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Towards new ecologies of automation: Robotics and the re-engineering of nature

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ABSTRACT

Climate/ecological breakdown and automation are two defining challenges of the current era, yet there is little research on their conjunctural intersection. Across experimental landscapes from agriculture to conservation to mining to weather modification, automation technologies are increasingly being presented as the key to fixing, managing and even transcending the turbulent ecologies of the Anthropocene which threaten social and economic reproduction. This emerging set of visions, experiments and uses rest on the systemic capabilities of bundled robotic and autonomous system technologies (e.g. advanced sensors machine vision, artificial intelligence, robotics) to see, know and intervene in the biophysical world in new ways. This, we argue, potentially represents a shift beyond logics of mitigation and adaptation towards engineering nature in the face of converging environmental threats. Synthesising insights from existing literature, we develop a conceptual framework for understanding the 'new ecologies of automation' and diverse, site-specific applications across what we call 'operational ecologies'. We then explore a range of diverse exemplars, creating a typology of operational ecologies before discussing key logics, themes and directions for critical research. Overall, the paper makes a significant and original contribution to knowledge in critical geography, and the under-researched intersection between political ecology and automation studies.

1. Introduction

Advances in the hardware and software of automation technologies is being felt in ever more domains of life, profoundly altering social and economic relations. In critical geography, there has been rising interest in how "algorithmic robotic technologies are increasingly becoming woven into, and thus helping to create, our complex, continuously evolving, and contingent socio-spatial realities" (Casino et al., 2020: 611). Yet while there is a burgeoning literature on the new geographies of automation, there is relatively little exploring what we call the 'new ecologies of automation' (although see Dauvergne, 2020). We address this gap by providing a synoptic view and conceptual framework for understanding the increasingly widespread use of automation and robotics across different environmental domains and claims that they could be crucial in tackling major ecological crises.

Emblematic of such claims is the *Fourth Industrial Revolution for the Earth* report (PwC, 2018), prepared for the World Economic Forum, in which the authors claim that the combined capabilities of this bundle of technologies offers "unparalleled opportunities to overcome" converging environmental challenges, with a specific focus on the uses of artificial intelligence (AI). Spanning climate, biodiversity loss, ocean degradation, water insecurity, clean air and natural disasters, the report highlights innovations in AI and other automated systems designed to forecast and protect against extreme weather events in real-time, radically reduce resource use and vastly extend the scope of environmental monitoring and control. This is augmented by the growing sophistication and dramatically falling costs of drones and other robots, which are transforming humans' ability to operate at a distance and in previously inaccessible environments.

This report sits within a wider set of debates about how technological change is opening up new ways of engaging with nature, including the use of AI and robotics, but also nanotechnology, geoengineering and large-scale carbon removal, synthetic biology, gene-editing, assisted evolution and de-extinction techniques (Buck, 2019; Nicholson and Reynolds, 2020; Preston, 2018; Thiele, 2020). In *The Synthetic Age*, Preston (2018) argues we are entering an era of "unprecedented degree of malleability of the Earth that new technologies are making possible", which will "reach deeply into the earth's metabolism … [changing] not just how the planet *looks* but also how the planet *works*" (p. xviii). As Nicholson and Reynolds (2020) put it: "Although humanity's impacts on Earth systems have thus far been largely unintentional, some emerging technologies would enable activities to alter basic planetary features

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intentionally" (p. 2). Significantly the environmental logic at the core of this emerging literature appears to be moving beyond prevailing modes of mitigation and adaptation, towards something more actively interventionist – which Thiele refers to as "engineering nature to save it" (p. 10).

Ideas and practices of using technology to intentionally shape and even 'engineer' nature are of course nothing new (e.g. Odum and Odum, 2003). Nevertheless, there is clearly increasing activity and experimentation taking place at the intersection of rapid technological change and growing stresses and pressures on Earth's capacities to sustain social and economic life. While there is a growing literature looking at the implications and governance of synthetic biology and geoengineering, research on automation and robotics is far less developed. Yet automation technologies potentially offer new ways of engaging with biophysical processes and resources, acting with greater speed, efficiency and precision at different scales, enabling new forms of environmental intervention, response and control – and spurring new socio-technical visions of how to manage the climate and other turbulent ecologies. Although the application of new and experimental technologies in nature remains highly contingent and constrained, the growing sense of environmental crisis, especially around climate breakdown is opening political space and potentially lowering thresholds of risk associated with more radical forms of intervention.

A shift towards a logic of 'engineering nature' would have profound social and ecological implications. Nicholson and Reynolds argue emerging technologies "will fundamentally change how humanity interacts with Earth systems and, by extension, how we see ourselves as human beings in relation to the nonhuman world" (2020: 2). Once established, this set of processes and relationships would not be easy to reverse. There may be opportunities to manage increasingly volatile environmental conditions, but the particular forms and sites of intervention will inevitably be selective and structurally constrained. This raises critical questions about who and what will be protected, empowered or sacrificed, and how different socio-technical infrastructures, projects, programmes and practices might be governed (Buck, 2019; Nicholson and Reynolds, 2020). Yet while the notion of 'engineering nature' is useful, we currently lack a common set of concepts and framework from a critical geographical perspective to think across different environmental domains and link together, theorise and analyse emerging socio-technical-ecological configurations being imagined and developed.

In this paper, we address this gap through the development of a geographically informed research agenda for understanding the 'new ecologies of automation'. We introduce a novel conceptualisation we term 'operational ecologies' as a way of framing this emerging landscape of projects, practices and experimentation – drawing on urban and landscape architecture theory and political ecology. Our analytical framework has three interlocking elements, each corresponding to a section of the paper. First, we highlight the eco-technical capacities of advanced automation technologies which combine increasingly sophisticated ways of seeing and knowing nature with new ways of responding to, intervening in and interacting with biophysical processes, identifying both potentials and limits. Second, we connect the new ecologies of automation across different domains through the notion of operational ecologies. Operational ecologies denote emerging and experimental sites of environmental enclosure, control, intervention and exploitation, which involve the provision and management of biophysical processes and resources vital for social and economic reproduction. Third, we argue that new uses of automation technologies move beyond prevailing modes of mitigation and adaptation and sites within a broader logic of 'engineering nature'. This distinctive logic embraces the idea of nature as malleable to intentional design and intervention, mediated by the blended capabilities of increasingly powerful automation technologies.

Importantly, our conceptualisation and framework allow us to think synoptically across different domains, contexts and cases and create a more systemic picture of the new ecologies of automation. It provides a basis for understanding what is new, while pointing to an uneven landscape of contingencies, specificities and struggles. The paper draws systematically on what is currently a highly fragmented literature on experimental, research and commercial robotic applications from within both the critical social sciences and technical and engineering disciplines. The conceptual framework and analysis of the bricolage of robotic applications makes a key contribution to work on new geographies of automation. This constitutes a novel area of research concerned with the role of automation and robotics in reconfiguring existing and new logics of 'engineering nature' and wider debates about the co-evolution of technological change and societal relations with nature. The paper opens up critical questions, from which we set out in the conclusion the key research priorities for the interrogation of the 'new ecologies of automation'.

The paper is the product of expansive desk-based research, designed to map and conceptualise the range of activity relating to experimentation and use of robotic and autonomous systems across different environmental domains. This involved scanning and reviewing fragmented academic research across different disciplines, identifying key themes and gaps, as well as collecting a significant volume of non-academic documentary material – including online articles, company blogs and websites, as well as reports and grey literature from various private sector, governmental and third sector sources. The material was generated slowly over approximately 18 months through regular online searches and content alerts using key search terms, and filtered according to their positive identification as examples where robotic action was claimed as a key capability for intervening in biophysical processes or contexts. Further conceptual development was achieved by analysing the examples in relation to: (i) the ecological problems or objectives identified; (ii) the robotic/automated capabilities mobilised in response; and (iii) the key claims relating to biophysical interventions and outcomes. Out of this analysis were derived the three key logics we attach to different 'operational ecologies'.

2. The new 'ecologies of automation'

Although definitions are often vague in this emerging field, we follow Del Casino et al (2020) who propose automation and robotics as a terrain that consists of the "hardware and software that can be found in the materialities of robot bodies, and the algorithmic logics and machine learning capacities of new emerging digital technologies" (p. 606). Recent geographical attention reflects developments in service and field robotics, which have enabled robots to move out of the controlled context of the factory, and interact with humans and more complex and unstructured environments (Royakkers and van Est, 2015; Thorpe and Durrant-Whyte, 2001; While et al., 2021). Innovation in these fields mean more sophisticated forms of robotic mobility, environmental response and physical functionality, leading to novel applications with inherently spatial implications.

The term robotics and autonomous systems (RAS) is used in engineering to reflect the related but separate domains of robotics and automation. Robots are programmable machines which interact with the physical world via sensors and actuators, with varying degrees of human control or autonomy, increasingly enhanced by machine vision and AI, while automation refers to the capability of machines more generally to carry out tasks with minimal or no intervention from humans in the process. It is the blending of these different elements to produce new functional capacities which we contend is of critical importance to the new geographies of automation, which must, as Del Casino (2020) et al argue, "take up the theoretical and political implications of the hardware/software matrix and what it means for human and more-than-human bodies and relations" (p. 607).

Crucially, the integration of robotics, which is about machines engaging and acting in the material environment, adds a distinctive dimension and pushes beyond the existing boundaries of digital geographies research. Navigation, perception, movement and manipulation are key to new robotic capabilities (Royakkers & van Est 2015, p. 8). This is not to separate and give primacy to physical robots over digital hardware and software. Automation technologies are deeply embedded in what Elliott (2017, p. 25) calls a "new protocological infrastructure" which collects, sorts, circulates and acts upon vast quantities of digital information. Robotic capacities depend on rapid and large-scale data processing, machine learning and decision-making algorithms which enable rationalisation of and response to dynamic material environments. What is central to the new geographies of automation is the building out and embodiment of digital infrastructures with "senses and hands and feet" (Royakkers & van Est 2015, p. 25) across a range of domains, and extends beyond information circuits to encompass a new set of relationships between humans, space and their environment.

Yet compared to the growing focus on the new geographies of automation, work that considers how automation technologies are reshaping societal relations with nature remains less developed. To advance this area as a distinct field of research, we introduce the notion of 'new ecologies of automation', which synthesises insights from the growing field of digital environmental geography – encompassing a range of research on 'Smart Earth' technologies, 'digital ecologies', 'data-driven' and 'algorithmic' forms of environmental governance – with an emerging but fragmented landscape of research work on environmental robotics. Research in digital environmental geography has primarily focused on how the hardware and software of advanced digital infrastructure is enabling new ways of seeing and knowing the biophysical world, and their implications for environmental governance (e.g. Bakker and Ritts, 2018; Gabrys, 2016; Machen and Nost, 2021; Turnbull et al., 2022). However, research on environmental robotics including conceptual design, real-world testing and commercial applications suggests the increasingly widespread use of automation technologies that purposefully engage with and materially alter the biophysical environment (e.g. Braverman, 2019; Nimmo, 2022; van Wynsberghe and Donhauser, 2018), in ways that digital environmental geographies literature has yet to fully explore.

In order to conceptualise the movement from extended ways of knowing to novel forms of material agency, we draw on theoretical development in landscape architecture. In their work on responsive landscapes, Cantrell and Holzman (2015) argue the capacities of emerging, bundled technology platforms enable qualitatively new ways of manipulating complex and indeterminate landscape processes. What they call 'responsive technologies' provide the infrastructural capacities to sense, process and actuate (bio)physical change within selected landscapes, and potentially alter and remake environmental conditions by design. Responsive technologies enable "the transformation of sensed and processed data into a form of physical or virtual action … where the field in which sensing is taking place is being modified or acted upon" (2015: 23). This, we argue, represents a new kind of material *agency* within biophysical systems and landscapes. We use the terms RAS and automation technologies rather than responsive technologies to explore the emerging technology platforms that blend new forms of remote or autonomous mobility, real-time and predictive data analytics and physical functionality. Our emphasis is the ecosystemic interweaving of hardware and software, material and digital, social, technological and natural worlds in what we call the new *ecologies* of automation. Furthermore, we conceptualise new ecologies of automation through novel capacities for seeing, knowing, acting in and altering nature.

2.1. *Seeing and knowing nature*

A central premise in literature on digital environmental geographies is the accelerating speed, scale and significance of environmental datafication. Contemporary datafication hinges on the falling costs and growing sophistication of the hardware and software that Bakker and Ritts (2018) call Smart Earth technologies. Analogous to the Smart City, the expansion of this networked infrastructure of diverse sensing and monitoring devices and techniques, together with growing cloud-based storage and computational capacities for processing information has dramatically increased the scope of collecting, aggregating and utilising environmental 'big data'. Growing abundance of data is in turn enhancing scientific abilities to assess spatial–temporal changes and understand innumerable biotic and abiotic processes. By rendering these highly complex biophysical processes and society's relationship with them legible in new ways, Smart Earth technologies are also providing opportunities for novel kinds of environmental governance, management and intervention by different state, capitalist and other social interests.

Automation technologies play an important role in this process (Adams, 2019; Dauvergne, 2020; Thayyil, 2018). With varying degrees of human oversight, algorithmic code, AI and machine learning platforms are employed to detect and identify particular environmental entities, features and phenomena, and digitally classify, filter, sort and aggregate sensed environmental data. Greater computational power for processing data is key to rendering the biophysical world 'programmable' (Gabrys, 2016) and malleable to new forms of virtual modelling and simulation. Growing sophistication of algorithmic techniques is advancing novel ways of analysing and forecasting complex processes of environmental change, while isolating the influence of particular social and environmental variables. As research has shown, these socio-technical systems are increasingly important in various modes of adaptive and anticipatory governance, real-time regulation, automated decision-making and 'precision' techniques of natural resource management and climate governance (Bakker and Ritts, 2018; Turnbull et al., 2022). As Machen and Nost (2021) argue with respect to climate governance, 'thinking algorithmically' is becoming hegemonic as a way of knowing socio-environmental processes, shaping policies and practices, in ways that crowd out alternative forms of knowledge and degrade democratic politics of ecology.

The gradual incorporation of robotics into the socio-technical assemblages of extended and intensified environmental datafication and knowledge production is a growing feature of this literature. The use of autonomous and remote-operated vehicles, drones and robots as mobile environmental sensors is increasingly prevalent in domains such as deep sea exploration (Lehman, 2018), farming (Carolan, 2020; Klauser, 2018), fishing (Toonen and Bush, 2020), forestry (Gabrys, 2020) and conservation (Adams, 2019). Advances in field robotics and machine vision are augmenting capacities to map, survey and monitor biophysical processes with additional spatial reach and flexibility, especially in extreme environments and places otherwise too remote or costly for sustained human presence. However, consideration of the robotic elements of Smart Earth systems is usually limited to their augmentative role in environmental datafication, integrated into existing frameworks of digital environmental geographies which focus on forms of representation over material agency. Less frequently attended to are the emerging capacities of automation technologies to materially interact with, manipulate and alter their (bio)physical environments.

2.2. *Acting in and altering nature*

There is emerging if fragmented research in this field (e.g. Braverman, 2019; Cantrell et al., 2017; Elliott, 2016; Gulsrud et al., 2018; Lockhart and Marvin, 2020; Nimmo, 2022; van Wynsberghe and Donhauser, 2018). Although this work is often focused on more experimental and speculative applications, it is broadly interested in how RAS are already being used in more direct and deliberate forms of biophysical and socio-material intervention. Actuation is the key element of Cantrell and Holzman's (2015) notion of responsive landscapes that signals a shift from extended ways of knowing to novel forms of material agency. They write about the growing and potential use of "responsive technologies and computation in ecological systems" (p. 5) and consider the possible applications and implications of autonomous systems able to “render, regulate, control, and automate environments” (p. 25). Although Cantrell and Holzman’s work is largely speculative in nature, Gulsrud et al (2018) note how automation technologies are increasingly mobilised to contribute “to the biophysical cultivation and maintenance of landscapes, from forestry and agriculture to conservation monitoring and management” (p. 86). We identify three features from this literature which help us conceptualise how automation technologies are already facilitating new ways of acting in and altering nature.

The first is about how remote operation and robotic mobility are transforming spatial relations and constituting new sites of environmental intervention. In existing landscapes of production and management, automation technologies offer the potential for intensifying the speed and scale of action, as Elliott (2016) discusses in his review of efforts to develop drones and robots to assist large-scale tropical forest regeneration through automated seeding and weeding. Furthermore, advances in field robotics mean aerial, terrestrial, subterranean and aquatic vehicles are increasingly able to navigate and function in locations where it is impractical, dangerous or costly for humans to operate, augmenting and extending capacities for interventions in places such as the deep ocean (Braverman, 2019).

The second is about functionality. In domains such as farming, mining and ecological restoration and management, robotic technologies are being developed to manipulate the biophysical environment around them. The emphasis is often on enhancing the degree of control, precision or efficiency of interventions through mechanisation and automation of tasks such as digging, picking, planting, spraying, injecting, heating, cooling, mixing, transporting and so on. There are a growing range of contexts where robotic capabilities and infrastructures are being configured to undertake specific biophysical processes within a larger ecosystem. Van Wynsberghe and Donhauser (2018) use the term ‘ecobots’ to describe robots designed to play specific ecological roles such as that of proxy predator. Nimmo (2022) examines ongoing investment, research and development of ‘robotic pollination’ as ecological substitute which seeks to replace the agro-economic functions of pollination ecologies decimated by industrial agriculture. Braverman (2019) meanwhile shows how robotic technologies are enabling new forms of invasive species control and coral reef repair, and are central to an emerging biopolitics of ‘making die’ and ‘making live’ in deep sea ecologies.

The third feature pertains to the bundling of these multiple capacities in ways that extend autonomous robotic engagement with the biophysical world. Cantrell et al (2017) develop the concept of an autonomous ‘wildness creator’ based on a “deep learning computing system that controls a physical infrastructure that can sense and manipulate the environment and interact with organisms” (p. 163). Although such a holistic system may be hypothetical, they observe that semi-autonomous technologies are already being widely embraced in conservation and restoration efforts. With technological developments in this area advancing, Cantrell et al (2017) ask what the prospect of the ‘machine as gardener’ – or more algorithmic ways of acting – might mean for social relations with nature and the role of the human in new socio-technological-ecological configurations.

In summary, conceptualising the new ecologies of automation helps us understand emerging algorithmic techniques which enable new ways of seeing, knowing, acting in and altering nature. Nevertheless, the growing variety of processes, projects and issues highlighted have not yet been explored in any systematic manner. Such work is vital, and we propose three questions for taking this agenda forward. First, there is the importance of understanding *where* and *why* automation technologies are being operationalised into new systems of action and engagement with nature. What social interests are involved and what are the particular ecological problems, contexts and logics of intervention in each case? Second, there is a need to unpack the scope and scale of new robotic capabilities. This means identifying what biophysical functions these systems are able to undertake, their transformative power and the different technical, economic and ecological limits to their application in the present and future. Third, research needs to explore the social and ecological implications of these novel socio-technological-ecological configurations. What sorts of ecologies are being produced and whose interests do they serve? Who and what will be protected, empowered or sacrificed, and how might these emerging socio-technical infrastructures, projects, programmes and practices be governed? In the following section, we address these questions to a range of real-world examples.

3. Operational Ecologies

In this section, we introduce the concept of operational ecologies to help frame and understand variation, logics and impacts of new ecologies of automation. Combining urban and landscape architecture theory and political ecology, *operational ecologies* provides a way of thinking about the ‘new ecologies of automation’ which brings together its geographical, socio-technical and ecological dimensions. *Operational ecologies* denote emerging and experimental sites of environmental enclosure, control, intervention and exploitation, enabled by the capacities of automation technologies, designed to fix, manage or transcend contemporary environmental turbulence. *Operational ecologies* draws first on Brenner and Schmid’s notion of operational landscapes in urban theory: the historical and geographical transformation and operationalisation of erstwhile countryside “in support of, or as a consequence of, the everyday operations and … most basic socio-metabolic imperatives … including the massive, highly regularized inputs (of labor, materials, food, water, energy, commodities, information and so forth)” associated with urban growth (Brenner and Schmid, 2015: 167).

More recently, Brenner and Katsikis (2020) have made explicit links between operational landscapes and Moore’s (2015) notion of capitalism’s reliance on ‘cheap nature’ through commodity frontiers – that is, urban hinterland zones as sites operationalised as ‘taps and sinks’ for the continued and extended provision of material inputs and ecological processes needed for planetary urbanisation. In this newer work, they describe operational landscapes as zones “transformed into configurations of large-scale territorial ecological machinery: mechanised assemblages of human and nonhuman infrastructure oriented towards capital accumulation within a planet-encompassing profit-matrix” (Brenner and Katsikis, 2020: 28). It is this more recent work that we find particularly useful, which we combine with Nimmo’s (2021) insights into the attempted use of robotics as capital intensive replacement for the ecological functions of cheap nature. Our term, *operational ecologies*, emphasises technologically mediated interventions in site-specific ecological and biophysical processes and resources needed to maintain social and economic reproduction, while decentring the distinctly (non) urban spatiality of operational landscapes.

In this section we explore exemplars of the new ecologies of automation, grouped as operational ecologies configured for: (i) opening new frontier ecologies; (ii) control and intensification of existing ecologies; and (iii) replicating ecological functions (Table 1). This approach helps us think more precisely about the site-specific design and integration of automation technologies in emerging operational ecologies and what they might mean for societal responses to environmental turbulence and the reshaping of nature-society relations. Central to the examples explored is our emphasis on ‘going beyond the digital’ to explore how ecological relations are being reworked through the combination of the machinic/robotic and algorithmic dimensions of automation technologies. Our focus is on why automation technologies are being applied, identifying the biophysical processes interventions being undertaken by robots and unpacking the claims surrounding these interventions and experiments.

3.1. *Opening new frontier ecologies*

Technological revolutions have always played a key role in frontier-

Table 1
Operational Ecologies: Frontiers, Intensifications, Replications.

Configuration	New frontier ecologies	Managing existing ecologies	Replicating ecological functions
Underlying Logic	Productive exploitation of remote, inaccessible, dangerous or 'underused' ecologies.	Intensified 'sweating' of stressed ecologies and management of problematic ecologies.	Managing threatened ecologies through selective replication or replacement of key ecological functions.
New / Enhanced Capacities	Extended and automated capabilities to operate remotely and semi-autonomously in new and remote spatial and ecological contexts.	Growing speed, range and efficiency of robotic mobilities combined with 'precision' forms of manipulation, control and productive intervention.	Sophisticated forms of robotic biomimicry and fine-grain interventions in animal and plant lifecycles and systems.
Exemplars	Mining in extreme ocean and off-world environments, offshore kelp farming, controlled environment agriculture.	Forestry, conventional agriculture, waste management, weather modification, epidemiology.	Invasive species management, conservation, crop pollination.

making projects, rendering new geographies legible and controllable, as well as operationalising new circuits of natural resource appropriation and commodification (Moore 2015). Automation technologies are central in efforts to constitute new productive environments, including in settings previously too difficult, remote or inhospitable for *in situ* human labour. Within the New Space Race for instance, ongoing advances and potential capabilities of space robotics sit at the heart of a range of visions, investment programmes and missions designed to explore, operationalise and ultimately exploit extra-terrestrial resources (Lockhart et al., 2021). Closer to home, constraints on conventional mining, growing demand and struggles for control of 'strategic' metals and minerals have all contributed to renewed interest in commercial seabed mining in recent years (Childs, 2018). Although commercially unproven, this has driven considerable experimentation and investment in underwater mining robots, such as those developed by (the now defunct) Nautilus Minerals, designed to and advance a viable extractive infrastructure in the extreme environment of the ocean floor (see e.g. Bogue, 2015).

In the realm of marine cultivation, advances in robotics are creating new opportunities to operationalise offshore environments for commercial kelp farming as a seaweed-based biofuel (Buck 2019). Commercially viable production would require vast amounts of land and is considered unsuitable for coastal areas where kelp naturally grows. Floating offshore farms have been proposed as one possible solution. In the US, Marine BioEnergy Inc – supported by the government-funded MARINER programme – has been experimenting with "low-cost underwater drones to tow farms of kelp in the open ocean, diving to depths to absorb nutrients [at night] and surfacing to absorb sunlight" (Marine BioEnergy, n.d.). This mobility sits beneath plans for the farms to be moved into deeper waters to avoid storms and passing ships, and transported to scheduled rendezvous points for regular harvesting. The Marine BioEnergy project relies on the growing affordability of underwater drones, which, while bespoke in design, can be assembled with off-the-shelf materials and systems. Connected to shipping and weather forecasting systems, the vision is of a robotically enabled, resilient farming infrastructure that can respond to a complex ocean environment, with automated and remote operability minimising labour costs and the need for dangerous work. The diverse kinetic capacities of these aquatic robots – including their vertical mobilities – would operationalise remote offshore seascapes as sites of 'low-impact' biofuel production.

In the controlled environment agriculture (CEA) sector, automation technologies have become increasingly important in the configuration of large-scale, indoor environments as frontiers of intensive commercial food production (Cambridge Consultants, 2019). For more than a decade, CEA has been positioned as a key opportunity for achieving food security, by operationalising new, protected spaces for agricultural production in an era of climatic turbulence and land degradation (Benke and Tomkins, 2017). Prior to the global pandemic, the sector was fuelled by a boom in venture capital funding and experimentation. By some estimates, the global market is already worth $15.7bn, and forecast to grow to $31.1bn by 2027 (EIT Food North-West and Innovate UK, 2022). Leading CEA firm Aerofarms claims to monitor "millions of data points" throughout their facilities through connected environmental sensors and machine vision (Aerofarms, n.d.). Predictive analytics and algorithms integrated into each step of the plant growth cycle, used to adjust growing conditions through automated HVAC, precision water, nutrients and oxygen delivery systems, and customisable LEDs which vary the spectrum, intensity and frequency of lighting for photosynthesis. The company's modular technology platform combines ways of understanding, controlling and optimising an indoor growing ecology which it claims facilitates dramatically higher levels of resource efficiency and productivity compared to conventional farming. In some senses, CEA is envisioned as breaking free of the natural limits of land productivity, applicable in spatial contexts otherwise impossible to cultivate. Yet despite significant hype and numerous operational sites across the world, rising costs – especially associated with the sector's very high energy inputs – is likely to limit CEA's commercial viability beyond a few niche cases (Reynolds, 2022).

3.2. *Control and intensification of existing ecologies*

If automation technologies are helping establish new frontiers, they are also being mobilised to intensify control or 'sweating' of degraded environmental conditions and ecologies. This includes a range of experimental robotic systems for managing extreme weather (BBC, 2021; Sky News, 2022), controlling spread of infectious diseases (Peckham and Sinha, 2019; Tirado and Cano, 2020), and clearing waste from river and ocean environments (McNabb, 2022; Quaglia, 2022). Robotics are already finding commercial applications in productive sectors such as farming, forestry and mining, where a mixture of resource exhaustion, environmental stressors and diminishing labour supply threaten long-term profitability (Carolan, 2020; Ellem, 2016; Mohan et al., 2021; Rogers et al., 2019; Stock and Gardezi, 2021).

In the forestry sector, resources are under growing pressure from climate change and increased risk of forest fires, as well as long-term deforestation. In response, forest management and reforestation for carbon sequestration and other 'ecosystem service' provision have risen up the agenda. In this context, robotic systems are being developed to carry out a range of tasks, from automating surveys to detecting and managing forest fires to carrying out mass tree planting (Gabrys, 2020; Robinson et al., 2022). Gabrys explores how combinations of robots, sensors, AI and data analytics being used in 'smart' forests, which not only assist with forest management, but help transform forests "into entities that are meant to operate as technologies" (2020: 7). The Estonian autonomous tank manufacturer Milrem Robotics (n.d.) meanwhile has developed a system of robotic foresters, which it claims can plant a hectare of trees in less than six hours. The vehicles can traverse difficult terrain, with modular systems able to build 3D images of planting areas, prepare the ground, plant, log the location and even prune new trees. The use of drones to aid reforestation programmes is also proliferating. Start-ups around the world such as Flash Forest in Canada and Seedcopter in India offer a range of drone reforestation services, promising rapid and precision aerial seeding capabilities over large spatial scales, despite limited evidence of its effectiveness (Castro et al., 2023).

Weather modification is another domain where automation technologies are being increasingly tested. Cloud seeding as a technique for inducing localised rainfall has a long history, but is attracting growing interest as a way of managing more frequent and extreme periods of hot weather and water shortages, especially in semi-arid regions such as the Middle East (BBC, 2021; Knowles and Skidmore, 2019). This has spurred new investment and experimentation in the design and testing of automation technologies which integrate new forms of real-time monitoring and prediction with the use of drones (DeFelice and Axisa, 2017). In late January 2016, for instance, an industry-research partnership in Nevada successfully tested the "first-ever autonomous cloud seeding aircraft platform" using a multi-rotor drone. This was designed to respond to a particular problem with existing techniques: the need to undertake "precise targeting of suitable clouds" (DeFelice and Axisa, 2017: 173). The platform provides the capacity for autonomous, real-time monitoring of meteorological conditions most conducive to cloud seeding to improve the efficiency of weather modification activities. It also affords novel payload capabilities to inject the cloud-seeding medium directly into the targeted clouds. Compared with conventional aircraft, the proposition is that autonomous drone systems could significantly reduce operational costs while extending the potential for expanding rainfall enhancement in "water stressed regions with limited infrastructure" (DeFelice and Axisa, 2017: 174). In this case, the claim is that automation technologies are being used to know and intervene in precipitation processes with increased precision. Whether these advances are realised or not, cloud seeding remains controversial, both in its efficacy and possible environmental impacts, but also as a form of atmospheric resource grabbing and operationalisation to protect particular regions and populations (Rubin and Denton, 2022).

Applications in epidemiology reflect a similar extension of existing modes of control. These include operational ecologies which incorporate and augment disease-carrying species in automated technology systems, configured in various ways for knowing and intervening in disease ecologies. The Microsoft Premonition Project has developed and tested a system of drone-deployed smart traps, genome sequencing and artificial intelligence to capture mosquitos and "detect the presence and movement of vector-borne diseases and predict outbreaks before they spill over into human populations" (Peckham and Sinha, 2019: 1207). As part of a system that Tirado and Cano describe as "automat[ing] field biology" (2020: 126), living mosquitos are operationalised as part of a socio-technological-ecological configuration which extends the scope of disease monitoring, forecasting and governance. Automation technologies are also being mobilised in various kinds of direct intervention, often operationalising volumetric space. 'Precision spraying' of mosquitos with drones has become common in recent years, as a way of lowering costs and increasing efficiencies of disease management (Amenyo et al., 2014; Mechan et al., 2023). The Moscamed Programme meanwhile, active in the Brazilian city of Juazeiro city since 2005, has developed a "fully automated adult mosquito release system" operated from a drone to enable the homogenous dispersal of a sterile male mosquitos (Bouyer at all 2020p. 1). The sterile males compete with wild males to induce sterility in the native female population. Although this technique has been possible for decades, releasing mosquitos from the ground is logistically challenging, and using vehicles or conventional aircraft has proved too expensive. By improving areal coverage while reducing the number of required release sites and field staff, it was claimed that operational costs could be cut from $20 per hectare for ground release to just $1 per hectare using drones (Bouyer et al., 2020). In these examples, mosquitos, drones, data analytics and algorithmic management have been operationalised in novel combination for intensifying control over disease ecologies and risk.

3.3. *Replicating ecological functions*

A final area of experimentation is in the replacement and augmentation of ecological functions with drones, robotic animals, insects and other forms of biomimicry. In this emerging field there are numerous examples of automation technologies or 'ecobots' (van Wynsberghe and Donhauser, 2018) being envisioned and configured in ways to maintain, restore or produce particular biophysical dynamics against a backdrop of ecological breakdown. From drones to autonomous underwater vehicles to robotic sloths, bees and fish, automation technologies are being developed and used for monitoring environmental change and behaviour, invasive species control and to mitigate species decline (Egerstedt, 2021; Marris, 2019; Morley et al., 2017; Nimmo, 2022; Polverino et al., 2022; Shields et al., 2019; Wang et al., 2021). Although intentional human interventions in ecosystems are nothing new in fields such as conservation biology, through selective culling and various kinds of (sometimes fine-grain) ecological engineering, roboticisation potentially opens up distinctive forms of techno-ecological hybridisation.

A key application of ecobots is as artificial predators to control 'problematic' species. Drones are being widely used to detect and cull rats, possums, stoats and ravens in hard-to-reach places through the 'precision' laying of poison or oiling of eggs. Robotic augmentation often follows familiar patterns of extension, intensification and the emergence of semi-autonomous capabilities. In the case of Crown-of-Thorns starfish, which threaten the coral of the Great Barrier Reef, population control has routinely been carried out by human divers. In recent years, conservationists have tested the underwater COTSbot and OceanOne humanoid robot which use machine vision, image processing algorithms and robotic arms to monitor and respond to ocean conditions while identifying and poisoning the invasive species on the seafloor. Part of the rationale for robotic ecological management is the replacement of what is a dangerous, time-consuming and expensive labour process with machines. While unable to address wider structural causes of ecosystem decline, conservationists hope that these systems may be able to operate more efficiently and productively than human divers over the longer term, slowing the process of degradation (Braverman, 2019).

In agriculture, projects have been underway for many years to develop new forms of artificial pollination in response to the threat of the continued catastrophic decline of bee colonies and other wild insect pollinators. Nimmo (2022) details programmes experimenting with small drones and ground-based BrambleBee robots designed to remotely or autonomously pollinate certain crops, as well as insect-inspired micro-robots such as the Delft University of Technology's DelFly and Harvard Microrobotics Lab's RoboBee. For Nimmo, the direction of research shows a clear aspiration "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" (2022: 431). As Nimmo shows, research and investment into robotic pollinators exemplify efforts to engineer hybrid ecologies around a particular set of utilitarian goals and profit-driven technological imaginaries. This is not only about operationalising new technology-based pollination ecologies, but sustaining the structure and relations of intensive agribusiness which is largely responsible for dramatic biodiversity loss. As such, it sits within the broader field of precision agriculture, a domain where digital and robotic technologies and the data produced are entrenching corporate control and rentiership in the industrial food system, and have become sites of growing resistance (e.g. ETC Group, 2022; Klauser, 2018; Stock and Gardezi, 2021).

The examples highlighted above demonstrate how new ways of seeing and knowing ecologies are being combined with robotic forms of action and intervention in the biophysical world. Automation and robotics are being used to extend logics of digitisation and mechanisation into new domains of environment-making activity, while reworking the configurations, spatio-temporal rhythms and boundaries between human, technological and ecological systems. As we have shown, the logic is often about engineering and operationalising new ecologies of automating as strategies for managed decline, selective adaptation or reconfigured forms of extraction in contexts of environmental turbulence. Although much of this activity remains niche or even speculative in nature, increasingly widespread experimentation and investment across multiple domains has potentially very serious implications for people and nature, and calls for a deeper and more systematic empirical research.

4. RAS and the re-engineering of nature?

The previous section shows the active and diverse landscape of operational ecologies where automation technologies are being developed, trialled and used. Drawing on our conceptual development in the first half of the paper, we suggest three sets of issues and questions to highlight what is at stake in the new ecologies of automation which should be of particular interest to critical geographers.

The first considers the socio-natural logics at play across different operational ecologies. To what extent are emerging uses of automation technologies part of a shift towards – in Nicholson and Reynolds' (2020) language – 'intentional' altering of basic biophysical conditions and processes? In one sense, new ecologies of automation reflect long-running trends of mechanisation and rising capital intensity in the web of life, driven by the engine of accumulation (Moore, 2015). Yet the eco-technics of automation technologies potentially afford new forms of environmental intervention. A key question is whether operational ecologies constitute something qualitatively new in the mediation of socio-natural relations. In many cases, the key logic appears primarily productivist and adaptive. These operational ecologies revolve around resource efficiency and precision techniques for 'sweating' the productive forces of nature and the roboticised intensification of various kinds of ecological intervention or restoration. In others, operational ecologies take on infrastructural characteristics (Barua, 2021; Lockhart and Marvin, 2020), with automation technologies configured for (re)active control or 'direct action' (Tirado and Cano, 2020) to manage or protect against turbulent ecologies such as extreme weather. Some are distinctive as frontier-making projects which push against a logic of limits, by opening and remaking previously inaccessible or unprofitable environments as sites of resource extraction or ecological action. In others, 'engineering nature to save it' seems particularly fitting. Automation technologies are being configured to replace or augment specific functions within an ecosystem to conserve its wider value in the face of long-term degradation and rising environmental threats (Braverman, 2019).

A second important set of issues concerns patterns of variation and how new ecologies of automation are being constituted in different geographical contexts. The rolling out of operational ecologies is not unproblematic, nor based on a unified or coherent set of priorities. Different interests are seeking to construct particular socio-technical visions of the future, reflecting investment priorities, economic conditions, pre-existing laws, regulations, expertise and practices, which will shape processes of experimentation, technological development and selective application (Braverman, 2019; Nimmo, 2022). As noted, much of the activity reviewed is experimental and speculative, and the new ecologies of automation are awash with hype and unrealisable claims. It is important to guard against an uncritical reproduction of techo-solutionist claims (Morozov, 2014) or what has been described as 'criti-hype' (Vinsel, 2021). The end of ultra-low interest rates which sustained patterns of investment after the Great Recession will prove one corrective to the many outlandish visions involving automated technologies which proliferated in this period. Yet this is likely to see a reconfiguration of the interests shaping technological investment and experimentation, rather than its end. Operational ecologies are already sites of significant struggle, especially where socio-technical visions translate to more material claims over environments and resources and new rent-seeking regimes. The emerging landscape of operational ecologies suggests the importance of particular domains, such as agriculture, forestry and conservation, ocean management and exploitation, environmental control, mining, waste and disease management. Beyond political economic questions, the materialities of different ecological contexts will shape the variegated configuration of operational ecologies and the bundling of eco-technical capacities and robotics in particular environments. Mapping and understanding what, by whom and how socio-spatial and ecological selectivity are being driven by will be a key area of future research.

Third, the new ecologies of automation raise profound questions about the nature, scale and implications of novel interventions in the nonhuman world. As Gabrys (2020: 2) points out, environments have increasingly become 'technologized' sites of data production, processing and analysis, and asks in what ways they are "generat[ing] different practices and ontologies for addressing environmental change". Turnbull and Searle similarly highlight how "digital entanglement produces forms of biopower that enrol individual nonhumans and ecologies into environmental governance in novel ways" and ask "how best to govern these emerging technologies which inaugurate a host of underexplored ethical challenges concerning human and nonhuman life" (2022: 18). Reframed beyond the digital, what 'new' natures and cyborg ecologies are being envisioned and experimented with through the capacities of automation technologies? How will they be governed and regulated? Who and what (human and nonhuman) will be protected and sacrificed – and to whose benefit and cost? To what extent do they risk obscuring structural causes of converging crises, while ceding greater power and control of collective ecological futures to corporate technology interests? A decade ago Grémillet et al observed a decade ago that "it is both striking and worrying that robotic developments [in ecology] are moving far ahead of law and ethics" (2012: 55). While again cautioning against uncritical propagation techno-solutionist claims, robotic augmentation and replacement have the potential to alter the balance of ecosystems in intended and unintended ways, as has been the case with the impacts of the globalised spread of non-indigenous plants, animals and diseases. While the introduction of genetically modified organisms and crops has been debated politically and in public, there has so far been limited discussion about the hybrid ecologies that are fast emerging and often sanctioned by a sense of urgency and crisis – ahead of democratic controls, regulatory capacity and expertise.

5. Conclusion

Climate/ecological breakdown and automation have become defining challenges of the present era, yet there remains little research on how they intersect and with what implications. There is a growing critical literature on digital environmental geographies which covers aspects of automation, but we have emphasised the importance of the bundling of novel forms of robotic capability as an area that has received less critical attention. We have highlighted the multiplicity of contexts in which automation technologies are being mobilised to intervene in various biophysical and socio-metabolic processes, often presented as technological solutions and with claims of intentionally managing and remaking ecological conditions.

Research has begun to explore these issues but remains largely fragmented across different academic disciplines, domains and ecologies of application. This paper makes a distinctive contribution by taking stock of this fast-developing field and provides a framework for understanding emerging ecologies of automation and their implications for ecology and society. Our approach focuses on the drivers of automation and experimentation in specific contexts, the enhanced functional capacities and affordances of automation technologies in operationalising particular ecologies, and the claims surrounding them. We have furthermore drawn attention to various distinctive logics of operational ecologies, including new ecological frontier-making, intensifying control and productive management of existing ecologies and maintaining or conserving threatened ecologies. While the new ecologies of automation are already sites of contestation and struggle, dominant themes already point towards extending the power of humans and capital to appropriate and exploit nature, while displacing socio-ecological problems to other geographies and into the future.

The paper has identified and brought together the work of currently highly dispersed researchers and developers who are focused on experimenting and learning from robotics and autonomous systems that aim to intervene in biophysical processes. We have suggested three sets of issues which future research might critically engage. First, to attend to the variety of socio-natural logics at play across different operational ecologies. Second, to explore patterns and understand how and why new ecologies of automation are being developed in particular domains and geographical contexts. And third to comparatively explore the longer-term implications of these emerging configurations and how these may fundamentally reshape the relations between humans, nature and technology.

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The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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