Algorithmically-controlled ecosystems and biodiversity

Matthias C. Rillig [1,2,3*], David W. Armitage [4], Jun Tani [5], and Hideyuki Doi [6]

[1] Freie Universität Berlin, Institute of Biology, 14195 Berlin, Germany
[2] Berlin-Brandenburg Institute of Advanced Biodiversity Research, 14195 Berlin, Germany
[3] Okinawa Institute of Science and Technology Graduate University, Theoretical Sciences Visiting Program (TSVP), Onna, 904-0495, Japan
[4] Okinawa Institute of Science and Technology Graduate University, Integrative Community Ecology Unit, Onna, 904-0495, Japan
[5] Okinawa Institute of Science and Technology Graduate University, Cognitive Neurorobotics Research Unit, Onna, 904-0495, Japan
[6] Graduate School of Informatics, Kyoto University, Yoshida-honmachi, Kyoto, 606-8501, Japan

*Author for correspondence
Matthias C. Rillig, Freie Universität Berlin, Berlin, Germany.
Email matthias.rillig@fu-berlin.de

Abstract
Algorithmically-controlled ecosystems are ecosystems in which at least one key process rate or property (e.g. biodiversity) is under control by algorithms, or if ecosystems contain robots/ machines. Algorithmic influence on ecosystems will be matter of degree, and we highlight the risks and opportunities of such algorithm-influenced ecosystems, as well as the need to have discussions about algorithmic control of ecosystems and their biodiversity now.

Keywords: digital technology; artificial intelligence; robotics; ecosystems; environment

Introduction

As integration of humans with machines unfolds, modern society can already be viewed as a complex human-machine social system[1]. Rapid advances in multiple fields, including computer science, virtual reality, robotics and artificial intelligence, make further steps along this path likely. This integration of computers with living beings will likely not stop at humans, but also affect ecosystems, in part because humans are a part of ecosystems. We are thus likely moving towards machine/ algorithm-influenced or -controlled systems. We here discuss important open questions and research needs that come with the rise of algorithmically-controlled ecosystems.

We define algorithmically-controlled ecosystems as ecosystems in which at least one key process rate (e.g. primary production, soil respiration) or property (e.g. biodiversity) is under control by machines, computational artefacts including physical devices or algorithms[1], or if ecosystems actually contain robots or organisms (including humans) with built-in machine interfaces. This definition thus has two aspects, machine-based process control or physical machine content, and either one is sufficient for being included in this category. We understand such systems to be a continuity of increasing machine influence (Fig. 1).

Most natural or semi-natural ecosystems are unlikely to become machine-controlled to any noteworthy degree in the foreseeable future. However, there are several types of ecosystems that could make this transition soon. Agricultural systems or urban ecosystems, as already strongly under human control and in some cases with the presence of robots, are the most likely candidates to qualify as machine-controlled ecosystems in the future, and some already are today. The field of agricultural robotics has been rapidly advancing [2], and represents a signature of an increasingly strong interface between ecosystems and machines. Other examples of ecological systems likely to advance in this direction could be engineered, synthetic microbial communities (SynComs) [3] and the resulting artificial ecosystems, assembled for specific purposes (e.g., biotechnological production). Potential candidates could also be strongly degraded or polluted ecosystems that are being restored, enlisting the help of algorithms to choose organisms for restoration, robotic sensor systems to monitor environmental data [4], or environmental swarm robots [5] to drive the restoration or renaturation process.

Currently, ecosystems are often delineated as ‘natural’ or semi-natural on the one hand, and as ecosystems under strong human influence on the other hand. Other terms that capture strongly human-altered ecosystems are anthromes or novel ecosystems. Machine-controlled ecosystems would occupy another position in this category space (Fig. 1).

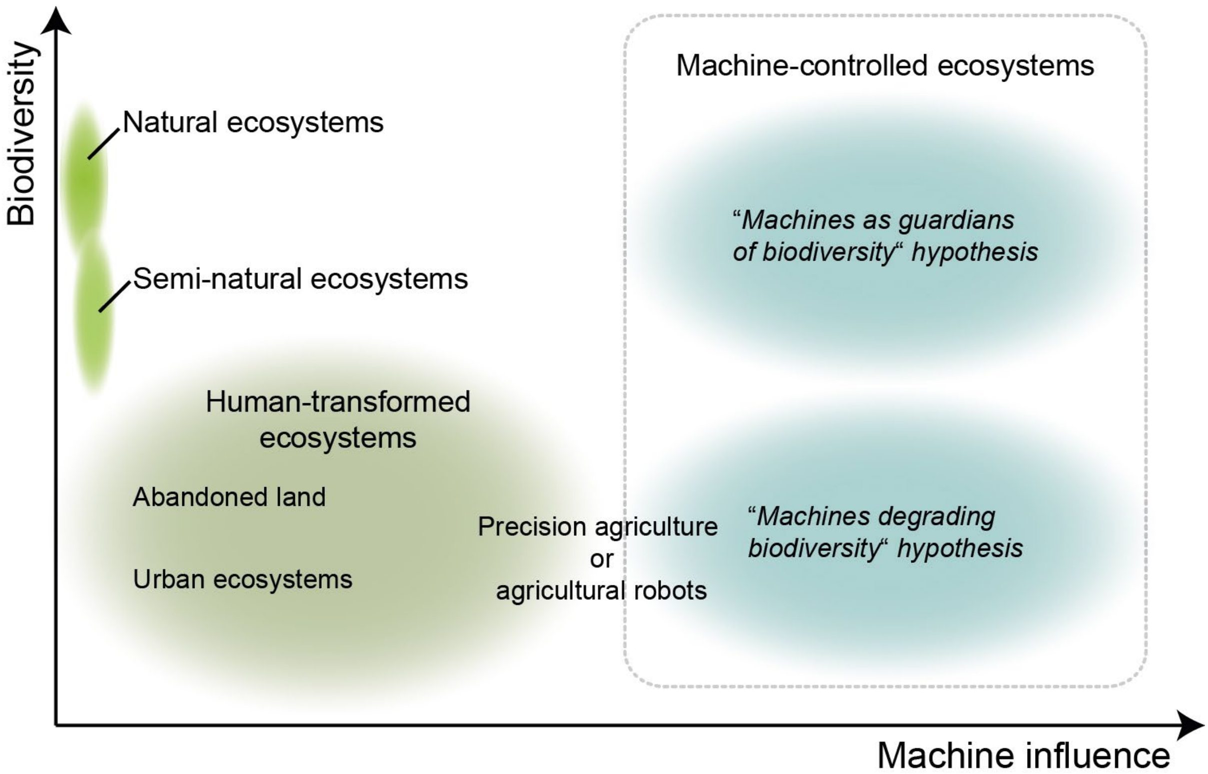

Fig. 1 Machine-controlled ecosystems arrayed along a gradient in machine influence and possible consequences for biodiversity. Other ecosystem types (natural, semi-natural, human-transformed) for comparison. Machines can be algorithms or physical presences (such as robots or organisms with machine interfaces) or both, where an increased physical presence of machines could have more pronounced effects. Depending on how increasingly machine/algorithmically-influenced ecosystems develop, consequences for biodiversity could be positive, neutral or negative.

Opportunities and risks of algorithmically-controlled ecosystems

Machine/ algorithmically-controlled ecosystems will bring several opportunities and risks. Extreme degrees of algorithm-based control might translate to more predictable system performance. For food systems this would include more reliable harvests, potentially leading to increased food security; for other systems it might mean more predictable delivery of goods such as biofuel. Real-time environmental data of unprecedented detail coupled with AI agents could provide early-warning systems for pollution or disease outbreaks, and foster improved understanding of ecosystem functioning and biodiversity. Given sufficient levels of understanding, management interventions might allow for better balance of ecosystem multifunctionality, including preserving soil health or water quality, and maintaining yield. Biodiversity might profit from precision conservation taken to a new level, using robots (e.g. for weeding) and sensor networks. In addition, restoration efforts could also become more successful, driven by robots removing invasive species or planting desirable local species, and constructing or improving habitats. In an urban context, technical urban ecosystems could be beneficial in terms of energy savings, climate change mitigation, waste processing, traffic control, and the maintenance of urban blue-green infrastructure, thus overall benefiting biodiversity [6].

There are also several challenges and risks. Extreme levels of algorithmic influence could present challenges for conservation, potentially leading to species extinctions or decreases in process rates resulting from unintended consequences of algorithmic control or unforeseen machine-nature interactions. Perhaps there will be problems with rogue technological entities, for example autonomous robots or other machines that would also influence adjacent ecosystems, causing spillover effects from highly algorithmically controlled systems. Increasingly algorithm-influenced ecosystems could also lead to a degraded human-nature experience[7], as also other digital technology innovations[8]. Electronic waste, for example stemming from mass-produced robots, could lead to widespread pollution unless ecosystem-embedded technology can be effectively retrieved or more sustainably constructed. Furthermore, cyberattacks and systems failures or malfunctions could imperil ecosystems at a scale that is presently unknown. Finally, increasing reliance on technology could also lead to a loss of traditional ecological knowledge.

Open questions

There are several open research questions about algorithmically-controlled ecosystems. We do not know if there are critical thresholds in the degree of machine integration at which ecosystems start to exhibit a sudden change in properties or behavior of ecosystems (machine-control ecosystem tipping points). Partly because of such tipping points, we may need to avoid the creation of ecosystems with a very high degree of machine influence on first principles, if possible. Biospherics (matter-closed, energy-open ecosystems) could be useful to explore unintended effects of machines in ecosystems[9]. It is interesting to ponder if future algorithmically-controlled ecosystems will permit ecological experiments that would be impossible today, for example by modifying environments (such as increasing or decreasing biodiversity) at a scale that would be impossible today. There will likely be evolutionary responses to increased machine control, and these are unexplored at this time, and difficult to predict. Machine-controlled ecosystems could influence neighboring ecosystems through meta-community dynamics, such as species dispersal, gene flow, or trophic interactions. Highly automated systems might disrupt regional biodiversity by altering connectivity or creating ecological sinks that affect meta-populations. Computational capabilities of ecological dynamics and networks[10] might be used to control machines, leading to complex feedbacks between machines and ecosystems. Perhaps we can increasingly design robots that are sustainable, not creating any waste but that are instead biodegradable [11], averting some of the waste-related issues.

As machine dominance becomes more pronounced, a key question will be consequences for biodiversity (Fig. 1): perhaps this technology integration will enable conserving and restoring ecosystems, enabling a much-needed ‘bending the curve’ on biodiversity loss (machines as guardians of biodiversity hypothesis). Or perhaps the opposite will occur, as an increasing machine intervention, coupled with malfunctioning algorithms, rogue robots, pollution from electronic parts, increased power needs, and proprietary algorithms not trained to foster biodiversity preservation but for other purposes will lead to precipitous species declines. We must do everything possible to avoid the latter. In addition, how should we account for robotic entities or biota with machine interfaces: will these become new components of ‘bio’-diversity, worth protecting in their own right, especially if they become important for ecosystem processes? Examples could be humanoid robots, which could be on the verge of being mass produced by big tech companies in the near future, integrated with large language models.

Conclusions and the way forward

It is a good idea to start having discussions about the development, deployment and governance of algorithmic control of ecosystems and their biodiversity now in order to build in fail-safe technological measures and to start drafting environmental policy regulating such ecological systems, especially as technology development generally outpaces scientific assessment of impacts[12]. Monitoring developments and generating research programs requires the collaboration of teams across a range of fields including ecology, global change biology, robotics and engineering, AI, sociology, human behavior, environmental policy/ law, and cybersecurity. Moving forward, funding agencies will need to accommodate this level of complexity.

<u>Author contributions</u>

MCR wrote the first draft of the paper; DWA, JT and HD added additional ideas.

<u>Competing interests</u>

The author declares that no competing interests exist.

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