproduction, fruit and seed production, and evolution [...]. Technology has taken tiny steps to try to address the pollination process of a few 'easy' crops such as sunflowers (*Helianthus annuus*) which have large disk-shaped easily accessible inflorescence, but is still barely out of the starting gates, while evolution, through high levels of functional biodiversity and complex ecology, crossed the finishing line millions of years ago. (2018: 666)

That would of course dispel the smokescreen of artificial pollination as a technology of sustainable production in terms of world food security, repositioning it as a strategy of sustained accumulation for specific sectors of capital-intensive agribusiness. But rather than acknowledge the apparently limited scope of application for artificial pollination technology, its proponents tend to point to the putative advantages of robotic over animal pollinators, citing their ostensibly greater precision, efficiency and reliability, and claiming that 'precision robotic pollination systems can not only fill the gap of declining natural pollinators, but can also surpass them in efficiency and uniformity, helping to feed the fast-growing human population on Earth' (Ohi et al., 2018: 1).

The uniformity of robotic pollination in particular is hailed as a significant advantage over animal pollinators, which are represented as relatively inefficient because their transfer of pollen is a secondary consequence of seeking nectar rather than the primary focus of their activity:

Bees forage for flowers primarily for the purpose of gathering food for themselves and their offspring, which provides pollination service as a by-product. Many pollinating insects, including bees, tend to habituate and revisit known flower locations in an effort to minimize

uncertainty in finding food. This behavior is beneficial to the insects in terms of finding food, but could be detrimental in terms of pollination uniformity because not all flowers may get visited. Robotic pollinators, like BrambleBee, can be focused on pollination effectiveness and uniformity, rather than food gathering. (Ohi et al., 2018: 2)

Rather than assessing the capacities of these emerging technologies against the existing complex ecology of insects and plants, this discourse inverts that logic and assesses insect pollination ecology according to criteria rooted in the functional requirements of agro-industrial production. Only when pollination is viewed from the perspective of the requirements of productivism and industrial monoculture in this way, can an invariant, uniform, machinic pollination technique be construed as superior and desirable. Thus, alongside the invocations of ‘bio-mimicry’ and ‘bio-inspiration’ in these projects, the models of biology and animality they mobilise are essentially mechanistic, inscribing biology, ecology and animality in functional economic terms, and situating pollinating insects as technologies of production disembedded from their complex co-evolved interrelationships within the web of life. Once nonhuman entities and their ecologies are viewed as machines performing functions for human agro-industrial economies, it becomes possible to imagine that actual machines might perform those functions more efficiently (Adam and Groves, 2007: 80–81; Plumwood, 2002).

This reframing of pollination ecology can be understood as a future-making material-discursive practice; it imagines and partially enacts a particular future by inscribing a specific ontology in the present, a specific web of meanings around ecology, economy, agriculture, technology, sustainability and their interrelations. This works from the imagined future backwards and from the imagined present forwards; by positing certain elements of the future as given and immutable, it entrenches an ontology in the present which is configured to produce that very future, rendering it viable, desirable, and seemingly rooted in a given reality (Brown and Michael, 2003; Michael, 2000; 2017: 513). It also partially materialises this ontology and this vision of the future, imbuing it with remarkable objectifying power relative to other visions. This is accomplished not just through the materiality of discourse and the materializing process of technological design, but by establishing a mobilising framework for the enrolment of capital, in such a way as to begin to assemble and crystallise this future while closing down other possibilities. This is not of course the exclusive work of the scientists and researchers themselves, who by and large are pursuing and promoting their particular specialisms within the opportunities afforded to them, with significant but strictly delimited agency; their inscriptions largely reflect and respond to their situation. It is in the enabling and shaping of these discursive and material opportunities that the future-making agency, not of any particular social actor, but of capital as a process, relation and assemblage, can be discerned. In the worlds of business and finance, the language of ‘futures’ is a language of speculation, opportunity and accumulation, and the future is that which can be invested in, commodified and colonised (Adam and Groves, 2007; Adkins, 2017). Thus, as John Urry suggests, ‘A key question for social science is who or what owns the future – this capacity to own futures being central to how power works’ (2016: 11). The following section addresses this by situating the future-making project of artificial pollination in its socio-ecological entanglement with capitalist strategies of accumulation.

Accumulation after cheap pollination

Robotics is perhaps more centrally involved than any other field in exhibiting what materialised capital might become, what futures it might mould, and what new conditions and relations of labour, production and accumulation it might forge. Robotics research thus mobilises material-discursive strategies centrally designed to attract investment, from which

it is possible to discern what kinds of futures capital is quite literally invested in. For example, the Dutch ‘MAVLab’ project developed the DelFly as a part of the ‘RoboValley’ initiative, described on its website as a ‘flourishing robotics ecosystem that attracts the best researchers, companies, start-ups and capital, and takes a leading role in the development of the next generation robotics’ (RoboValley, 2020). A more government-centred example is the UK’s ‘Transforming Food Production’ initiative announced in 2018 as part of its new industrial strategy, which committed to make available £90 million of funding to ‘strengthen connections between innovative businesses, farmers and end users to accelerate the development and adoption of precision approaches to increase agricultural productivity’. This involved creating ‘an Investor Partnership programme to encourage venture capital firms to take a stake in innovative UK agri-tech businesses’ (UKRI, 2020). Similarly, the EU’s ‘European Coordination Hub for Open Robotics Development’ supports research consortia ‘composed of partners from industry, academia or research institutes in conjunction with the potential users of the robotics technology’. This incorporates a funding stream on agriculture and food robotics, with projects including ‘mobile agricultural robot swarms’ and ‘swarm robotics for agricultural applications’ (ECHORD, 2019). These exemplify the assemblages of research teams, entrepreneurs, investors and governmental agencies that characterise agro-technoscience in general and robotic pollination in particular; the future-making discourses, practices and inscriptions that emerge from these networks are not the work of any single primary agent or driver, but are the collective product of the ‘ecosystem’ or assemblage, enabled and impelled by capital. RoboValley presents itself as addressing societal and socio-environmental challenges – ‘climate change, ageing societies, growing world population and food shortage: these are issues which can be partly solved by robotics’. The proffered solutions turn out also to be potential profit-making opportunities where prescient investors might make impressive returns beyond the possibilities of business as usual. In this way, socio-environmental problems and crises are translated via the material-discursive practices of technological design and investment into new terrains for capital and new frontiers and strategies of future accumulation.

Tracing these dynamics through pollination ecology requires an approach that can understand the constitution and logic of the capital relation within the organic assemblages of human and nonhuman entities that make up the living world. While many scholars have theorised the relation of capital *to* nature, by reading Marx through the prism of ecology and vice versa (Burkett, 2014; Castree, 2000; Foster, 2000, 2002; O’Connor, 1998), Jason Moore’s recent work is distinctive in the consistency with which it posits the capital relation itself as co-produced within and through ecosystems or ‘the web of life’. Human and ‘extra-human’ natures are grasped as intrinsic and constitutive elements of a dialectic of exploitation and appropriation at the heart of capitalism and the value-form (Moore, 2015, 2018). Thus, it is not a question of bringing a discrete ‘nature’ into the existing social ontology, theorising nonhuman agencies and adding them to human agencies, or looking at the interaction of the two, but rather of understanding how human and nonhuman agencies are relationally constituted and co-productive in a ‘double internality’ that Moore calls ‘*Oikeois*’, aptly enough a term coined by the Greek philosopher and botanist Theophrastus to refer to the relationship between a plant species and its environment (Moore, 2015: 35). Moore uses the term to refer to the creative and dynamic internal relationship between *and within* human and extra-human natures:

If nature is indeed a historical protagonist, its agency can be comprehended adequately only by stepping out of the Cartesian binary. The issue is emphatically not one of the agency of Nature

and the agency of Humans. These are unthinkable without each other. Rather, the issue is how human and extra-human natures get bundled. [...] This is, too often, left out of arguments of nature's agency: the capacity to make history turns on specific configurations of human and extra-human actors. Human agency is always within, and dialectically bound to, nature as a whole – which is to say, human agency is not purely human at all. It is bundled with the rest of nature. (2015: 37)

This enables a reading of capitalism's value-form which goes beyond the classical focus on socially necessary labour time as the substance of value, and reckons with the immanent role of extra-human natures in the logic of value and its conditions of expanded reproduction.

The core argument is that while the sphere of capitalist production and the value form rests upon continually advancing labour productivity and thus the exploitation of commodified labour, this soon exhausts the health and vitality of the human and nonhuman natures caught up directly in commodity production, undermining the necessary conditions for further productivity increases (Moore, 2015: 67–69). To sustain accumulation therefore requires the massive appropriation of 'Cheap Nature',⁶ which Moore defines as the unpaid work/energy⁷ of human and extra-human natures which are located in domains of reproduction outside of the immediate commodity system, but without which the commodity system cannot continue to sustain increases in labour productivity (2015: 54, 58, 62). In short, commodity production is not sustainable as a closed system, but must continually expand and appropriate from outside of itself. This drives new commodity frontiers and the expansionary territorial dynamics of historical capitalism as it seeks out Cheap Natures for appropriation (Moore, 2015: 73). Produced 'when the interlocking agencies of capital, science and empire succeed in releasing new sources of free or low-cost human and extra-human natures for capital', Cheap Nature is marked historically by periodic dramatic reductions in the socially necessary labour-time of food, labour-power, energy and raw materials (2015: 53).

This can be fruitfully compared with recent reappraisals of 'primitive accumulation', which was Marx's term for the way in which capitalism came into being through the forcible seizure and enclosure of people's land and their expulsion by means of violence, enslavement and colonialism, creating a property-less and landless class ripe for exploitation (Perelman, 2000). Several contemporary scholars have argued that primitive accumulation is not just a historical 'stage' in the emergence of capitalism, which precedes the development of capitalism proper whereupon it becomes outmoded, as in orthodox Marxist theory, but rather is a continuing process which takes diverse and evolving forms and remains necessary for capitalist accumulation on a world scale, particularly in providing a sort of safety-valve of cost-lowering measures to ease its periodic crises (De Angelis, 2001; Harvey, 2003; Perelman, 2000). Where Moore's 'Cheap Nature' differs from these accounts is that, while they similarly conceptualise primitive accumulation as functionally necessary for the ongoing reproduction of capitalism, they nonetheless consistently situate it as external to capitalism proper, conceived around the centrality of the commodity system and exploited wage labour. Whereas, in Moore's account, capitalism is effectively redefined around an incorporation of this broader movement of appropriation into the dialectic of value relations, conceived as a doubly internal relation of capital-in-nature and nature-in-capital (Moore, 2015: 68–69).⁸ In this approach, therefore, capitalism does not merely act upon nature but also through nature. One consequence is that Moore's conception of appropriation places a less narrow emphasis upon the role of political and economic violence, coercion and outright plunder, though this is duly acknowledged, while giving more emphasis to the active appropriation of the work/energy of extra-human natures through historical

formations of power-knowledge and technology, or ‘technics’, which themselves produce new historical natures (2015: 152–153). This renders ‘Cheap Nature’ both more posthumanist and more ecological than comparable reworkings of primitive accumulation. It is instructive to consider, firstly, the historical trajectory of commercial pollination, and then the contemporary crisis of pollination and emergence of artificial pollination technologies, in light of this analytic framework.

Historically, Moore identifies the vast new commodity frontier established by the European colonisation of North America, with the conversion of huge tracts of land for farming, and the westward spread of European agricultural practices and labour relations, as pivotal in overcoming the decline of agricultural productivity in England in the early 19th century and thus to fuelling the full flowering of industrialisation in the middle decades of that century. As he puts it, this ‘was an extraordinary development in human history; no civilisation had relocated its agro-ecological heartland from one continent to another’, as ‘the American Midwest became capitalism’s newest breadbasket’ (2015: 246–247). Moore focuses on the appropriation of the fertile soils as a source of unpaid work/energy, noting that ‘the Midwestern and Great Plains frontiers offered up millennia of accumulated nutrients (and water) which sustained industrial agriculture’s rapid advance in the closing decades of the nineteenth century’ (2015: 248). But this was also facilitated by the European honey bee, which was first introduced to the east coast by the colonial settlers in 1622 (Horn, 2005). A particularly industrious pollinator amenable to the semi-domestication of living in managed beehives, and which could therefore be physically transported along with the expanding frontier, the spread of the honey bee facilitated a dramatic transformation of the American landscape, enabling the introduction of European seeds and saplings as well as the spread of white clover and other English grasses more amenable to the imported livestock (Horn, 2005; Preston, 2006). In this way, the honey bee facilitated the levels of agricultural productivity which produced the Cheap Nature essential for capitalism’s westward expansion. So synonymous was the honey bee with the European settlers that the Native Americans referred to the species as ‘the white man’s fly’, in the wake of which they knew would follow their violent displacement from the land, territorial enclosures, cattle, commodities, and a transformed environment (Hardy, 2016). Two hundred and thirty years after its introduction, the honey bee finally reached the West Coast (KEI) (Kellar, 2020). Thus, the increased yields and rising agricultural productivity of the 20th century’s long Green Revolution were facilitated not just by new agricultural technologies but by the proliferation of commercial apiculture in-step with the growth of industrial farming, as farmers increasingly turned to the practice of hiring honey bee hives as a means to increase the fertility of their monoculture crops.

Returning to the present, the species which played such a key role in enabling the agricultural colonisation of North America and the growth of agricultural productivity in the 20th century is afflicted by increasing vulnerability in the US and Europe (Durant, 2019; Potts et al., 2010), combining increasing winter losses in recent years (Bruckner et al., 2019), with an uneven decline during the period since the mid-20th century (National Research Council, 2007), and in the context of a wider global decline of a swathe of pollinating insects (Cardoso et al., 2020). Honey bees and other pollinating insects were an abundant stream of ‘ecological surplus’, yet they are becoming neither so cheap nor so abundant. Their cost is steadily rising as bees and beekeepers suffer the effects of industrial agriculture’s unprecedented and sustained toxification of the environment with chemical pesticides and insecticides, and these costs are translated into higher prices for commercial hives (Ferrier et al., 2018; Goodrich, 2019). Meanwhile, and more fundamentally, the unpaid work/energy of wild pollinators is diminishing as all insects suffer declining numbers, leading to a still

greater demand for commercial apiculture (Aizen and Harder, 2009). The automation of pollination marks an attempt to break this circle of escalating costs by subsuming pollination directly under agri-food capital. The substitution of robotic pollinators for living pollinators would be a decisive step in a process of commodification already manifest in the proliferation of large-scale intensive commercial apiculture (Cilia, 2019; Ellis et al., 2020; Nimmo, 2015a), marking a shift from the formal subsumption to the real subsumption of pollination under capital. But large-scale investment in the automation of pollination would also involve a double shift in the composition of agricultural capital, with systemic implications:

Firstly, the automation of pollination would mean a reduction in the value of investment in variable capital or labour, relative to constant capital, or machinery and technology. By reducing the socially necessary labour required to produce a given quantity of commodities, this would reduce the ratio of surplus value relative to investment across the sector (Marx, [1894]1991: Ch. 13). So while robotic pollination might offer a competitive advantage to the large agri-food firms able to make early investments, once these technologies became more widely adopted – wreaking destruction on smaller producers in the process – then any competitive advantage would be undermined by rising investment costs and lower rates of profit for the whole sector.⁹ A second compositional shift flows less from Marx's theory of the tendency for the rate of profit to fall than from Moore's posthumanist ecological reading of capital accumulation. Recall that at the heart of Moore's analysis is what he calls 'the dialectic of appropriation and capitalization', that is, the relationship between accumulation by means of exploitation within the commodity system, and accumulation by the appropriation of unpaid or low-cost human and extra-human work/energy from beyond the immediate commodity nexus (2015: 152). As previously stated, appropriation is crucial for the reproduction of capital as self-expanding value, since it enables continued accumulation by off-setting the tendency of commodity production to exhaust the vitality, energy or health of the human and extra-human natures caught up in it directly. But as the sphere of capitalization expands and those human and extra-human natures are increasingly incorporated into the commodity system directly, this inevitably means diminishing opportunities for the appropriation of Cheap Nature on a finite planet (2015: 157). The result, Moore argues, is a 'tendency for the rate of ecological surplus to fall', in the context of depleting finite resources, rising toxification, collapsing ecosystems and disappearing frontiers.

This underlines the significance of the fact that insect pollinators reproduce and propagate themselves of their own volition and undertake pollination activities at no or remarkably low cost to beekeepers and farmers. Their free or incompletely commodified work/energy has been historically and remains today a very significant source of ecological surplus for appropriation. A sense of the scale of this is indicated by estimates of the annual economic contribution of pollinators at around €150 billion, equivalent to around 10% of the total value of world food production (Gallai et al., 2009), with the annual cost of pollinator disappearance estimated at around €300 billion. These are likely to be underestimates given that whatever is appropriated is by definition not fully commodified and thus cannot be accurately measured in terms of financial contribution. In another measure, between \$235 and \$577 billion of annual global food production is estimated to rely on direct contributions by pollinators (IPBES, 2016). With human hand pollination, which is more fully commodified, costs are higher, but can still be kept relatively low by appropriating surviving pockets of peasant social reproduction, or through neoliberal acts of redistribution such as extending working hours and holding down wages. In contrast, while robotic pollinators are neither prone to dwindle when exposed to pesticides nor to resist exploitative conditions like human hand pollinators, every robot must be designed, assembled, maintained, upgraded

and replaced as necessary – it cannot be appropriated, even in part, but must be paid for in full. Thus, even if it were to overcome the very formidable technical obstacles to automating pollination on a large scale, this technology cannot replace the capacity of insect pollinators to provide an abundant stream of Cheap Nature for appropriation. Although its purpose is to make accumulation self-perpetuating by rendering agri-food production autonomous of failing pollination ecosystems, in fact robotic pollination drives not only toward accelerating insect extinction and ecological collapse but also toward deepening agro-economic crises.

Conclusion

This article has argued that artificial pollination technologies inscribe and partially materialise a future in which large-scale automation of pollination enables industrial capitalist agri-food production to survive and to grow in the context of the escalating ecological crises it is itself deeply involved in driving. Although capable of acknowledging the agro-economic drivers of pollinator decline, artificial pollination discourse inscribes these drivers as ineradicable and the existing structures of industrial agriculture as given and immutable. This tacitly backgrounds alternative futures in which structural transformations of agriculture and the world food system are able to mitigate and avert pollinator decline and biodiversity loss, and minimises the scope of political agency in potentially forestalling or reversing these trends. While invoking notions of sustainability and food security, discourses of robotic pollination define these in anthropocentric, economistic and self-referential terms, as a matter of enabling the reproduction of agro-industrial capital accumulation. In this respect, robotic pollination embodies and crystallises the propensity of capital to invest in sustainable futures only insofar as sustainability equates to the reproduction of capital itself as a system of self-expanding value. Where the avoidance of ecological collapse requires structural changes that would hinder or restrict this, capital will more readily invest in technologies which seek to valorise the perceived economic opportunities presented by the anticipated collapse.

I have shown how the presentation of artificial pollination as a potential alternative to insect pollinators involves reframing pollination ecology through a series of reductions. Pollinating insects are dislocated from their organic embeddedness in ecological networks and reduced to their pollination functions. Wild pollinators are backgrounded, leaving commercial pollinators, that is, honey bees, as the only pollinators of relevance. Thus, pollination ecology is reconceived through the perceived requirements of agri-food production, stripping away the complexities of plant-insect co-evolution and disregarding the sustainability of food production outside of capital-intensive monocrop agribusiness. With pollination ecology reduced to its economic functions, and honey bees reduced to machines of production, it becomes possible to imagine that actual machines could replace living pollinators. While robotic pollination research is nowhere close to overcoming the key technical obstacles standing in the way of artificial pollinators becoming viable replacements for insects, the discourses around the technology are characterised by confident expectations of progress. Robotic pollinators are even positioned as potentially more efficient than insect pollinators. But I have argued that robotic pollinators are not intended to replace insects directly but to replace human labour after living pollinators have disappeared, given that the cost of robotic pollinators could not conceivably fall below that of insect pollinators except in a future in which insects have declined catastrophically. This reveals how the deep rationale of robotic pollination is to navigate an eco-apocalyptic future by rendering future agri-food production less reliant upon the vagaries of a human labour force with its capacity for resistance to exploitation.

Finally, I have drawn upon the posthumanist political ecology of Jason W Moore in order to situate the future-making project of robotic pollination in relation to the dynamics of capital accumulation. Insects reproduce themselves at either no cost, in the case of wild pollinators, or low cost, in the case of managed honey bee hives, and they undertake unpaid pollination work as a consequence of their nectar-gathering activity, hence providing a rich source of 'Cheap Nature' or ecological surplus for agricultural capital, but they are vulnerable to the pesticides which are a mainstay of intensive industrial farming. Human pollinators in contrast must be paid, and while these labour costs can be suppressed by various means, this in itself incurs costs for capital. Machines are invulnerable to pesticides and incapable of organised resistance, and therefore seem to offer significant advantages to producers, but the automation of pollination marks the real subsumption of pollination under capital and its full incorporation into commodity production. Hence, unlike the work/energy of human and extra-human natures, the use-values created by pollination robots cannot be appropriated, even in part, but incur the full costs of research, development, construction, manufacturing and maintenance. With neither an ecological surplus to be appropriated nor human labour to be exploited, artificial pollination cannot therefore replace the Cheap Nature that is indispensable for the reproduction of capital accumulation. The notion of a technological means by which industrial agribusiness could become self-sustainable by escaping the consequences of its own expansion within the web of life, is therefore a fantasy of capitalist separation, a mirage of accumulation-without-limit rooted in a dislocation of economy from ecology that was never material. Even in terms of its own inner logic, artificial pollination is a self-negating technology, since it cannot insulate agro-industrial capital from its own ecology; it cancels the future it makes.

Highlights

- Undertakes a critical socio-ecological analysis of emergent technologies of robotic pollination as future-making practices.
- Traces how robotic pollination reframes pollination ecology around a mechanistic and productivist ontology, geared to the materialization of a particular future.
- Shows how the future inscribed by robotic pollination is undergirded by a stark ecological fatalism combined with technological hubris.
- Draws upon posthumanist political ecology to situate the rationale of artificial pollination technologies within strategies of capitalist accumulation within the web of life.

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Notes

1. While I regard the 'Anthropocene' as useful for posing fundamental questions, I accept the thrust of critiques of the concept for its tendency to invite, variously, a lingering anthropocentrism and dualism (Nimmo, 2015b, 2020), inadequate socio-economic and socio-ecological historicization (Moore, 2016, 2018), fantasies of technoscientific rationalization and managerialism of the biosphere (Crist, 2016, 2019), and depoliticization (Swyngedouw and Ernstson, 2018).
2. For an analysis of the 'uncanny' Anthropocene cultural (bio)politics of robot bees in science fiction read as technocultural entities haunted by their living referents, see Cettl (2020).
3. The focus on micro-scale is partly explicable in terms of the connection of micro-robotics with potential surveillance and military applications (Buiani, 2015: 205). The US Department of Defence was a key early source of funding for RoboBee (Webb, 2016). See also Kosek (2010) on bees and warfare.
4. As with aerial micro-robotics, research on 'swarm intelligence' is influenced and sometimes part-funded by military interests and agencies. The objective of creating an 'autonomous swarm' is not only – or even principally – about industrial pollination but is also about high-tech surveillance and warfare (Buiani, 2015: 205; Kosek, 2010; Webb, 2016).
5. US Patent Application Publication 2018/0065749 A1, March 8 2018, Systems and Methods for Pollinating Crops via Unmanned Vehicles.
6. Cheap Nature' is capitalised because the category reflects 'capitalism's way of seeing the world' (Moore, 2015: 53).
7. 'Work/energy' encompasses not just commodified labour, but 'the totality of waged and unwaged activity performed by humans and the rest of nature' within reach of what Moore calls 'capitalist power', encompassing the power-knowledge apparatuses of biopolitics, technoscience and empire (Moore, 2015: 102). The concept of 'work/energy' eschews any absolute distinction between human work and extra-human energy, and grasps these as interrelated in the 'double internality' in which human and extra-human natures enter into the relations of capital while capital also enters into the reproduction of human and extra-human natures. As Moore puts it, 'I speak of work/energy rather than simply work because we are dealing with work in a broadly biophysical sense, comprising the activity and potential energy of rivers and soils, of oil and coal deposits, of human-centred production and reproduction' (2018: 242).
8. Onur Ulas Ince (2018: 890–892) misreads Moore on precisely this point, in my view.
9. Marx's theory of the tendency for the rate of profit to fall and his labour theory of value, which underpins it, have been much criticised as well as vigorously defended in the literature on Marxist economics. I do not want to engage with those debates here beyond noting that recent econometric research that has attempted to quantify and test the TRPF theory does appear to offer some empirical support for a falling rate of profit over the long term (Basu and Manolakos, 2012).

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