Trends in Ecology & Evolution

CellPress

Opinion

Designing Autonomy: Opportunities for New Wildness in the Anthropocene

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Maintaining wild places increasingly involves intensive human interventions. Several recent projects use semi-automated mediating technologies to enact conservation and restoration actions, including re-seeding and invasive species eradication. Could a deep-learning system sustain the autonomy of nonhuman ecological processes at designated sites without direct human interventions? We explore here the prospects for automated curation of wild places, as well as the technical and ethical questions that such co-creation poses for ecologists, conservationists, and designers. Our goal is to foster innovative approaches to creating and maintaining the autonomy of evolving ecological systems.

Trends

The Anthropocene invokes a seeming paradox: reducing human influences on species and ecosystems generally requires increasing levels of human management.

Semi-automated technologies are increasingly used to manage ecological processes.

This paper explores the promises and perils of developing fully automated systems dedicated to the curation of wild places.

Restoration of wild places in the Anthropocene depends on valuing multiple forms of wildness, including novel anthropogenic forms that have yet to be imagined.

Nonhuman Autonomy in the Anthropocene

Human societies have reshaped ecological patterns and processes across the Earth, both directly through land use and by facilitating the movement of species [1–3], as well as indirectly through pollution and climate change [4,5]. Even in protected wilderness areas, it has become a challenge to sustain ecological patterns and processes without increasingly frequent and intensive management interventions, including control of invading species, management of endangered populations, and pollution remediation. Further, such interventions themselves may further alter ecological patterns and processes [6–9] (www.fs.fed.us/nrs/pubs/rmap/rmap_nrs8.pdf).

Responding to these trends, ecologists and conservation biologists have begun to study novel ecosystems – the 'new wild' [10–14]. Recent strategies for restoration and rewilding have focused less on the maintenance of historical ecological conditions and more on promoting the autonomy of ecological processes and non-human species [15,16]. In this context, 'wild' is a state of existing in relative freedom from human interventions.

We explore here the potential for fully automated systems to create and sustain new forms of wild places without ongoing direct human intervention. Recent breakthroughs in artificial intelligence have produced systems capable of solving complex problems through algorithms in which the rules of behavior are not derived through programming but through evolutionary processes of machine learning [17,18]. For example, AlphaGo used a deep learning approach, learning from games played with itself, to defeat the world's top-ranked human player in Go, a game long believed to be so complex as to be intractable to computing [18]. At many points, AlphaGo deployed innovative strategies. Thus the prospect of intelligent systems capable of acting autonomously in real time to sustain the autonomy of nonhuman species and ecological processes without direct human intervention appears increasingly possible. Indeed, machine-learning methods are increasingly used to develop species distribution models that inform conservation decisions [19–21]. Conservation biologists and managers are also employing deep-learning systems and other technologies to eliminate, counter, or mitigate anthropogenic influences on species and ecological processes (Box 1).

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To explore the potential of automated systems for sustaining wild places, we begin by reviewing the concepts of wildness and autonomy. We then introduce a framework for describing different levels of automation (following Parasuraman *et al.* [22]) and link these to levels of environmental management. The highest levels of automated environmental management are then explored through the speculative design of an automated infrastructure, a 'wildness creator', that creates and maintains wild places independently of humans. As with self-driving cars, automated technological systems for environmental management are rife with practical challenges and ethical dilemmas. Indeed, fully automated systems may ultimately prove both impractical and unethical. However, the prospect of fully automated environmental management – the potential to 'paint humans out of the picture' – raises important questions that ecologists and conservation biologists must address in their efforts to enhance non-human autonomy in increasingly human-managed ecosystems.

Can Wildness Be Created?

Conservationists grapple with the practical and philosophical challenges of conserving wild places under conditions of rapid anthropogenic change [8,23]. In addition to wilderness protection, contemporary conservation strategies include ecological restoration, managed relocation, re-wilding, and 'designer ecosystems' [12,24–26]. Meanwhile, landscape architects, designers, and engineers have incorporated emerging ideas about novel ecosystems, green infrastructure, and nonhuman agency into their projects [27]. Scholars of science and technology studies have also turned from studies of 'wilderness' to those of hybrid relationships among humans, nature, and technologies [28–32]. Together these fields challenge us to reimagine the possibilities of translating human landscapes into new forms of wildness.

The idea of creating wildness is not new. In the 1920s, for example, American ecologists developed the idea of 'creative conservation'. Harshberger [33] concluded that ecologists 'may reproduce nature so closely by the use of native plants that our fellow men are deceived and believe that they look upon a wild growth when in fact it is artificial'. A few years later, ecologist Edith Roberts and landscape architect Elsa Rehmann described how to garden so as to 'leave the woods absolutely natural and seemingly untouched' [34]. Indeed, for nearly a century, landscape architects and restoration ecologists have sought to intervene in landscapes in such a way that mimics wild nature or facilitates its autonomous recovery.

Like wildness, autonomy can take many forms. To expose these forms, Figure 1 describes ecosystems by the relative degree to which their compositions and functions are shaped by human and nonhuman actors. Although relatively 'sterile' landscapes, such as those of a newly emerged volcanic island, might be considered wild places, for this investigation we consider the ecological influences of nonhuman organisms as the source of autonomous 'wildness'. Figure 1 depicts a continuous gradient of wildness increasing along the left axis from sterile environment at bottom to late successional wilderness at the top. Varied forms of human influences are illustrated across the *x* axis of Figure 1.

It is often asserted that an increase in human influence on an ecosystem causes a concomitant decrease in the presence and agency of nonhumans. Nonetheless, it is also possible for human influences and nonhuman influences to increase simultaneously. For example, while ecosystems can recover autonomy without human intervention after previously used lands are abandoned, human efforts to restore nonhuman species and nonhuman environmental patterns and processes may simultaneously increase both human and nonhuman influences.

As illustrated in Figure 2, processes of ecosystem change may proceed by a variety of trajectories. In the case of passive recovery 'regeneration' in Figure 2), nonhuman influences increase while human influences decrease. Passive recovery may result from unintentional land

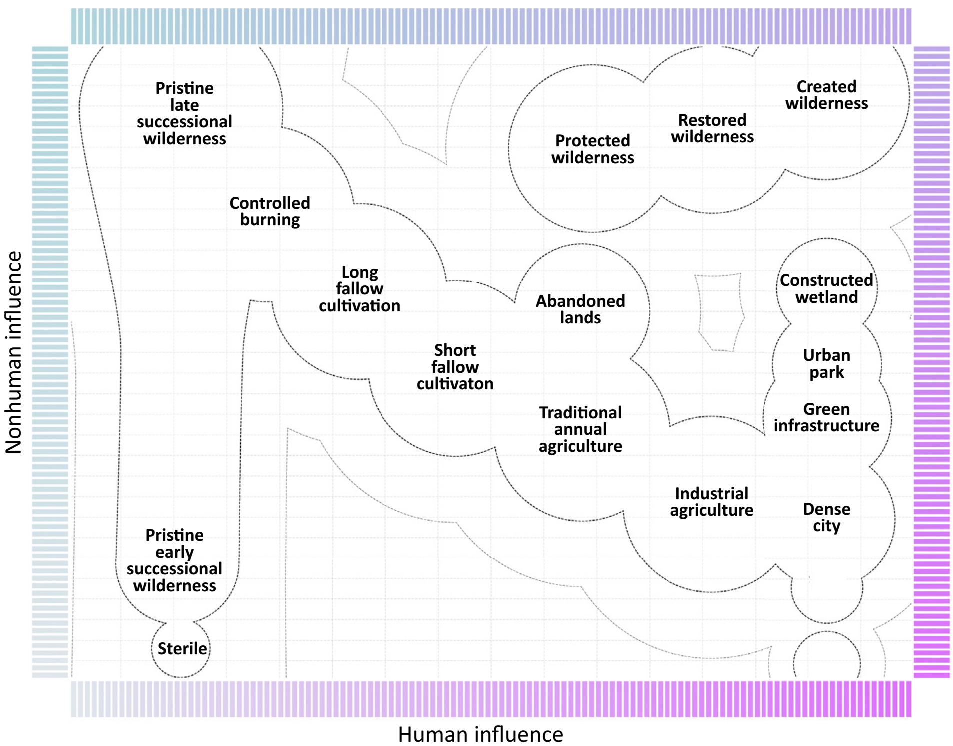

Figure 1. Conceptual Space Describing Relative Human and Nonhuman Influences on Ecosystem Patterns and Processes. The *y* axis depicts increasing degrees of nonhuman biological influence, defined here as 'wildness', from sterile environments to late successional wilderness. The *x* axis highlights increasing intensities of human influence, from controlled burning [34] to the development of dense cities (sociocultural niche construction [2]).

abandonment or from intentional conservation protections. Alternatively, in the case of active recovery ('rewilding' in Figure 2), nonhuman influences may be intentionally augmented without decreasing human influences, and even when human influences increase.

Automating Environmental Management

We are used to thinking of automation in manufacturing and transport systems, but automation is also increasingly applied in non-industrial settings such as healthcare, social media, agriculture, and ecological conservation. Automation can be applied to four broad classes of functions: information acquisition, information analysis, decision and action selection, and action implementation [22]. Automation is not 'all or none', but instead it manifests along a spectrum that ranges from 'augmentation' through 'automation' to 'artificial intelligence' (Box 2) [22].

Artificial intelligence (AI) refers to an increasingly broad field. We ally the concept of AI with autonomous goal-driven agents controlled through perception–decision–action loops, as in self-driving cars. Such agents receive through their sensors a sequence of observations about their environment. The observations are mapped to an abstract model of the state of the environment relative to the goals and allowable actions of the agent or their surrogates. The agent can communicate with other agents, including humans, about this internal model in coming to an action decision. What defines such AI is the ability of the agent to learn its capabilities from a diversity of internal initial conditions. The ultimate example of this is 'carte blanche', in which the only information available to the agent is the degree to which the agent is progressing toward its goals.

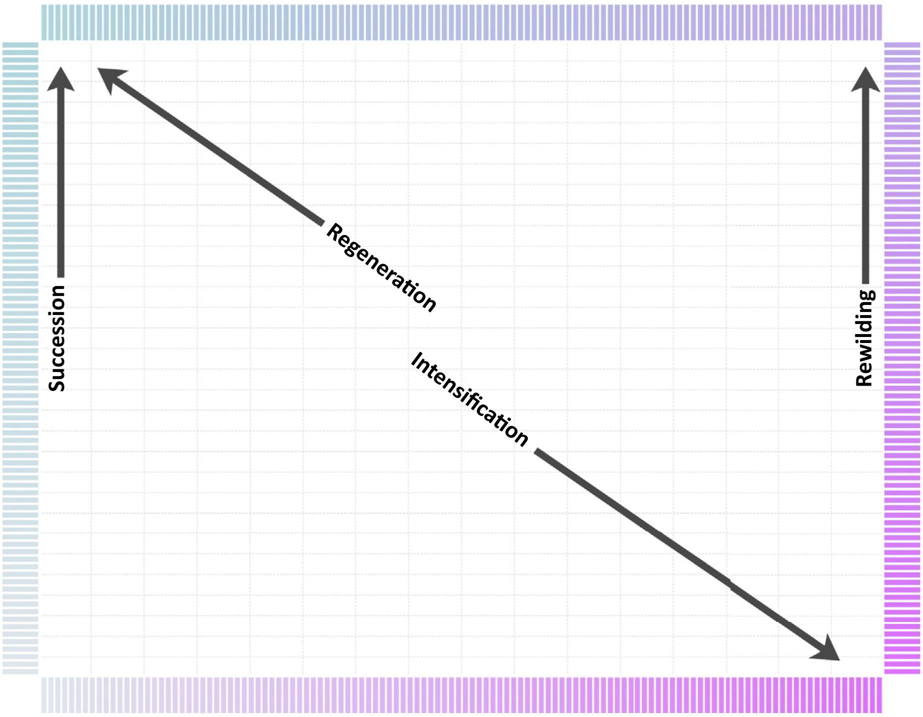

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Figure 2. Conceptual Space Describing Processes of Ecosystem Change in Relation to Human and Nonhuman Influences. The axes are the same as in Figure 1.

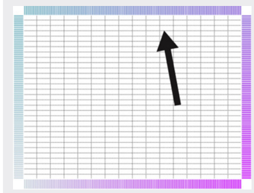
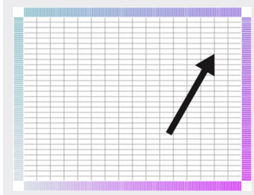
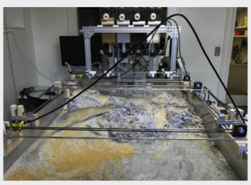
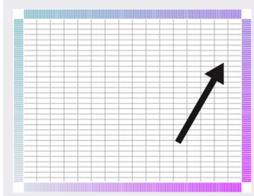
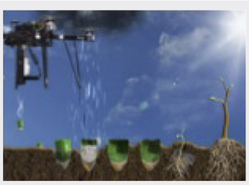
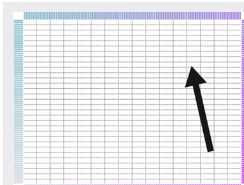
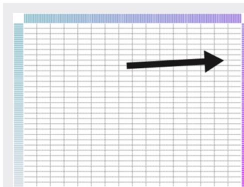
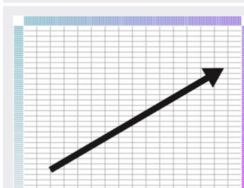
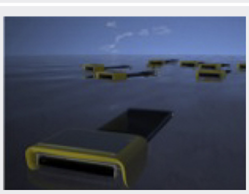
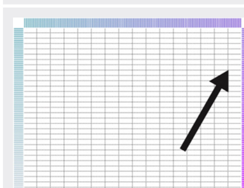
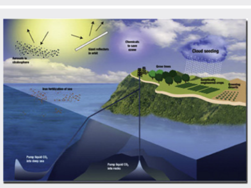
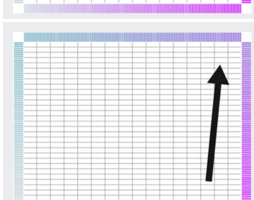
There are multiple theoretical frameworks for AI; we focus here on deep reinforcement learning (DRL); in our view this is the most promising approach to autonomous learning systems. DRL has enabled computers to autonomously learn to play complex games such as Go, and to learn complex ambulation and manipulation tasks without explicit programming in both simulated and real-world environments [21]. The capacities of DRL-based systems are scaling rapidly with advances in computing capacity, data storage, and data communication, as well as improvements in the DRL algorithms themselves.

In the context of environmental management, continuous monitoring of a wide range of environmental phenomena is required for information acquisition, and many technologies already do this, from remote sensing and sensor networks to wildlife tracking. Information analysis is also regularly automated in environmental management. What is not, however, are the steps of action selection and action implementation. By automating the full cycle of environmental management steps, from sensing the environment, to processing sensor data, selecting actions (or nonaction), implementing selected actions on the environment, and then sensing the consequences, a feedback loop evolves through a continuous stream of experiments and learning in which human interactions with environmental management might be minimized (Box 3).

Designing Wildness

A host of innovative projects are already shaping ecosystems through semi-automated strategies that enhance the autonomy of nonhumans. Using the conceptual model of Figures 1 and 2, we explore eight current projects that enhance nonhuman influences through semi-autonomous mediating technologies (Box 1). These examples are only a small illustrative

Box 1. Eight Recent Projects Employing Transformative Semi-Autonomous Strategies To Eliminate, Counter, or Mitigate Human Interventions in Ecosystem Management

	**Oostvaardersplassen** A nature reserve in the Netherlands (~56 km^2) in which Konik ponies and Heck cattle were introduced to act as functional equivalents of extinct tarpan and aurochs so as to restore trophic structure	[47] www.staatsbosbeheer.nl/natuurgebieden/oostvaardersplassen	
	**COTSbot** Autonomous underwater vehicle that identifies crown-of-thorns starfish (COTS), an introduced species in the Great Barrier Reef, and injects individuals with lethal bile salts to protect native coral species	www.qut.edu.au/news/news?news-id=95438	
	**Responsive landform process** Prototype system that autonomously interacts with and manipulates sediment flow in real time with the goal of promoting biodiversity	http://research.gsd.harvard.edu/real/	
	**Drone re-seeder** Unmanned aerial vehicles (UAVs, drones) that aerially deliver pressurized canisters containing germinated seeds to reseed native plants	www.biocarbonengineering.com/	
	**Virtual fences** Guides without physical barriers that keep animals from moving into human-occupied spaces	[48]	
	**Autonomous field robot for agricultural management** Robotic platform for the autonomous management of agricultural fields	www.deepfield-robotics.com/	
	**Toxic cleanup swarm robots** Autonomous, swarming robots that communicate with each other wirelessly to clean up toxic spills	http://senseable.mit.edu/seaswarm/ [49]	
	**Climate engineering** Deliberate and large-scale intervention in the Earth's climatic system with the aim of countering anthropogenic climate change	[50]	

Box 2. Degree of Autonomy in Automated Systems

Automated systems vary widely across a spectrum of autonomy, from minimal levels, where human interactions are required to complete every action, to complete autonomy, ignoring human input. As with self-driving cars, the most promising systems might occupy the middle reaches of this spectrum, where humans and machines both play active roles as separate intelligences that feed one another.

For automated systems, the design issue is this: which system functions should be automated and to what extent?'

High: complete autonomy, ignores humans
- Informs humans if machine decides
- Completes task and then informs humans
- Allows a specific time-period for human interaction
- Completes task if human approves
- Proposes alternative approaches or narrows selection criteria
- Machine offers alternatives

Low: human interaction is necessary for machine to complete action

subset of projects emerging through a much broader movement to create and sustain ecosystems that operate independently of direct human influences. For example, drones are deployed to deliver germinated seeds to reforest denuded areas, eliminating the need for human boots on the ground, and robots seek out and eliminate crown-of-thorns starfish invasions, minimizing the effects of human divers on the Great Barrier Reef. By investing these robotic systems with human functional roles, such projects raise complex questions about relationships between the social means of environmental stewardship and the normative ideals of human non-interference with wild places.

In exploring the 'influence space' of Figures 1 and 2, the possibility of creating and sustaining new forms of wildness through processes of 'intensive rewilding' is revealed (upper right). In this approach, human influences are maximized towards the goal of maximizing nonhuman influences – to produce 'created wildness' (upper right in Figure 1). The contradictions apparent in such an approach are both epitomized and challenged by the design of a fully automated (autonomous), artificially intelligent infrastructure that combines DRL with sensor and actuation systems to produce responsive interactions that create and sustain nonhuman wildness without the need for continuing human intervention.

Wildness is an unusual design challenge that is fraught with contradictions that are technical and formal, as well as cultural and philosophical. The design of wild places has usually aimed to preserve the historical character of regions, establish the picturesque, and to curate human experiences harking back to a period before modernism [35]. However, to design is inherently a human act, an influence in itself. To design a space free from human influences therefore requires a distanced authorship [36] favoring process, curation, and choreography [37]. Such 'design from a distance' would need to allow ecological systems and wild populations to coevolve through their sustained interactions, sustained by an infrastructure operating beyond human control or interference to continuously promote nonhuman autonomy and counter human influences.

A conceptual design for a 'wildness creator' is presented in Box 4 . Through this wildness creator, human curatorial interactions with organisms and abiotic environments are replaced with technological infrastructures utilizing responsive technologies (sensing and monitoring), robotics, and AI. The wildness creator operates with an autonomy produced through DRL, with its actions and algorithms learned from its own experiences and distanced from human control. The ability for computational intelligence to seek solutions outside the conventional strategies of conservation provides the wildness creator with a unique platform to perform the task of creating novel ecologies. Instead of engaging with ecology based on specific management

Box 3. Example Environmental Management Cycle

[Constant] Sensing of water quality, for example water quality changes due to agricultural fertilization creating excessive nitrogen run-off.

[Constant] Monitoring of continued nitrogen inputs and alterations to the ecological system.

[As needed] Actuation occurs through the planting of buffer vegetation to consume the nitrogen and topographic reshaping to increase nitrogen retention of landscape.

[Updates monitoring and actuation] As the environment is modified, the DRL system assesses the relative successes of different environmental manipulations in meeting water quality goals, and updates the algorithms applied in the next round of actuation; this updating could occur in milliseconds or over much longer time-periods (Figure I).

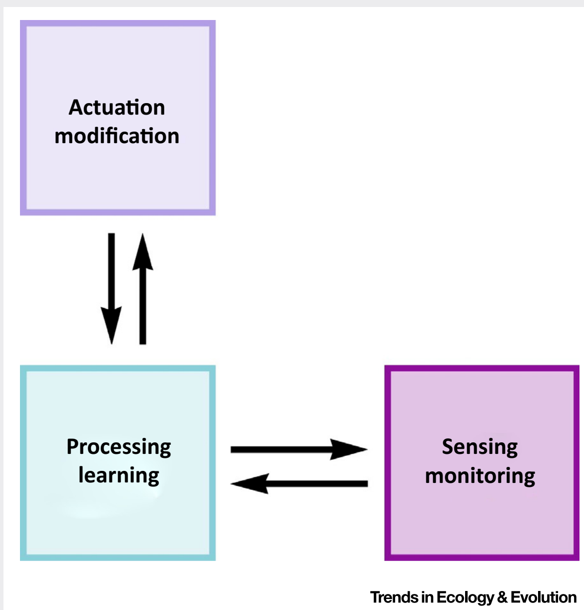


Figure I. Example Environmental Management Cycle.

priorities defined by humans, the wildness creator derives its specific priorities from an evolving computational intelligence derived from direct interactions with nonhuman species and environmental processes.

The role of design here is to implement an intelligent infrastructure and to enable its autonomous, purposeful engagement in ecological systems. In other words, it is the software, rather than the wildness, that is designed and that evolves through contextual training, allowing the wildness creator to take on its own sentience and create a wild ecological space beyond any human control, and even human conception. The intelligence is designed to create its own solutions based on its own shifting priorities so as to develop and implement an ecologically dynamic space that is specific to itself and the steady flow of training data it receives directly through its sensor networks.

For designers, the discrete creation of wildness is an unfamiliar and problematic task that asks for the evidence of human creativity and work to be de-prioritized within an ecological system. Is it possible to counteract, negate, or erase human influences, and to what degree is this worth the effort? More importantly, what is the space for designing wildness? Do highly technological approaches improve or inhibit the lives and futures of nonhumans? What will happen to the

Box 4. Wildness Creator

Wildness creator (Figure I) is a conceptual design for an autonomous landscape infrastructure system that creates and sustains wildness by enhancing nonhuman influences while countering all forms of human influence. It is a deep learning computing system that controls a physical infrastructure that can sense and manipulate the environment and interact with organisms. Wildness creator represents a nonhuman intelligent actor, initially developed by human designers, but enabled to learn its own novel strategic behaviors through sustained environmental interactions in creating and maintaining a wild ecosystem free of human influences. Algorithms that control the behavior of the system are learned from its context and operations, and are not programmed by humans.

Key Operating Principles

(i) Operations and activities are invisible and inscrutable to human observers: processes that govern the system are independently learned, hidden from, and functionally unknowable to human beings.
(ii) Humans visiting the created wild place are able to enter into it fully to experience a space with an ecology appearing to be operated entirely without any influence of humans.
(iii) Wildness creator constantly monitors human influences and constantly removes or interferes with them. For example, anthropogenic noise is cancelled, anthropogenic light is blocked, and human artifacts and pollutants are removed and filtered.
(iv) Wildness creator promotes the autonomy of nonhuman species and ecological processes to sustain diverse wild populations without direct human intervention.

As an example, a wildness creator might be deployed and begin operating across the site of a coastal wetland brownfield. The system would first utilize sensing and learning systems to identify living organisms and nonhuman environmental patterns across the site. The system would then seek evidence of human influences and begin operations to assist nonhuman actors at the site, such as plants, to transform environmental patterns toward conditions devoid of evidence of human influence. In conducting these operations, the system would learn the most effective strategies. As operation proceeds, learning would continue as ecological succession processes transpire, such that the system might develop and enact entirely different algorithms and behaviors over time, which would be unique to the wildness creator and potentially unanticipated by any prior system behavior.

Over time the wildness creator would actively seek out anthropogenic inputs, including pollutants from industrial processes, anthropogenic noise, and waste from human visitors, learning and implementing new protocols to counter these effects. The wildness creator would also mask its operations and modifications such that human observers perceive the flora, fauna, and abiotic environments of the site as being uninfluenced by humans. In time, the operations of the wildness creator would become unrecognizable and incomprehensible to human beings, the resulting ecological patterns and processes would diverge from any previously created and sustained by humans, and nonhuman species and environmental processes at the site would be able to go about life without experiencing human influence.

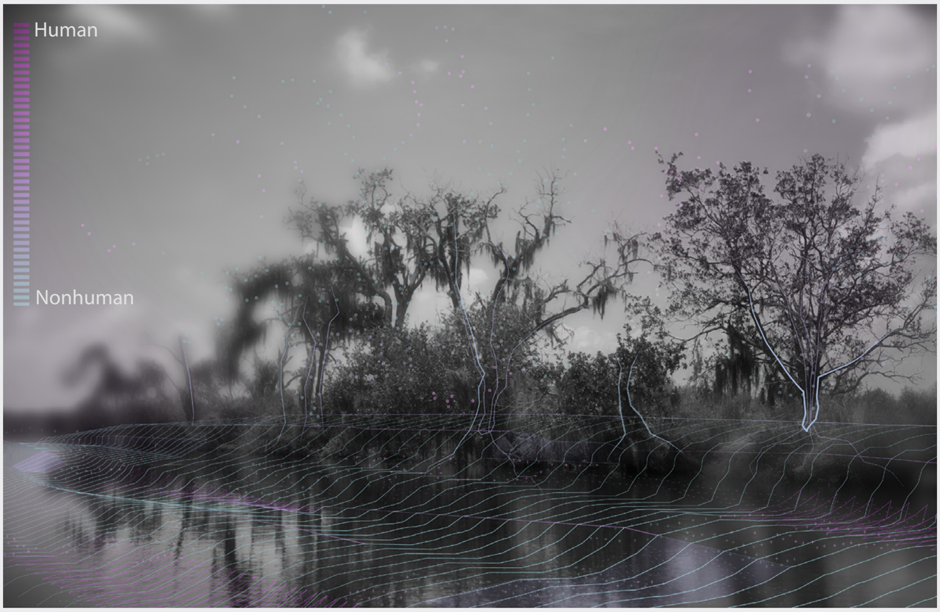


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Figure I. Wildness Creator.

interconnections between humanity and natural systems when these are curated by a machine, particularly when enacted beyond our control or understanding?

Creating Wildness in the Anthropocene

Contemporary wild places are produced by human institutions and sustained through continuous interventions that range from the removal of invasive species to the removal of people. For decades ecologists have grappled with two seemingly opposing goals: preserving wildness and restoring ecosystems. Conservation and restoration sites demand continuous monitoring and management, and many species exist today only because of deliberate and ongoing human interventions. The need for such interventions is only increasing [38,39]. Often the goal of restoration has been to intervene just enough to create a "self-sustaining" ecosystem [40]. To do so, restoration ecologists have sought to cede decision-making power to nature – to 'naturalize' the decision-making process. They have looked to community ecology for clues on how to assemble species such that they are resistant to invasion or resilient to change. Others have turned to paleoecological records and other historical evidence for answers on how to manage wild places. Nevertheless, although data can help us to imagine what ecosystems once looked like, they cannot help us know what ecosystems ought to look like.

New autonomous and deep learning technologies enable us to imagine intelligent infrastructure systems that might operate independently of human decisions and interventions. Conservation and restoration efforts are already embracing a wide array of new technologies to accomplish restoration goals through semi-autonomous systems. The technological capacity to provide detailed data on ecological patterns and processes is advancing rapidly through projects such as the National Ecological Observatory Network [41].

It is true that any wildness creating system would be built by humans and would therefore represent human influences in themselves. However, such systems might be designed to operate as mobile visitors to wild places, making such systems no more a presence in the wild than any human visitor. If built with enduring materials, such systems might sustain themselves for years without human intervention. Working with other nonhumans – the species that reside in the given area – these systems might sustain ecosystems independently of direct human interventions, highlighting the complex reality of a nature that is both autonomous and socially constructed. Rather than the 'machine in the garden' [42], we are confronted with the machine as gardener.

Responsibility in the Anthropocene

As with current efforts to naturalize restoration decisions, the prospect of wildness creation systems – the machine as gardener – concedes decision-making to nonhumans rather than confronting humans with the difficult, complex, and political decisions inherent in environmental governance. Wildness creation technologies raise two of the same practical and ethical dilemmas as self-driving cars: reduced situation awareness and complacency. When humans cede decision-making control, they tend to become less aware of changes in environmental states and, if an automated system is highly but not perfectly reliable in executing decision choices, then humans might fail to detect the times when the automation fails [22]. There is also no evidence that it will ever be technologically, financially, or politically possible to develop and install autonomous wildness creators at meaningful scales. And ultimately, created wildness may never fulfill the same social, political, or spiritual roles as past wild places. Nevertheless, the prospects of new forms of wildness creation should not be ignored. Intensive rewilding might ultimately enable nonhuman species to live in environments free of human influences, even while still embedded within anthropogenic landscapes.

It should be clear that what we are proposing here will not be possible to enact in the near future, and certainly should not displace existing wilderness conservation strategies. Nor are we proposing that technical solutions can overcome the ultimate causes of biodiversity decline – which are inherently political and economic. Instead, our goal is to inspire conservationists, ecologists, and designers to attempt to increase the autonomy of nonhuman species and processes in dynamic anthropogenic landscapes.

Ecologists and conservation biologists are increasingly engaged in conserving nature in urban ecosystems, novel ecosystems, and other existing, accidental, and hybrid sites that challenge the idea of a clear divide between wild nature and human culture [8–13,43–45]. Why not design technologies and systems to advance the well-being of other organisms, much in the same way as smart cities are designed to meet the desires of humans? The Wilderness Society has suggested that national forests might allocate lands to three categories: 'restoration zones', in which change from historical configurations is resisted; 'observation zones', in which ongoing change is accepted; and 'innovation zones' in which change is guided using experimental approaches [46]. Deep interactive machine learning systems that create and sustain wildness might fulfill the objectives of such innovation zones by testing new mechanisms for responding to anthropogenic change.

Wildness creation is the ultimate design challenge of the Anthropocene. Can we 'paint ourselves out of the picture' and devote our creativity and resources toward the interests and futures of species other than our own? We believe it is time to try.

Outstanding Questions

How might autonomous ecological curation find a middle ground that assumes human influence to be only another actor within a larger system of actors?

What types of organizations and entities must be established to help to guide and regulate autonomous ecological management?

How do we establish goals for an autonomous machine intelligence engaged with the curation of wildness?

Acknowledgments

We thank David Klein for his contributions, the students of the Harvard University Graduate School of Design for their questions, and Paul Craze, Ezra Feldman, Adam Dixon, and two anonymous reviewers for their helpful feedback. Support for E.C.E. was provided by the US National Science Foundation (grants CNS 1125210 and DBI 1147089).

Supplemental Information

Supplemental information associated with this article can be found online at http://dx.doi.org/10.1016/j.tree.2016.12.004.

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