RESTORATION ECOLOGY
The Journal of the Society for Ecological Restoration

REVIEW ARTICLE

Bionovelty and ecological restoration

John P. Volpe[1,2], Eric S. Higgs[1], Jonathan M. Jeschke[3,4], Katie Barnhill[5], Conrad Brunk[6], Joan Dudney[7,8], Laura L. Govers[9,10], Richard J. Hobbs[11], Karen Keenleyside[12], Stephen D. Murphy[13], Philip J. Seddon[14], Jayce Sudweeks[15], Orkan Telhan[16], Sonia Voicescu[1]

Anthropogenic activity has irreparably altered the ecological fabric of Earth. The emergence of ecological novelty from diverse drivers of change is an increasingly challenging dimension of ecosystem restoration. At the same time, the restorationist's tool kit continues to grow, including a variety of powerful and increasingly prevalent technologies. Thus, ecosystem restoration finds itself at the center of intersecting challenges. How should we respond to increasingly common emergence of environmental system states with little or no historical precedent, whilst considering the appropriate deployment of potentially consequential and largely untested interventions that may give rise to organisms, system states, and/or processes that are likewise without historical precedent? We use the term *bionovelty* to encapsulate these intersecting themes and examine the implications of bionovelty for ecological restoration.

Key words: bionovelty, ecological systems, policy, risk assessment, technology

Implications for Practice

- Novel organisms or ecosystems having no historical precedent are both the target and potential consequence of emerging interventions, innovations, and technologies applicable in ecological restoration.
- Increasing restoration efficiency can have ambiguous benefits due to unpredictable outcomes of gene drives, GMOs, nano, and synthetic organisms.
- Restorationists need substantial preparation to identify opportunities and pitfalls accurately; the pace of technological development is overtaking the current capacity for effective restoration response.
- Singular interventions can be assessed for their impact on restoration practices, but tracking larger, policy-relevant patterns emerging across multiple and only partially connected technologies, pose significant challenge.
- Greater reliance on novel field-deployed technologies will likely to intensify the commercialization and privatization of restoration practices.

Introduction

Although millennia of anthropogenic activities have transformed ecosystems around the world (Boivin et al. 2016), the past two centuries of increasing industrialization and global trade, and especially during the "great acceleration" (Steffen et al. 2015), have produced unprecedented ecological conditions. Ecological novelty (Heger et al. 2019), and the more specific idea of novel ecosystems (Hobbs et al. 2013), refer to new organisms and unprecedented assemblages of organisms with which traditional approaches to environmental management struggle. This is consistent with the identification of "novel entities" as one of a suite of control variables defining planetary boundaries. Novel entities "…include synthetic chemicals and substances (e.g. microplastics, endocrine disruptors, and organic pollutants); anthropogenically mobilized radioactive materials, including nuclear waste and nuclear weapons; and human

Author contributions: JPV, ESH set the meeting agenda and oversaw development of the manuscript; all authors contributed to developing the core ideas and contributed to writing as per individual expertise; JPV, ESH compiled and wrote the manuscript with support from JMJ, SDM, PJS; all authors participated in editing and revising the manuscript.

[1]School of Environmental Studies, University of Victoria, Victoria, BC, Canada
[2]Address correspondence to J. P. Volpe, email jpv@uvic.ca
[3]Leibniz Institute of Freshwater Ecology and Inland Fisheries (IGB), Berlin, Germany
[4]Institute of Biology, Freie Universität Berlin, Berlin, Germany
[5]Forestry and Environmental Resources, North Carolina State University, Raleigh, NC, U.S.A.
[6]Department of Philosophy (Emeritus), School of Environmental Studies, University of Victoria, Victoria, BC, Canada
[7]Environmental Studies, University of California Santa Barbara, Santa Barbara, CA, U.S.A.
[8]Bren School of Environmental Science & Management, UC Santa Barbara, Santa Barbara, CA, U.S.A.
[9]Groningen Institute for Evolutionary Life Sciences, Groningen University, Groningen, The Netherlands
[10]Department of Coastal Systems, Netherlands Institute for Sea Research, 't Horntje, Texel, The Netherlands
[11]School of Biological Sciences (Emeritus), University of Western Australia, Perth, Australia
[12]International Union for the Conservation of Nature (IUCN), Chelsea, PQ, Canada
[13]School of Environment, Resources, and Sustainability, University of Waterloo, Waterloo, Ontario, Canada
[14]Department of Zoology, University of Otago, Dunedin, New Zealand
[15]Department of Public and Non-profit Studies, Georgia Southern University, Statesboro, Georgia, U.S.A.
[16]Ecovative Inc, Green Island, NY, U.S.A.

doi: 10.1111/rec.14152

modification of evolution, genetically modified organisms, and other direct human interventions in evolutionary processes" (Richardson et al. 2023). The relevance to restoration is perhaps the most striking given that historical system conditions are often used as targets for the recovery of degraded ecosystems. In a time of rapidly changing land use and climate, addressing ecological novelty is a signal issue recognized by the UN Decade on Ecosystem Restoration (2021–2030) (Fischer et al. 2021). The challenge extends to ecosystem management more generally; wildlife conservation, afforestation, and sustainable agriculture, for example, are increasingly confronted by the emergence of ecosystems that challenge conventional restoration approaches, which anticipate relatively stable ecosystem composition and configuration (Beller et al. 2019). We examine this challenge through the lens of ecosystem restoration and draw attention to an additional issue likely to dominate restoration practice in the Anthropocene: emergence of new technologies (e.g. artificial intelligence devices; Cantrell et al. 2017), and organisms (e.g. synthetic organisms and designer hybrids) that will shape future ecosystems defined by novel functions and compositions without precedence.

Contemporary decision-makers must confront increasingly complex drivers of change including those that destabilize core ecological concepts. The increasing rate and extent of environmental (e.g. climate, nitrogen deposition, land use, and habitat fragmentation) and ecological changes (e.g. invasive species, range shifts) challenge historical continuity as the determinate basis of management objectives (Higgs et al. 2014; Hobbs et al. 2014; Beller et al. 2020). For example, anthropogenic climate change drives amplitudes of variance that exceed historical norms (Harris et al. 2006; Hobbs et al. 2013; Oliver et al. 2015), requiring recalibration of those norms and goal setting. Likewise, invasive species change the composition and function of ecosystems, reducing the efficacy of restoration strategies formulated around native ecosystems (Kueffer 2017; Roy et al. 2024). Indeed, the interaction of a wide range of drivers of change are leading to novel ecosystem composition and function at rates unprecedented in the Holocene (Truitt et al. 2015; Heger et al. 2019). With increasingly novel environmental conditions, restoration practitioners and programs must continually challenge and adapt conventional ideals organized around historical alignment with past system states.

Navigating such ecological and environmental change comes with growing acknowledgement of diverse cultural priorities (Wehi & Lord 2017). For example, pre-colonial or pristine targets for ecological restoration have predominated in North America despite long histories of indigenous land-use practices. The limitations of such perspectives are particularly acute in many European, African, or Asian ecosystems, which have complicated legacies of human presence (Deary 2015). Furthermore, management priorities may attempt to serve multiple objectives such as aesthetic, recreational, and biodiversity services; however, in regions experiencing rapid environmental change and/or grinding poverty, creation of sustainable livelihoods may be prioritized (Cowie et al. 2018).

In this article, we draw attention to an additional challenge that is likely to grow and potentially dominate ecological restoration in the Anthropocene (Corlett 2015): the rise of new technologies and organisms that will shape future ecosystems defined by novel functions and compositions. We extend from Heger et al. (2019) by incorporating novel ecological states, technologies, and organisms into the broader term "bionovelty" to describe their emergence and impact, and identify conditions under which they could support or frustrate ecological management goals. Indeed, it is this duality that is both an intriguing prospect for ecological restoration science and practice—solving new problems with new approaches—and the portent of further difficulties: What is unleashed in the service of restoration? We further recognize the intensifying interweaving of natural and artificial systems in the Anthropocene (i.e. green cities, smart farms) which serves to lower the bar for technology adoption, while also increasing the breadth and magnitude of potential unintended consequences.

Bionovelty

Novelty is associated with a new, original, or unprecedented category or state. Present challenges facing restoration practitioners and scientists are unprecedented due to the accelerating rates at which novelty is emerging across all levels of nested hierarchical biological organization, from molecules to the biosphere (Williams & Jackson 2007; Hobbs et al. 2009). Managing ecosystems with limited historical precedent or continuity is challenging enough; anticipating how novel hierarchical and multiplicative interactions may manifest greatly complicates the restoration challenge. For example, top-down effects of global climate change are easily observed at population genetic levels (Hoffmann & Sgrò 2011), while bottom-up impacts of introduced species can be observed at the landscape level (Fei et al. 2014)—novel causes and novel effects can operate in both directions. The prospect for restoration practitioners will be to grapple simultaneously with the increasingly common phenomenon of unprecedented ecological configurations as well as the rapid expansion of novel interventions and technologies that have no historical precedent, such as synthetic biota and pseudo-biota (e.g. micro- and nano-scale robotics).

Bionovelty comprises two interacting dimensions:

(1) *Ecological novelty* at different scales of biological organization, from organisms and communities to ecosystems and landscapes with no historical precedent (sensu Heger et al. 2019).
(2) *Novel interventions, innovations, and technologies* that can give rise to or amplify ecological novelty, for example, novel organisms or ecosystems having no historical precedent.

The first dimension is ecological novelty (sensu Heger et al. 2019) at different scales of biological organization, resulting from either intentional design or unintentional human action (Table 1), the latter potentially through novel technologies mentioned above. This dimension extends the concept of novel ecosystems, defined as "a system of abiotic, biotic and social components (and their interactions) that, by virtue of human influence, differ from those that prevailed historically, having

Table 1. Discriminating intentionally designed from unintentionally emergent ecological novelty.

	Intentional	*Unintentional*
Ecosystems	Designed ecosystems require intent and maintenance (Higgs 2017). Some could become self-assembling and autocatalytic eventually, but they require initial curation.	Other novel ecosystems arise unintentionally. They do not require maintenance, arise from self-assembly and are immediately autocatalytic (Albano et al. 2021; Kreyling et al. 2021; Sanchez-Vidal et al. 2021).
Organisms	Designed organisms include synthetic organisms or genetically modified organisms (Jeschke et al. 2013).	Other novel organisms include invasive non-native species, range-expanding species, or emerging pathogens (Jeschke et al. 2013).

a tendency to self-organize and manifest novel qualities without intensive human management" (Hobbs et al. 2013). The novel ecosystems concept arose from concerns about ecosystems that challenged ecological restoration guided by historically continuous trajectories. The widespread adoption of the concept of novel ecosystems acknowledges its ascent to prominence in a rapidly changing world (Perring & Ellis 2013). Heger et al. (2019) generalized this concept to reflect multiple scales of "ecological novelty," and to tie together ecological and evolutionary processes. In their account, ecological novelty comprises both "novelty for organisms" as shaped by new environmental conditions and species interactions (organism-centered perspective), and "novelty of landscapes, ecosystems, and communities" as assessed from historical references (site-specific perspective).

The second dimension of bionovelty acknowledges a wide and expanding range of novel interventions, entities, and technologies designed and engineered to solve challenges (Table 2). Some are direct extensions of biological manipulations aimed at specific outcomes. For example, gene drives (a technological intervention to rapidly "drive" the addition, deletion, or modification of alleles throughout a population) can be used to extirpate high-impact invasive species. Emerging developments in synthetic biology—de novo development of organisms—foreshadow new possibilities and portend ecological and ethical implications. Others are pseudo-biota, such as nanoscale robots used as analog organisms. We include technologies that create changes in ecosystems without remaining as active agents. For example, drone swarms using advanced artificial intelligence promise to improve the pace of deployment and ecological outcomes for forest recovery. In cases such as these, the technological intervention (e.g. tree planting) changes the ecosystem outcome and is potentially guided by machine learning decisions (novel decision processes). Although the scale, design, and type of deployment vary widely, these interventions share the capacity to alter, often very rapidly, foundational ecological processes. The temporal dimension of bionovelty is important; the rate of ecological change, independent of magnitude, alone can trigger negative, potentially catastrophic outcomes (Pinek et al. 2020; Synodinos et al. 2023). These agents have not evolved in real-world natural systems and thereby miss the long-term trial-and-error integration typical of co-evolved organisms and ecological processes.

Such a diverse array of interventions in ecosystems necessitates acknowledgement of the complicated interplay of objects, inventions, systems, and software with human beliefs and activities (e.g. Borgmann 1984; Latour 2005). The "device paradigm" (Borgmann 1984) advances a pattern-based theory of technology in which "focal things" (i.e. things that provide meaning for individuals and communities) are stripped of direct human engagement and rendered as "devices," which are split into commodities in foreground of human experience and machinery largely concealed in the background. For example, the relationship a group of restoration volunteers experiences with an ecosystem using mostly traditional techniques is transformed by new devices (e.g. gene drive, drone swarm) into a practice that is simultaneously more efficient and less engaging. Borgmann argues it is not the device itself that matters most but the relationship that extends between people and devices. Thus, it is not a singular instance of bionovelty that is of concern but a restoration practice in which the norm becomes bionovel and the relationship people have with ecosystems becomes increasingly detached and commodity-laden. A pattern-based view confers technology as the dominant character of relationships that extend between people and devices (including systems, software, etc.). This is in contrast to conventional instrumental definitions of technology that render technology as objects. The instrumental view of technology places moral responsibility on the individual whereas in a pattern-based view, responsibility is diffused among an increasingly complicated set of relationships often beyond immediate control which tends to generate intensifying patterns of technological relationship. Thus, it is not just the individual technologies that matter but how the pattern of interaction forms and reinforces more of the same. This approach allows for a wide sweep of interventions and the search for pattern among a dizzying array of recent, emergent, and imagined ecological therapies. For restoration practitioners, the challenge is not only positively engaging novel ecological systems but the normalization of professionalized device-laden interventions with distraction from deeper focal engagement.

It is theoretically possible to consider each of the two bionovelty dimensions separately, but the process focusses of the second dimension combined with the significant entanglements of the ecosystem- and organism-based views of the first makes such an approach unworkable. We incorporate these novel ecological states, organisms, and technologies and their interactions into the broader term bionovelty to describe their emergence, interdependence, and impact, while identifying conditions under which they could support or frustrate ecological restoration goals. Furthermore, we recognize that field interventions

Table 2. Example interventions capable of manifesting bionovelty and how each deviate from conventional practices organized along a gradient; those derived from extant biological entities and operating in or manifesting novel ecological systems (top) to those arising through de novo technologies (bottom). [a]Dozens to thousands of drones in coordinated flights using algorithms and local sensors to achieve unprecedented deployment (forestry reseeding) and surveillance (invasive/endangered species) among others. [b]Selfish genetic elements transmitted to progeny at super-Mendelian frequencies. [c]Programmable organisms designed by computers and assembled from living stem cells.

Bionovelty	*Example*	*Deviation From Norm*	*Reference(s)*
De-extinction	Proposed translocation of functional proxies of extinct species as ecological replacements to restore lost ecosystem functions and processes, for example, proposed creation of a *mammophant*—Asian elephant-woolly mammoth hybrid to address climate change impacts	Functional proxies created using genetic engineering and inter-species cloning will be GM hybrids with potentially unanticipated ecological interactions	(Seddon 2017)
Assisted colonization	Translocation of species to favorable non-native habitats to offset human-induced threats	Intentional introduction of species beyond native range to avoid extinction in the current range	(IUCN 2013; Seddon et al. 2015)
Rewilding (trophic rewilding)	Ecological replacement of lost megafauna to restore the ecosystem processes lost following keystone species extinctions, e.g. Pleistocene Park, Siberia	Novel assemblages of both domestic and wild species of grazers and browsers replacing the herbivory and soil disturbance functions of extinct megafauna	(Zimov et al. 2012; Perino et al. 2019; Carver et al. 2021)
Accelerated natural regeneration	Drone swarms[a] deploying seed missiles	A priori testing of immediate widespread change in community structure absent	(Elliott 2016; Murphy 2018)
Gene drives[b]	Drive invasive or pathogenic population to local extinction	Introduction of GMOs into natural environments that deviate from Mendelian inheritance norms	(Windbichler et al. 2011; Kofler et al. 2018)
Genetically modified organisms (GMOs)	Sterilization of potential agriculture escapees Climate-proofing (i.e. corals) More efficient agriculture species Pathogen resistance	Creation of genetic and/or phenotypic traits that would otherwise be unlikely/impossible to manifest naturally	(Alphey 2014; Piaggio et al. 2017; Ricciardi et al. 2017; Steiner et al. 2017; Noble et al. 2019; Serr et al. 2020)
Habitat restoration using non-native/bionovel species	Planting exotic tree species to benefit Bornean Orangutan	Ecological function and climate mitigation trump native species identity	(Lee et al. 2019; Seddon & King 2019)
Carbon sequestration	Carbon farming, ocean fertilization	Oceanic-scale carbon sequestration via alteration of primary production rate	(Yoon et al. 2018)
Manufactured habitats	Artificial, biodegradable reefs to aid in the restoration of coastal ecosystem engineers (e.g. mussels, seagrasses, salt marshes)	3D-printed, biodegradable artificial habitats biologically integrated into restored habitat	(Temmink et al. 2020)
Pollution mitigation	Pollutant (pharmaceutical, hydrocarbon, plastic) consuming microbes	Bacterial lab strains equipped with a pollution degradation pathway to aid biorecycling processes	(Espinosa et al. 2020)
Nano robotics	Xenobots[c]	Pluripotent frog stem cells (Xenopus laevis) for novel and human-programmed behavior	(Kriegmana et al. 2020)
Synthetic Organisms	Entirely synthesized organism	De novo life without biological antecedents	(Fredens et al. 2019)
Biological design	Growing or harvesting novel materials (from bacteria, yeast, algae, mycelium)	Microbial cellulose or mycelium as an animal leather alternative. Cultured algae plastic replacement	(Bloom Inc. n.d.; Bolt Inc. n.d.)

applying novel technologies may increase the probability of the emergence of novel ecological states, which in turn hasten the next technology iteration, and so on (Fig. 1). Some may bristle at a new term—bionovelty—in addition to relatively recent terms such as novel ecosystems and ecological novelty. It is the distinctive reinforcing pattern central to bionovelty, and the fact that it represents more than technology-as-machinery that compels new terminology.

Bionovelty and Ecological Restoration

Bionovelty presents two major challenges to conventional approaches to restoration:

(i) *Unprecedented efficiency*: The potential for greatly accelerated rates and spatial extent of effects resulting from novel interventions are without precedent regardless of whether the focus is restoration of species composition or ecosystem function(s) (Fig. 2). For instance, molecular-level gene-drives quickly manifest community-level benefits of invasive species extirpation. But, however, precise the elimination of specific pathogens or non-native species might be, the outcome immediately affects the hierarchical architecture of the host natural system; seemingly modest interventions at lower organizational levels may yield dramatic and disproportionate effects at higher levels affecting evolutionary trajectories is generally unplanned ways (Sarrazin & Lecomte 2016). Thus, novelty can emerge in the guise of either a new challenge to be overcome (e.g. a novel pathogen), or a solution that has been previously unavailable (e.g. engineered pathogen resistance). It presents as a double-edged sword, not only offering unprecedented opportunity but also opening the window to unintended consequences and potentially initiating the autocatalytic loop of bionovelty (Fig. 1).

(ii) *Complex performance metrics*: The criteria of success (or failure) of a novel organism or technology are measured at the system level (population or higher), not organismal level. Thus, a gene drive engineered to eradicate invasive individuals would be evaluated using community diversity and composition metrics, similar to how a conventional intervention might be evaluated. However, a gene drive is much more than a technical widget: its deployment comes with a web of social, economic, and cultural connections and implications; it implies a singular perspective of how the system is seen and valued, it shifts the perception of who is a trustful expert or stakeholder, whose voice decides the course of action and what expertise is needed or irrelevant. The substantial social engagement typical of successful conventional restoration programs (Suding et al. 2015) may be displaced by the need for increasingly professionalized and sophisticated technologies, a pattern noted well before the advent of ecological novelty (Higgs 2003). This has immediate negative implications for projects that lack financial or technical resources to confront ecologically novel states or to adopt ecologically novel approaches. Financing and technical capacity are two of six major barriers to success identified in the UN Decade on Ecosystem Restoration.

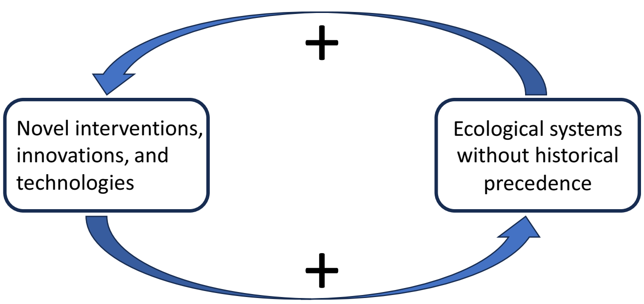

Figure 1. The bionovelty autocatalytic loop. Novel ecological states facilitate development and deployment of novel interventions, innovations and/or technologies. These activities may result in amplifying ecological novelty and hastening a new round of deployment. Once initiated, the cycle rate is likely to increase.

These new approaches hold great promise in increasing the ability of ecosystems to track environmental change, but rapid ecosystem shifts combined with changes in management that leverage novel technologies could also precipitate accelerated, unforeseen, and potentially undesirable changes (Table 2). Developing strategies to reduce unintended consequences of innovation in management is therefore critical to reducing the risk of counterproductive or worse restoration outcomes. These emerging technologies and interventions have the potential to generate bionovelty—unprecedented alterations to organisms, and/or novel processes emerging at scales from population to the landscape with unprecedented compositions, functional attributes, and network topologies of energy and matter flows (Heger et al. 2019). These emerging technologies and interventions can have intended salutary benefits for ecosystems and thus warrant serious attention. However, while some may pose relatively modest risks of unintended consequences, for others the risks are largely unknown. The prospect of tree-planting drone-swarms that will vastly increase the pace and efficacy of landscape-scale reforestation is tantalizing, until assessed against potential losses of human community autonomy and cultural engagement. Gene drives, similarly, pose enormous potential benefits in targeted eradication or reduction of harmful species (Ricciardi et al. 2017) but potentiate significant unforeseen consequences.

Each intervention—gene drive, synthetically produced organism, drone swarms, and so forth—taken individually, generates both operational and ethical challenges. For instance, the risk–benefit analysis of deploying a gene drive for eradication of an invasive species on a small isolated island is likely to be more accurate and precise relative to a similar analysis involving large contiguous landscapes that potentiate broad spread. New principles to guide appropriate action are needed to address unconventional interventions (Macfarlane et al. 2022). The result of inappropriate or missing principles might be that critical interventions end up being shelved because of their association with higher-risk approaches, or

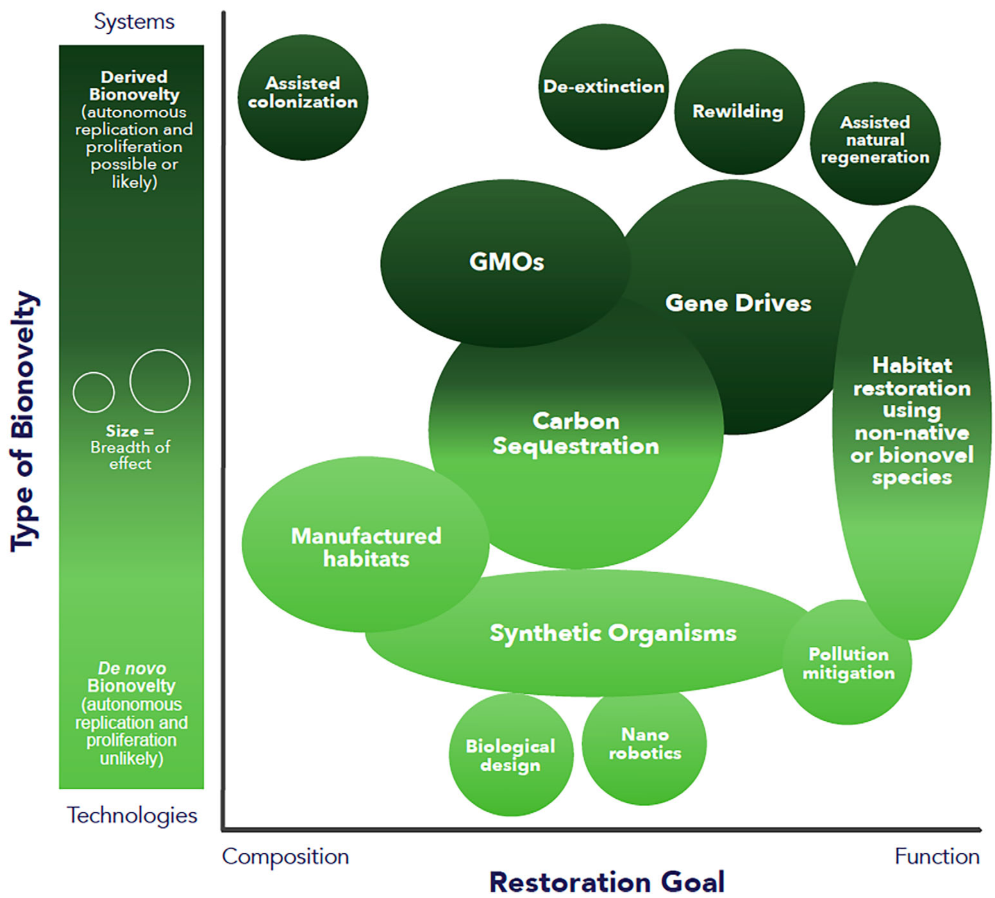

Figure 2. A potential trajectory for ecosystem restoration, showing established shifts from classical to more open and flexible approaches to restoration in the past four decades. Restoration 3.0 suggests a new type of restoration that adapts to the inevitable consequence of bionovelty.

that higher-risk approaches will be deployed because of a misunderstanding of consequences or fatigue in addressing so many simultaneous drivers of change.

Significance for Ecosystem Restoration

Ecological restoration in its earliest conception, "Restoration 1.0," sought to hasten return to historical benchmarks via interventions such as biological control, seed germination, predator release, and structural habitat amendments, (e.g. coral reefs to restore past states). Restoration 2.0 (Higgs et al. 2014) used history as a guide rather than template, shifting emphasis toward system configuration and a sensitivity to human livelihoods within and adjacent to focal sites. It is clear this paradigm is not sufficient: how far can restoration stretch to meet new demands and challenges? Scientists, practitioners, and the private sector are coming to grips with global-scale ecological paradigm shifts such as climate change, hastening a new generation of interventions that emphasize precision, efficiency, and perfectibility guided by objectives that might not have historical precedent. Although global change drivers, including climate change and invasive species, are widely studied, there are far fewer accounts of the possible impacts of emerging drivers of change. This may point to a new model of ecosystem restoration in the future. Below is an initial and incomplete list of potential implications.

Novelty does not diminish the role of restoration: A criticism leveled at the concept of novel ecosystems was that the aim was to replace or undermine restoration (Standish et al. 2013; Murcia et al. 2014). This was not the intent of those who initially developed ideas around novel ecosystems, and it is not the intent when raising broader issues around ecological novelty. Bionovelty exists no matter the terminology or conceptual formulation, and new types of technological and biological innovations are arising all the time. Recognizing bionovelty does not mean promoting it. There is much work ahead in determining whether and how novel technologies are indeed helpful innovations in restoration, and effective ways of appraising them are needed to decide if they should be introduced to the restoration tool box.

Novel problems do not mandate novel solutions: Bionovelty emphasizes the widely recognized inadequacy of essentialist norms of restoration (Martin 2022) be it grappling with long standing problems like invasive species or rapidly emerging challenges such as those associated with climate change. In so doing, bionovelty intensifies the imperative to develop and implement carefully revised guidelines for restoration interventions that nonetheless remain true to existing, well-articulated values that have driven the science and practice of ecosystem restoration. Bionovelty is not, and should not, evolve into a driving value or end in itself. It is a condition that must be taken seriously in the degradation of environments, and hence also a means by which environmental and ecosystem values can be more effectively realized for the greatest array of stakeholders and rightsholders.

Design responsibility for bionovelty involves a critical assessment of the full costs of designing and promoting ecologically novel technologies and/or system states. Beyond immediate considerations of ecological restoration, uses of living matter as raw ingredients, fuel source, or labor to fabricate novel bioproducts often promise silver-bullet solutions to ecological harms. Potentially, they offer environmentally safe, less polluting, and renewable alternatives to polluting, toxic, or extraction-based supplies. However, it is important to think critically regarding the economic and socio-political realities that influence bionovel products. For instance, a shift from sourcing Artemisinin, an antimalarial lactone, from farmed sweet wormwood (*Artemisia annua*) to yeast fermentation proved unviable since exploitative farming practices remained financially more advantageous than building technical infrastructure (Peplow 2016). Value propositions are multidimensional and successful designs must be responsive to all.

Private and public benefits: The development of most bionovel technologies involves extensive research and capital investment to bring them to specialized application in restoration projects. The allure of new "miracle" devices is at least partly offset by considerations of their proprietary quality and their removal from democratic forms of regulation and decision-making (see *Governance*). There is a rich history documenting corporatization and concentration of power in the development of new technologies. One challenge here is that corporations have an obvious conflict of interest in the evaluation of their technology, and may thus not, or only partially, share critical data and information, so that an unbiased evaluation by others may not be possible (see e.g. Jeschke et al. 2019 and references therein).

Continuity is a tacit assumption in ecosystem restoration. Ecosystems change in response to environmental, ecological, and human drivers. When an ecosystem's integrity is compromised, restoration is invoked to restore its continuous, historically defined trajectory. The concept of novel ecosystems identified ruptures in this continuity that prevented the practical restoration of ecosystems that were significantly altered in composition and function. However, continuity still matters for novel ecosystems, as embedded in original formulations of the novel ecosystem concepts, which suggests novel ecosystems arise from historically continuous ones (Hobbs et al. 2009; Hallett et al. 2013). Bionovelty pushes the emergence of novelty and attendant ruptures even further, risking a nearly complete disassociation with historical continuity. Higgs et al. (2014) and others argue that historical continuity is a critical aspect of restoration despite ongoing changes in ecosystems, and continuity is both a historical fact in the sense of being a procession of patterns, compositions, and structures through time, and also the value people ascribe to the places restored.

Unintended consequences: Despite significant precautions, unintended effects on nontarget organisms (and also on human health) can be significant, including displacement, consumption, fear, competition, and host–parasite interactions. The use of biological control agents is widespread and can generate bionovelty through unintended consequences for native species (Louda et al. 2003). Genetically engineered releases via gene drives or synthetic organisms can unintentionally establish an uncontrolled population in the wild (Jeschke et al. 2013). In addition, if for example, a genetic modification spreads in the population(s) of other organisms, it can genetically and phenotypically alter these populations. In dramatic cases, resident species may be altered to the point of technical extinction, as their original genome and phenotype no longer exist. This is a more severe example of the common scenario of genetic introgression by a non-native species (e.g. ruddy duck genetic introgression amplifies threat to already endangered white-headed ducks; Muñoz-Fuentes et al. 2013).

Erosion of boundaries: In his seminal essay, Wiens (1989) argued all ecological phenomena are scale-dependent. Observations taken within a single system but at different scales reflect different realities. A particularly challenging dimension of bionovelty is common to many technological innovations: managing repercussions when the friction of space and time is erased. Novel ecological states are typically the result of erosion of temporal or spatial boundaries that hasten the adoption of a novel intervention as a putative fix. Table 2 highlights the diversity of bionovel ecologies and technological responses, a tug-of-war between the erosion and reestablishment of spatiotemporal boundaries. For instance, gene drives largely eliminate the friction of time to overcome rules of inheritance and dramatically accelerate a gene's introgression into a target population. The attraction of drone swarms is the capacity to erase both spatial and temporal friction in the dissemination of biotic materials. However, despite scaling effects being widely acknowledged as central to ecosystem function, ecologists have made little progress in reconciling this reality in their studies (Estes et al. 2018). In short, scientists and practitioners appear to lack the necessary enzymes to digest the complex effects of scale in unaltered, natural systems. Thus, removal of the structuring effects of temporal and spatial boundaries in natural systems is likely to render a serious challenge to practitioners and regulators alike, who may struggle with the immediacy and expanse of responses.

Temporal scale: The erosion of boundaries as described above highlights the need to identify appropriate temporal scales of monitoring and evaluation of ecological restoration—a long-standing important management consideration. But bionovel systems may introduce new dimensions: for example, a genetically engineered tree that might live well over 100 years creates opportunities to reimagine adaptive management and other governance principles (Barnhill-Dilling et al. 2021). How might we appropriately use resources to parse out monitoring and management considerations across the lifespan of long-lived species or across several generations of mammalian gene drives? How might these questions surrounding the appropriate temporal scale potentially invite new ways to consider reciprocal

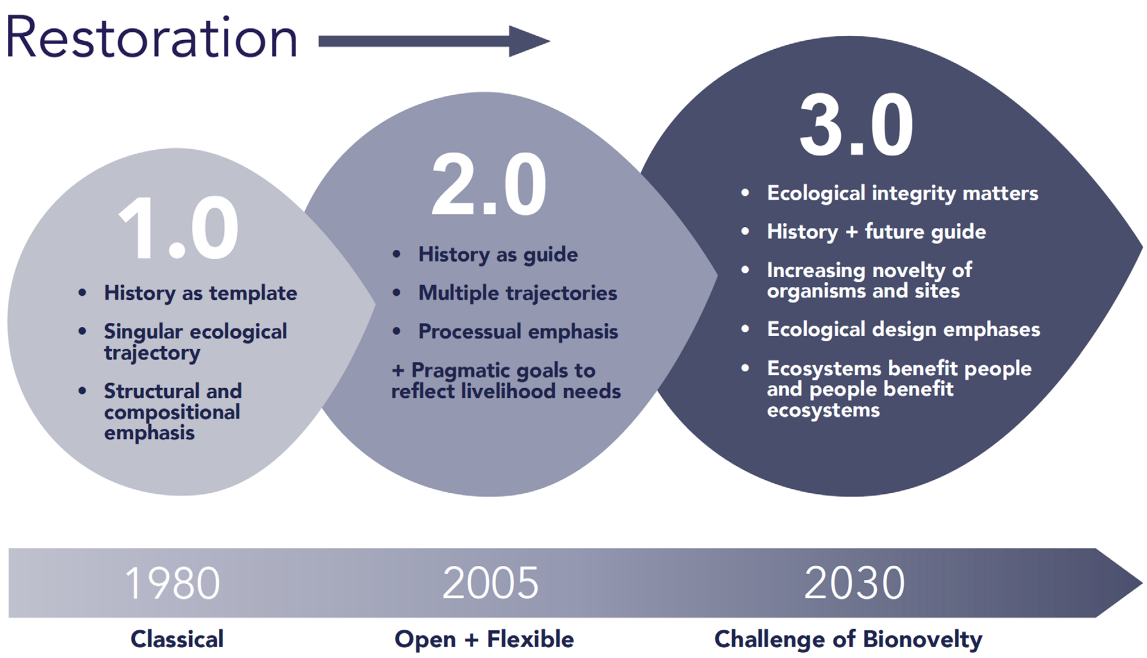

Figure 3. Bionovel ecological restoration interventions differentiated by the type of bionovelty and restoration goal. *Type of Bionovelty* identifies where an intervention manifests a bionovel reality absent an historical precedent along a gradient ranging from target ecological system to the technology itself. *Restoration Goal* differentiates those interventions aimed predominantly at restoring species occupancy and system composition versus those targeting system function(s). Interventions are shade-coded as to their derivation. Those derived from or leveraging extant biological entities and may replicate, proliferate, and adapt, potentiating unpredictable future impacts are darkly shaded whereas lighter shaded de novo interventions can be engineered to preclude autonomous replication and proliferation. Circle size reflects the magnitude of state space occupied by the intervention.

stewardship? Might ongoing systems of monitoring serve to reshape human relationships to non-human nature in ways that are more line with notions of reciprocity?

Integration of science and socio-cultural perspectives: It is increasingly acknowledged that the inclusion of sociocultural and economic perspectives is essential to restoration ecology (e.g Pfadenhauer 2001; Suding et al. 2015; Hein et al. 2019). Emerging ecological novelty might accelerate this (re-)integration of science and the perspectives of Indigenous Peoples and local communities, and wider stakeholders. People have inexorably changed the natural world and restoration of natural ecosystems may require recognizing shifting baselines of accepted standards for environmental conditions (Soga & Gaston 2018) continue to alter cultural priorities for restoration.

Keeping the focus on adaptation: When the goals of restoration extend beyond recovering degraded ecosystems to including increasing resistance to and adaptive capacity for global change (Suding et al. 2015), bionovelty provides capacity to help a system track shifting environmental conditions (Allen & Holling 2010; Dudney et al. 2018). Robust restoration approaches already include strategies that future-proof the system to regime change (e.g. reintroducing disturbance regimes or increasing habitat connectivity). In some systems, this may require focusing on strategies that build adaptive capacity rather than restoring historic states (Dudney et al. 2022). For example, introducing bionovelty (e.g. engineered species) through restoration can accelerate the rate of adaptation that may be critical for sustaining populations presently at risk of extinction (Levin et al. 2017). Facilitating ecosystem transformations towards novel states may conserve ecosystem services in otherwise highly vulnerable systems (Chapin et al. 2010; Millar & Stephenson 2015), but may also modify evolutionary pathways, trophic interactions, and ecosystem feedbacks, which can lead to undesirable outcomes that threaten ecosystem services (Chaffin et al. 2016; Newton 2016; Aplet & McKinley 2017). Careful planning and risk–benefit analyses will be critical to determine whether restoration that introduces ecological novelty can better sustain a desired ecosystem than traditional restoration approaches. Keeping the focus on the historic identity, and the structure and function of ecosystems—while also recognizing that bionovelty can be critical for adaptation—will improve restoration outcomes and help constrain the emergence of unintended consequences.

Governance: Just as bionovelty prompts us to reimagine ecological restoration, it likewise necessitates a reimagining of governance systems. A bionovel future, by definition, is one at least partially characterized by human decisions and interventions. Significant challenges await the construction of innovative governance systems that integrate scientific knowledge with a multiplicity of worldviews and values. How do we link governance processes across scales when global decisions have localized impacts, and local decisions may have global implications (Kofler et al. 2018)? How might we consider governance processes across landscapes and jurisdictions, particularly efforts that effectively include varied worldviews and sovereignty (Barnhill-Dilling et al. 2021)?

Restoration for the Future

Identifying the overlapping and cumulative opportunities and consequences of ecological novelty for ecosystem restoration is a first step toward improving outcomes for biodiversity, ecosystem services, and human communities. There is much work ahead to assess how best to accommodate bionovelty, especially in light of increasingly rapid environmental and ecological change. While individual technologies have consequences for restoration science and practice, in combination they support a pattern of intensifying human management of ecosystems, novel system states and the perceived need for increasingly technological solutions. We think such intensification will have distinct consequences for restoration, including, and not limited to, shaping the values that underpin it.

Our purpose in this article is not to recommend a particular trajectory for ecosystem restoration, but to illuminate patterns and implications brought about by myriad challenges and opportunities driven by bionovelty (Fig. 2). We propose a forward-looking version of ecological restoration that embraces whole-system integrity as a developmental stage of restoration science and practice. This version of restoration, Restoration 3.0 (Fig. 3), continues a trend to greater flexibility in setting goals for restoration, while holding tenaciously to commitments to ecological integrity in the face of rapid change. We intend this not as a capitulation to bionovelty, but as a call for greater attention to, and clarity about, emerging bionovelty. A forward-looking version of ecosystem restoration embraces whole-system integrity as a developmental stage of restoration science and practice.

Acknowledgments

This work was made possible by a grant from Genome British Columbia's *Genomics in Society Interdisciplinary Research Teams* (GiSIRT) program, which sponsored authors to meet in Vancouver on 15–17 April 2019. We wish to thank Kate Harland and Ana Cienega of Genome BC for their vision and support through this process.

LITERATURE CITED

Albano PG, Steger J, Bošnjak M, Dunne B, Guifarro Z, Turapova E, Hua Q, Kaufman DS, Rilov G, Zuschin M (2021) Native biodiversity collapse in the eastern Mediterranean. Proceedings of the Royal Society B: Biological Sciences 288:20202469. https://doi.org/10.1098/rspb.2020.2469

Allen CR, Holling CS (2010) Novelty, adaptive capacity, and resilience. Ecology and Society 15:15. https://doi.org/10.5751/ES-03720-150324

Alphey L (2014) Genetic control of mosquitoes. Annual Review of Entomology 59:205–224. https://doi.org/10.1146/annurev-ento-011613-162002

Aplet GH, Mckinley PS (2017) A portfolio approach to managing ecological risks of global change. Ecosystem Health and Sustainability 3:15. https://doi.org/10.1002/ehs2.1261

Barnhill-Dilling SK, Kokotovich A, Delborne JA (2021) The decision phases framework for public engagement: engaging stakeholders about gene editing in the wild. Hastings Center Report 51:S48–S61. https://doi.org/10.1002/hast.1320

Beller EE, Spotswood EN, Robinson AH, Anderson MG, Higgs ES, Hobbs RJ, Suding KN, Zavaleta ES, Grenier JL, Grossinger RM (2019) Building ecological resilience in highly modified landscapes. Bioscience 69:80–92. https://doi.org/10.1093/biosci/biy117

Beller EE, Mcclenachan L, Zavaleta ES, Larsen LG (2020) Past forward: recommendations from historical ecology for ecosystem management. Global Ecology and Conservation 21:e00836. https://doi.org/10.1016/j.gecco.2019.e00836

Bloom Inc (n.d.) More algae less oil! https://www.bloommaterials.com/ (accessed 22 Mar 2024)

Boivin NL, Zeder MA, Fuller DQ, Crowther A, Larson G, Erlandson JM, Denham T, Petraglia MD (2016) Ecological consequences of human niche construction: examining long-term anthropogenic shaping of global species distributions. Proceedings of the National Academy of Sciences of the United States of America 113:6388–6396. https://doi.org/10.1073/pnas.1525200113

Bolt Inc (n.d.) Meet Mylo™. https://boltthreads.com/technology/mylo/ (accessed March 22 2024)

Borgmann A (1984) Technology and the character of contemporary life: a philosophical inquiry. University of Chicago Press, Chicago

Cantrell B, Martin LJ, Ellis EC (2017) Designing autonomy: opportunities for new wildness in the Anthropocene. Trends in Ecology & Evolution 32:156–166. https://doi.org/10.1016/j.tree.2016.12.004

Carver S, Convery I, Hawkins S, Beyers R, Eagle A, Kun Z, et al. (2021) Guiding principles for rewilding. Conservation Biology 35:1882–1893. https://doi.org/10.1111/cobi.13730

Chaffin BC, Garmestani AS, Angeler DG, Herrmann DL, Stow CA, Nystrom M, Sendzimir J, Hopton ME, Kolasa J, Allen CR (2016) Biological invasions, ecological resilience and adaptive governance. Journal of Environmental Management 183:399–407. https://doi.org/10.1016/j.jenvman.2016.04.040

Chapin FS, Carpenter SR, Kofinas GP, Folke C, Abel N, Clark WC, et al. (2010) Ecosystem stewardship: sustainability strategies for a rapidly changing planet. Trends in Ecology & Evolution 25:241–249. https://doi.org/10.1016/j.tree.2009.10.008

Corlett RT (2015) The Anthropocene concept in ecology and conservation. Trends in Ecology & Evolution (Amsterdam) 30:36–41. https://doi.org/10.1016/j.tree.2014.10.007

Cowie AL, Orr BJ, Sanchez VMC, Chasek P, Crossman ND, Erlewein A, et al. (2018) Land in balance: the scientific conceptual framework for land degradation neutrality. Environmental Science & Policy 79:25–35. https://doi.org/10.1016/j.envsci.2017.10.011

Deary H (2015) Restoring wildness to the Scottish highlands. In: Hourdequin M, Havlick DG (eds) Restoring layered landscapes: history, ecology, and culture. Oxford University Press, Oxford, UK. https://doi.org/10.1093/acprof:oso/9780190240318.003.0006

Dudney J, Hobbs RJ, Heilmayr R, Battles JJ, Suding KN (2018) Navigating novelty and risk in resilience management. Trends in Ecology & Evolution 33:863–873. https://doi.org/10.1016/j.tree.2018.08.012

Dudney J, D'antonio C, Hobbs RJ, Shackelford N, Standish RJ, Suding KN (2022) Capacity for change: three core attributes of adaptive capacity that bolster restoration efficacy. Restoration Ecology 9. https://doi.org/10.1111/rec.13647

Elliott S (2016) The potential for automating assisted natural regeneration of tropical forest ecosystems. Biotropica 48:825–833. https://doi.org/10.1111/btp.12387

Espinosa MJC, Blanco AC, Schmidgall T, Atanasoff-Kardjalieff AK, Kappelmeyer U, Tischler D, Pieper DH, Heipieper HJ, Eberlein C (2020) Toward biorecycling: isolation of a soil bacterium that grows on a polyurethane oligomer and monomer. Frontiers in Microbiology 11:9. https://doi.org/10.3389/fmicb.2020.00404

Estes L, Elsen PR, Treuer T, Ahmed L, Caylor K, Chang J, Choi JJ, Ellis EC (2018) The spatial and temporal domains of modern ecology. Nature Ecology & Evolution 2:819–826. https://doi.org/10.1038/s41559-018-0524-4

Fei SL, Phillips J, Shouse M (2014) Biogeomorphic impacts of invasive species. Annual Review of Ecology, Evolution, and Systematics 45:69–87. https://doi.org/10.1146/annurev-ecolsys-120213-091928

Fischer J, Riechers M, Loos J, Martin-Lopez B, Temperton VM (2021) Making the UN decade on ecosystem restoration a social-ecological endeavour. Trends in Ecology and Evolution 36:20–28. https://doi.org/10.1016/j.tree.2020.08.018

Fredens J, Wang KH, De La Torre D, Funke LFH, Robertson WE, Christova Y, et al. (2019) Total synthesis of Escherichia coli with a recoded genome. Nature 569:514–518. https://doi.org/10.1038/s41586-019-1192-5

Hallett LM, Standish RJ, Hulvey KB, Gardener MR, Suding KN, Starzomski BM, Murphy SD, Harris JA (2013) Towards a conceptual framework for novel ecosystems. Pages 16–28. In: Hobbs RJ, Higgs ES, Hall CM (eds) Novel ecosystems: intervening in the new ecological world order. John Wiley & Sons, Ltd, Chilchester, UK. https://doi.org/10.1002/9781118354186.ch3

Harris JA, Hobbs RJ, Higgs E, Aronson J (2006) Ecological restoration and global climate change. Restoration Ecology 14:170–176. https://doi.org/10.1111/j.1526-100X.2006.00136.x

Heger T, Bernard-Verdier M, Gessler A, Greenwood AD, Grossart HP, Hilker M, et al. (2019) Towards an integrative, eco-evolutionary understanding of ecological novelty: studying and communicating interlinked effects of global change. Bioscience 69:888–899. https://doi.org/10.1093/biosci/biz095

Hein MY, Birtles A, Willis BL, Gardiner N, Beeden R, Marshall NA (2019) Coral restoration: socio-ecological perspectives of benefits and limitations. Biological Conservation 229:14–25. https://doi.org/10.1016/j.biocon.2018.11.014

Higgs E (2003) Pages 1–341. Nature by design: people, natural process, and ecological restoration. The MIT Press, Cambridge, MA

Higgs E (2017) Novel and designed ecosystems. Restoration Ecology 25:8–13. https://doi.org/10.1111/rec.12410

Higgs E, Falk DA, Guerrini A, Hall M, Harris J, Hobbs RJ, Jackson ST, Rhemtulla JM, Throop W (2014) The changing role of history in restoration ecology. Frontiers in Ecology and the Environment 12:499–506. https://doi.org/10.1890/110267

Hobbs RJ, Higgs E, Harris JA (2009) Novel ecosystems: implications for conservation and restoration. Trends in Ecology & Evolution 24:599–605. https://doi.org/10.1016/j.tree.2009.05.012

Hobbs RJ, Higgs E, Hall CM (2013) Novel ecosystems: intervening in the new ecological world order. Wiley-Blackwell, Chichester, West Sussex. https://doi.org/10.1002/9781118354186

Hobbs RJ, Higgs E, Hall CM, Bridgewater P, Chapin FS, Ellis EC, et al. (2014) Managing the whole landscape: historical, hybrid, and novel ecosystems. Frontiers in Ecology and the Environment 12:557–564. https://doi.org/10.1890/130300

Hoffmann AA, Sgrò CM (2011) Climate change and evolutionary adaptation. Nature 470:479–485. https://doi.org/10.1038/nature09670

IUCN (2013) Guidelines for Reintroductions and Other Conservation Translocations. Version 1.0., Gland, Switzerland

Jeschke JM, Keesing F, Ostfeld RS (2013) Novel organisms: comparing invasive species, GMOs, and emerging pathogens. Ambio 42:541–548. https://doi.org/10.1007/s13280-013-0387-5

Jeschke JM, Lokatis S, Bartram I, Tockner K (2019) Knowledge in the dark: scientific challenges and ways forward. Facets 4:423–441. https://doi.org/10.1139/facets-2019-0007

Kofler N, Collins JP, Kuzma J, Marris E, Esvelt K, Nelson MP, et al. (2018) Editing nature: local roots of global governance environmental gene editing demands collective oversight. Science 362:527–529. https://doi.org/10.1126/science.aat4612

Kreyling J, Tanneberger F, Jansen F, Van Der Linden S, Aggenbach C, Blüml V, et al. (2021) Rewetting does not return drained fen peatlands to their old selves. Nature Communications 12:5693. https://doi.org/10.1038/s41467-021-25619-y

Kriegmana S, Blackiston D, Levin M, Bongard J (2020) A scalable pipeline for designing reconfigurable organisms. Proceedings of the National Academy of Sciences of the United States of America 117:1853–1859. https://doi.org/10.1073/pnas.1910837117

Kueffer C (2017) Plant invasions in the Anthropocene. Science 358:724–725. https://doi.org/10.1126/science.aao6371

Latour B (2005) Reassembling the social an introduction to actor-network-theory. Oxford University Press, Oxford. https://doi.org/10.1093/oso/9780199256044.001.0001

Lee ATK, Carr JA, Ahmad B, Arbainsyah FA, Handoko Y, Harsono R, et al. (2019) Reforesting for the climate of tomorrow: Recommendations for strengthening orangutan conservation and climate change resilience in Kutai National Park, Indonesia. IUCN, Gland, Switzerland

Levin RA, Voolstra CR, Agrawal S, Steinberg PD, Suggett DJ, Van Oppen MJH (2017) Engineering strategies to decode and enhance the genomes of coral symbionts. Frontiers in Microbiology 8:11. https://doi.org/10.3389/fmicb.2017.01220

Louda SM, Pemberton RW, Johnson MT, Follett PA (2003) Nontarget effects - the Achilles' heel of biological control? Retrospective analyses to reduce risk associated with biocontrol introductions. Annual Review of Entomology 48:365–396. https://doi.org/10.1146/annurev.ento.48.060402.102800

Macfarlane NBW, Adams J, Bennett EL, Brooks TM, Delborne JA, Eggermont H, et al. (2022) Direct and indirect impacts of synthetic biology on biodiversity conservation. iScience 25:105423. https://doi.org/10.1016/j.isci.2022.105423

Martin LJ (2022) Wild by design: the rise of ecological restoration. Harvard University Press, Cambridge, Massachusetts

Millar CI, Stephenson NL (2015) Temperate forest health in an era of emerging megadisturbance. Science 349:823–826. https://doi.org/10.1126/science.aaa9933

Muñoz-Fuentes V, Green AJ, Negro JJ (2013) Genetic studies facilitated management decisions on the invasion of the ruddy duck in Europe. Biological Invasions 15:723–728. https://doi.org/10.1007/s10530-012-0331-9

Murcia C, Aronson J, Kattan GH, Moreno-Mateos D, Dixon K, Simberloff D (2014) A critique of the 'novel ecosystem' concept. Trends in Ecology & Evolution 29:548–553. https://doi.org/10.1016/j.tree.2014.07.006

Murphy SD (2018) Restoration Ecology's silver Jubilee: meeting the challenges and forging opportunities. Restoration Ecology 26:3–4. https://doi.org/10.1111/rec.12659

Newton AC (2016) Biodiversity risks of adopting resilience as a policy goal. Conservation Letters 9:369–376. https://doi.org/10.1111/conl.12227

Noble C, Min J, Olejarz J, Buchthal J, Chavez A, Smidler AL, Debenedictis EA, Church GM, Nowak MA, Esvelt KM (2019) Daisy-chain gene drives for the alteration of local populations. Proceedings of the National Academy of Sciences of the United States of America 116:8275–8282. https://doi.org/10.1073/pnas.1716358116

Oliver TH, Heard MS, Isaac NJB, Roy DB, Procter D, Eigenbrod F, et al. (2015) Biodiversity and resilience of ecosystem functions. Trends in Ecology & Evolution 30:673–684. https://doi.org/10.1016/j.tree.2015.08.009

Peplow M (2016) Synthetic biology's first malaria drug meets market resistance. Nature 530:389–390. https://doi.org/10.1038/530390a

Perino A, Pereira HM, Navarro LM, Fernández N, Bullock JM, Ceauşu S, et al. (2019) Rewilding complex ecosystems. Science 364:351. https://doi.org/10.1126/science.aav5570

Perring MP, Ellis EC (2013) The extent of novel ecosystems: long in time and broad in space. Pages 66–80. In: Hobbs RJ, Higgs ES, Hall CM (eds) Novel ecosystems: intervening in the new ecological world order. Wiley-Blackwell, Newark

Pfadenhauer J (2001) Some remarks on the socio-cultural background of restoration ecology. Restoration Ecology 9:220–229. https://doi.org/10.1046/j.1526-100x.2001.009002220.x

Piaggio AJ, Segelbacher G, Seddon PJ, Alphey L, Bennett EL, Carlson RH, et al. (2017) Is it time for synthetic biodiversity conservation? Trends in Ecology & Evolution 32:97–107. https://doi.org/10.1016/j.tree.2016.10.016

Pinek L, Mansour I, Lakovic M, Ryo M, Rillig MC (2020) Rate of environmental change across scales in ecology. Biological Reviews 95:1798–1811. https://doi.org/10.1111/brv.12639

Ricciardi A, Blackburn TM, Carlton JT, Dick JTA, Hulme PE, Iacarella JC, et al. (2017) Invasion science: a horizon scan of emerging challenges and opportunities. Trends in Ecology & Evolution 32:464–474. https://doi.org/10.1016/j.tree.2017.03.007

Richardson K, Steffen W, Lucht W, Bendtsen J, Cornell SE, Donges JF, et al. (2023) Earth beyond six of nine planetary boundaries. Science. Advances 9:eadh2458. https://doi.org/10.1126/sciadv.adh2458

Roy HE, Pauchard A, Stoett P, Renard Truong T, Bacher S, Galil BS, et al. (2024) IPBES invasive alien species assessment: Summary for policymakers. IPBES Secretariat, Bonn, Germany. https://doi.org/10.5281/zenodo.7430692

Sanchez-Vidal A, Canals M, De Haan WP, Romero J, Veny M (2021) Seagrasses provide a novel ecosystem service by trapping marine plastics. Scientific Reports 11:254. https://doi.org/10.1038/s41598-020-79370-3

Sarrazin F, Lecomte J (2016) Evolution in the Anthropocene. Science 351:922–923. https://doi.org/10.1126/science.aad6756

Seddon PJ (2017) De-extinction and barriers to the application of new conservation tools. Hastings Center Report 47:S5–S8. https://doi.org/10.1002/hast.745

Seddon PJ, King M (2019) Creating proxies of extinct species: the bioethics of de-extinction. Emerging Topics in Life Sciences 3:731–735. https://doi.org/10.1042/ETLS20190109

Seddon PJ, Moro D, Mitchell NJ, Chauvenet LM, Mawson PR (2015) Proactive conservation or planned invasion? Past, current and future use of assisted colonisation. Pages 320. In: Armstrong D, Hayward M, Moro D, Seddon PJ (eds) Advances in reintroduction biology of Australian and New Zealand Fauna. CSIRO Publishing, Canberra, Australia

Serr ME, Valdez RX, Barnhill-Dilling KS, Godwin J, Kuiken T, Booker M (2020) Scenario analysis on the use of rodenticides and sex-biasing gene drives for the removal of invasive house mice on islands. Biological Invasions 22:1235–1248. https://doi.org/10.1007/s10530-019-02192-6

Soga M, Gaston KJ (2018) Shifting baseline syndrome: causes, consequences, and implications. Frontiers in Ecology and the Environment 16:222–230. https://doi.org/10.1002/fee.1794

Standish RJ, Thompson A, Higgs ES, Murphy SD (2013) Concerns about novel ecosystems. Pages 296–309. In: Hobbs RJ, Higgs ES, Hall CM (eds) Novel ecosystems: intervening in the new ecological world order. Wiley-Blackwell, Newark

Steffen W, Broadgate W, Deutsch L, Gaffney O, Ludwig C (2015) The trajectory of the Anthropocene: the Great Acceleration. The Anthropocene Review 2: 81–98. https://doi.org/10.1177/2053019614564785

Steiner KC, Westbrook JW, Hebard FV, Georgi LL, Powell WA, Fitzsimmons SF (2017) Rescue of American chestnut with extraspecific genes following its destruction by a naturalized pathogen. New Forests 48:317–336. https://doi.org/10.1007/s11056-016-9561-5

Suding K, Higgs E, Palmer M, Callicott JB, Anderson CB, Baker M, et al. (2015) Committing to ecological restoration. Science 348:638–640. https://doi.org/10.1126/science.aaa4216

Synodinos AD, Karnatak R, Aguilar-Trigueros CA, Gras P, Heger T, Ionescu D, et al. (2023) The rate of environmental change as an important driver across scales in ecology. Oikos 2023:11. https://doi.org/10.1111/oik.09616

Temmink RJM, Christianen MJA, Fivash GS, Angelini C, Bostrom C, Didderen K, et al. (2020) Mimicry of emergent traits amplifies coastal restoration success. Nature Communications 11:3668. https://doi.org/10.1038/s41467-020-17438-4

Truitt AM, Granek EF, Duveneck MJ, Goldsmith KA, Jordan MP, Yazzie KC (2015) What is novel about novel ecosystems: managing change in an ever-changing world. Environmental Management 55:1217–1226. https://doi.org/10.1007/s00267-015-0465-5

Wehi PM, Lord JM (2017) Importance of including cultural practices in ecological restoration. Conservation Biology 31:1109–1118. https://doi.org/10.1111/cobi.12915

Wiens JA (1989) Spatial scaling in ecology. Functional Ecology 3:385–397. https://doi.org/10.2307/2389612

Williams JW, Jackson ST (2007) Novel climates, no-analog communities, and ecological surprises. Frontiers in Ecology and the Environment 5:475–482. https://doi.org/10.1890/070037

Windbichler N, Menichelli M, Papathanos PA, Thyme SB, Li H, Ulge UY, et al. (2011) A synthetic homing endonuclease-based gene drive system in the human malaria mosquito. Nature 473:212–215. https://doi.org/10.1038/nature09937

Yoon JE, Yoo KC, Macdonald AM, Yoon HI, Park KT, Yang EJ, et al. (2018) Reviews and syntheses: ocean iron fertilization experiments—Past, present, and future looking to a future Korean Iron Fertilization Experiment in the Southern Ocean (KIFES) project. Biogeosciences 15:5847–5889. https://doi.org/10.5194/bg-15-5847-2018

Zimov SA, Zimov NS, Chapin Iii FS (2012) The past and future of the mammoth steppe ecosystem. In: Louys J (ed) Paleontology in ecology and conservation. Springer-Verlag, Berlin. https://doi.org/10.1007/978-3-642-25038-5_10

Coordinating Editor: Henny Van der Windt

Received: 24 April, 2023; First decision: 23 August, 2023; Revised: 22 March, 2024; Accepted: 26 March, 2024