Manipulating Time by Cryopreservation: Designing an Environmental Future by Maintaining a Portal to the Past

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Abstract: This article explores how time-related metaphors frame advanced cryopreservation technologies in environmental conservation. Cryopreservation "stops" or "freezes" biological time and "buys time" desperately needed to preserve species and ecosystems. We advance a framing of these technologies as logistical, highlighting how they create opportunities to shift materials, knowledge, and decision-making power through space and time. As logistical technologies, advanced cryopreservation techniques require active planning in the present rather than deferring responsibility and accountability to the future.

Introduction

Engineers working to develop methods of advanced cryopreservation often describe their work as "stopping the biological clock"[1] and "freezing biological time."[2] Applied to a wide variety of biological materials, including tissues, organs, gametes, embryos, and organisms, the cooling and warming techniques under development aim to use "extreme cold to slow or even halt the decay that is the usual fate of all living things."[3] Advanced cryopreservation technologies can improve and extend the ability to store and transport biological materials for many purposes, including organ transplantation and various biomedical uses, food system applications, aquaculture, biological research, and environmental conservation.

When we consider the profound and rapid global alterations being induced by human activities, including climate change, the significance of advanced cryopreservation technologies becomes more immediate and imperative. This article explores how metaphors that are used to explain advanced cryopreservation

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technologies in terms of pausing or stopping biological time or traveling through time illuminate opportunities and hazards in the domain of environmental conservation. In contrast with other evaluations of cryotechnologies as warping biological essences, we frame the nature of these technologies as logistical, not existential. Value-based decisions arise as we consider how to manage the logistics of interventions that might address future problems such as biodiversity collapse. By framing them in this way, we aim to direct attention to aspects of conservation that require planned coordination on a variety of timescales, from those that are intuitive in the human experience (days, weeks, and months) to those that are longer than the human lifespan and therefore require imaginative speculation.

An Accelerating Crisis

There is strong evidence that we are on the brink of major biodiversity loss, manifest in an increasing rate of species extinction and declining plant and animal populations overall.[4] According to one report, global vertebrate populations have declined 68% since 1970.[5] The rate of species extinction appears to be accelerating, and as more species become regionally extinct, ecosystems grow less stable, driving an acceleration in biodiversity loss and making recovery to prior abundance less likely and slower if it occurs at all.[6] More complex models that take interconnectivity among systems into account show a higher likelihood that thresholds for collapse will be crossed more quickly.[7] The speed of change is much more rapid than can be met by evolutionary adaptation, and for some species and ecosystems, biodiversity loss is readily apparent. For example, the first recorded mass coral bleaching event occurred in 1998, but subsequent change has been so rapid that by 2021 about half of the world's coral reefs were degraded. By 2030, coral bleaching is expected to be a regular occurrence, and without significant improvement, living coral reefs will be rare or non-existent by 2100.[8]

The harms that can result from biodiversity loss are apparent. Like many — probably most — environmental ethicists and conservationists, we believe that healthy and resilient ecosystems have intrinsic value in addition to supporting human well-being.[9] The predominant drivers of biodiversity loss are well known and include anthropogenic climate change, loss of habitat to development and extractive industries, pollution, and overharvesting of fisheries and other natural resources. Conservation activities are unlikely to succeed in the long run without curbing the impact of these drivers. However, even optimistic timeframes for mitigating climate change and addressing the social, economic, and cultural drivers of biodiversity loss are too long to prevent further extinctions. This leads conservationists to ask: How can we buy more time?

How quickly will species and ecosystems decline as a result of the combined assaults of climate change, introduction of non-native species, pollution, and development? How soon will the rate of climate change slow, level off, or even reverse? How quickly can humans learn to support natural processes to buffer or reverse the effects of anthropogenic assaults?

How quickly will species and ecosystems decline as a result of the combined assaults of climate change, introduction of non-native species, pollution, and development? How soon will the rate of climate change slow, level off, or even reverse? How quickly can humans learn to support natural processes to buffer or reverse the effects of anthropogenic assaults? Conservation scientists do not know the answers. The decline of coral reefs, for instance, has happened much more quickly than was predicted thirty years ago, creating a "shifting baseline syndrome," in which what seemed like severe damage thirty years ago is now judged as only moderate damage relative to current expectations.[10] Even if we had perfect knowledge, disagreements would likely remain about which entities and strategies to prioritize. The goal of this article is not to settle questions about conservation priorities but rather to examine how advanced cryopreservation technologies might function together with other biotechnologies and ecological management strategies to conceptualize time for the sake of a coordinated conservation response.

Banking on the Future

Diverse biological materials can be cryopreserved indefinitely ("banked") in tanks cooled with liquid

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nitrogen at a temperature so low that metabolic activity ceases (–150 to –196 °C). Cryopreserved materials are considered viable if it is possible to avoid irrecoverable damage on returning them to a temperature at which normal biological function resumes. Although human gametes and embryos are routinely cryopreserved to secure fertility options for use in IVF, this is not currently possible for all mammals, much less all lifeforms. *Advanced* cryopreservation techniques — those under development now and in the near future — will expand the types of materials that can be cryopreserved through special treatment before cooling and during warming.[11] Such methods may be complemented by parallel efforts in the development of other forms of biopreservation such as lyophilization (freeze-drying by manipulation of temperature and pressure), which enables the long-term storage of biomaterials at or near room temperature.[12]

The engineering goals that cryopreservation researchers are working toward have relevance for conservation. One goal is to increase the size of materials that can be cryopreserved. Just as the ability to cryopreserve organs would transform organ transplantation, the ability to cryopreserve complex organisms, such as adult coral polyps, could transform conservation activities. Another goal is to standardize and routinize cryopreservation techniques for complex tissues. Biomaterials respond differently to cryopreservation, and the protocols that work for a certain cell type in one species may not work for a different species, even if they are closely related or have a similar morphology. For example, the protocol for cryopreserving plant shoot tips in one species is not necessarily successful in related species or even in different genotypes of the same species.[13] Currently, development of individualized protocols for different tissues and different species by multiple, often competing, research groups is unnecessarily slow, labor intensive, and repetitive. Advances in developing platform-based, standardized cryopreservation technologies will streamline the experimentation required to preserve each new sample type and species and will simplify the labor involved in training technicians, sharing knowledge between sites, and building cryopreservation infrastructure. Work with the axolotl, a critically endangered salamander, provides an example of bench-scale research designed to be scalable to high-throughput application using an approach from industrial engineering (process mapping) that provides a common workspace for community interaction and standardization, while also enabling generalization of the approach to benefit other species.[14] Development of new forms of community-focused research will expand the menu of tools and opportunities for cooperation that can be made available for conservation interventions.[15]

Biobanks are important resources for conservation. They store a wide variety of collections that serve many purposes in biomedical, food system, and environmental research. Samples have been collected from many taxa, encompassing diverse sample types such as DNA, cell cultures, tissues, and whole specimens. Cryopreserved samples are an important source of genomic information that can be used to study the genetic diversity of populations and to answer biological and ecological questions. The data associated with samples are equally important to the function and utility of a repository: collection conditions, preservation protocol, sample identity, and other data must be as rigorously collected, structured, stored, and protected as the samples themselves.[16] In some cases, stored samples can be studied with no intention of returning them to normal biological function. However, when cryopreservation technologies are described as "stopping biological time" or "freezing time," this metaphor suggests a return to metabolic function and viability, and thus carries the implication of travel through space and time.

Biodiversity repositories have existed for decades — in 1975, the San Diego Zoo established the Frozen Zoo. Early collections of frozen somatic cells were established to support the study of cytogenetics, as well as other areas of biological investigation, such as cell research and aging. Their utility for supporting a wide variety of research areas, as well as conservation activities, has expanded well beyond those early expectations. For example, in 2020, a cloned black-footed ferret, Elizabeth Ann, was born to a domesticated mother ferret that had been implanted with an embryo derived from a somatic cell line cryopreserved in 1988.[17] Conservationists hope that she will serve in a captive breeding program to increase the genetic diversity of black-footed ferrets for eventual reintroduction to the wild.

News stories about Elizabeth Ann emphasize the gee-whiz factor and techno-futurist narrative describing how her parent cell line was banked almost a decade before the first confirmed mammal clone through somatic cell nuclear transfer.[18] Oliver Ryder, then director of the Frozen Zoo, tells the story in a way that expresses not only hope but also a charge from the thrill of serendipity: "Famously, there was a poster that hung above the Frozen Zoo with a quote that said, 'You must collect things for reasons you don't yet understand.' ... We felt that we were stewards of this growing collection that was going to have value to the future in ways we weren't able to appreciate then."[19]

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However, there were good reasons at the time to generate and preserve the cell line. By the late 1980s, it seemed possible that techniques could be developed to obtain cellular constituents, such as enzymes and DNA, from cell cultures in a fresh state. Uses of cell cultures in assisted reproduction and cloning were in the realm of speculation; they could be seen on the horizon, even if they were not routine at the time. Both then and now, the details and timing of future biotechnologies may remain unknown although plausible strategies and the general direction of development are intelligible. In exaggerating the unknowability of the future and our dependence on serendipity, we risk failing to anticipate and prepare for possibilities we can foresee even if they are not yet available. Biobanks continue to offer the possibility of unanticipated, novel, and exciting future applications, but they also offer the possibility of preparing for improvement to conservation and manipulation techniques, which in turn can greatly increase the value of collections. Because collection and preparation of specimens, metadata management, and liquid nitrogen storage are costly, the expansion and coordination of biobanking activities raise questions about prioritization that may not be judiciously addressed if informed planning in the present is neglected in favor of ill-defined hopes for the future.

Stopping Time?

Scholars critical of cryopreservation also embrace the metaphor of "stopping biological time" used by engineers to describe low temperature storage. Environmental humanities scholar Matthew Chrulew expresses fatalism as a response to how biodiversity repositories halt biological processes, both metabolic and evolutionary. In examining the role that biobanks play in the politics of zoos, aquaria, and conservation initiatives, Chrulew finds that "cryobanking is a practice of *suspension* that freezes genetic information and its vital potentiality in order to secure life against the political and environmental vagaries of living itself."[20] According to this critical view, the materials stored in a biobank are not exactly dead, and neither are they discarded; instead, they are suspended in time and stuck in place, going nowhere. The metaphor of "stopping" time creates this impression, while a conceptual framework that emphasizes change, movement, and the resumption of a cell's capacity to divide shifts our focus to the research and environmental changes that banking cells supports.

When bioengineers describe the capability of cryopreservation to pause metabolic activity and decay, they often describe this as the ability to keep samples "cryopreserved indefinitely."[21] In Chrulew's description, the banked materials are disconnected from a sense of purpose, as though the end of biobanks is long-term storage, a purpose unto itself. We can call on abundant images of library and museum collections to enhance this depiction: musty books in closed stacks that are not accessible to the public and trays of hundreds of thousands of colorful but empty bird skins in natural history museums. Although such natural history collections are useful for many forms of historical and biological research, they are also blemished by the suspicion that, at least in some instances, collectors themselves hastened the demise of the populations they admired.[22] If the main purpose of biodiversity banks is to store materials for the sake of future curiosity or merely to learn about these species after they are gone, then banks have a funereal air. Without connecting biobanks to ecological research and to conservation action, the value of samples seems to be merely that they would allow future people to more accurately measure the scale of biodiversity loss. It encourages us to think of cryopreserved samples as having retrospective value, as a lens into the past. Collections that promote understanding of the past are valuable, but the value of biobanked collections is much higher when we consider how they can also be a source of knowledge about current species and ecosystems and a source of genetic material for future management actions. The metaphorical language we use to describe the opportunities afforded by biobanks might instead invite us to imagine benefitting the future, generations of humans from now.

As we've seen, the description of cryopreservation as "stopping time" is usually taken to mean that metabolic processes in a sample have been halted but could resume. We observe also that the phrase could refer to how indefinitely banked samples, through advanced cryopreservation, might become out of step with their conspecifics. Some threatened species collected now will go extinct, and others that adapt to rapid environmental change may be different in a century. Biobanks would thus prevent extinction in only a technical, reduced sense. They could preserve genetic resources for study, and perhaps we could learn more about remaining species and how to steward them, but they would not help to address the biodiversity crisis directly — through conservation of organisms, populations, species, and ecological communities. Banked cells of species that no longer exist in the wild could not reproduce without human intervention and therefore could not naturally evolve. Thus, biobanks could be responsible for the production of "evolutionarily torpid" species, those that are not extinct, but for

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which evolutionary time has stopped temporarily.[23] They will have lost their connections to mates, descendants, conspecifics, food webs, and natural processes.

However, this is an impoverished description of the role that biobanks play in the context of conservation interventions. Rather than separating samples from the ecological complexity of the natural world, why not think of cryopreservation and biobanks as building connections? They can contribute logistical support for conservation and thereby enable effective actions to slow, prevent, and reverse biodiversity loss. Next, we consider metaphors of time travel to highlight how advanced cryopreservation technologies shift decision-making and advance planning capabilities at the same time that they permit managing and moving biomaterials.

Traveling: Cryopreservation as Managing the Logistics of Time and Space

The primary goal of conservation biodiversity banking is to collect biomaterials for conservation science and practice. Conservation is a mission-oriented science, and the mission was famously identified by Michael Soulé, one of the field's founders, as providing "principles and tools for preserving biodiversity."[24] Conservation biology was formed as a "crisis science" with a commitment to acting in good faith on the basis of the best scientific evidence without waiting for certainty to emerge when waiting would require sacrificing the mission. Indeed, Soulé envisioned a future of human population growth and development that would deplete so many wild populations and species that cryopreservation and biobanking would be needed to maintain the genetic diversity required for captive breeding programs to restore ecosystems over a period of centuries.[25]

There is an inevitable tension between the swift pace of conservation action required to meet the biodiversity crisis head-on and the slow pace at which the emergence of scientific consensus can satisfy the precautionary principle.[26] In order to maintain a pace that is effective at countering biodiversity decline, newly developed tools, techniques, and strategies must be presented for community debate and inspection and aligned with regulatory mechanisms, oftentimes before there is irrefutable proof of efficacy. Because there is a tension between the proactivity needed and the precaution that is desirable, tools and techniques that enable monitoring, forecasting, and learning from global conservation practice are as essential as other technologies.[27]

Advanced cryopreservation and the suite of novel conservation interventions it supports are currently at the stage where they are being tested by the conservation community for efficacy and ethical merit. There have been a few successes in cloning endangered species, as well as achievements in population reintroduction and translocation. Standardizing, routinizing, and generalizing cryopreservation technologies will support scaling up diverse conservation activities, expanding them from a handful of cost-intensive one-offs to a comprehensive toolbox from which conservation practitioners can pick an appropriate tool or technique to address a conservation problem.

Let us consider again the basic premise that cryopreservation enables travel through time and space. First, through time: While cryopreserved, a sample remains static while the world around it changes. Conservationists are focused on how it is possible to store something now so that in the future we can reach back in time to find essential material resources or discover knowledge. Far from representing isolation, separation, interruption, or stoppage, this capability can provide connection, coordination, continuation, and sharing. It challenges us to build out protocols and infrastructure to make use of cryopreserved materials even before we are fully aware of the nature and scale of future needs and opportunities. In accepting this challenge, we can shape those opportunities.

Second, through space: Resources can be shared among geographically separated laboratories, breeding facilities, and restoration sites. For example, a mammalian embryo developed as a result of in vitro fertilization or cloning in one place can be thawed and placed within a womb in a different place to resume development until parturition and subsequent development. Advanced cryopreservation technologies can also simplify the movement of aquatic organisms. These normally require transport and husbandry in water, which is heavy and bulky to move from place to place. Consider frozen oyster larvae, which on thawing can continue to develop and live unassisted in a new place or time. Though not widely accessible with current technologies, advanced cryotechnologies could make ex situ breeding and transport cost-effective to scale up; advanced cryopreservation facilities could become essential for large-scale restoration of aquatic ecosystems.

Coral reefs are particularly under threat and comprise an ecosystem where conservationists are exploring many protection and management strategies, including coral gardening, larval enhancement, translocation, hybridization, and genetic engineering.[28] The role of cryopreservation for coral reef restoration could be transformative by providing support for scaling up restoration efforts that include any of these

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novel techniques. Most of these plans will assist coral in building new community connections by moving organisms or genes from one place to another or one time to another, including the photosynthetic symbiotic algae that reside within coral cells. Organisms will travel through laboratories, tanks, or gardens on their way to sites where they can be offered better protection or where they can resume natural processes that had been interrupted by climate change, pollution, and other anthropogenic harms.

Some restoration scenarios include translocating coral varieties with genotypes adapted to warmer waters to places that are experiencing rises in temperature. More advanced cryotechnologies could provide options to move them more efficiently, whether as gametes, larvae, or adult polyps. Coral scientists are also experimenting with travel through time to facilitate the sexual form of coral reproduction.[29] Because many coral species release gametes only once annually, their reproduction schedule is limited, and restoration is consequently time-limited as well. Cryotechnologies could make it far easier to collect gametes and move them to another location for spawning to maintain diversity; they could also support the diversity of broodstock in captive facilities. If it were possible to store and rewarm embryos and adult polyps reliably at scale, this would add to restoration options. At present, effective cryotechnologies such as slow freezing, rapid liquid nitrogen plunge cooling, and laser rewarming are proven for coral sperm, certain larvae, and symbiotic algae.[30] Moreover, it has been shown to be possible to settle and grow adult corals from cryopreserved and laser-rewarmed larvae.[31] Recent developments show preliminary success in whole adult tissue with emerging technologies including laser warming and isochoric (constant-volume) cryopreservation.[32] However, to create the most effective restoration initiatives, advanced cryopreservation techniques should be routinized, generalized (to encompass multiple species), and standardized (or at least harmonized), so that they can be applied to diverse coral species and so that facilities can be built at sites around the globe where they are needed. Significant investment is necessary in parallel initiatives such as facility development, recordkeeping, genomic evaluation, and quality management to ensure that samples and the necessary information are available for effective use in future programs.

Playing for Time: Strategic Delay

Advanced cryotechnologies could play a role in restoration activities that require coordinating the movement of various biomaterials from one site to another, where it is key that each step be flexibly timed according to season, weather events, reproductive opportunities, labor availability, regulatory permits, funding, and advances in knowledge. At a variety of temporal scales, successful biodiversity conservation requires temporal coordination and, therefore, at times may also require strategic delay. Biomaterials may need to be cryopreserved until the next stop on their journey has been prepared to receive them. Because conservation initiatives are innovating solutions rapidly, there will inevitably be unanticipated practical obstacles and bottlenecks, and advanced cryopreservation techniques can untie the logistical knots of conservation planning.

One objection to the novel management techniques that cryopreservation supports is that their use could lead to a shift in values such that, having introduced some intentional modifications to a gene pool, there will be reduced apprehension about introducing additional interventions. This violates a common precept of conservation — that natural processes are preferable to intensive management — and is a legitimate concern. Conservation is driven by a strong sense of urgency, and urgency can tempt us to lower the standard against which effectiveness and ethics are judged — the tempting thought being that a small chance of success, however costly, is preferable to risking the entire loss of organisms, populations, and species. This shifting-values objection to novel biotechnologies pushes back against the perceived pressure to move as quickly as possible. It recommends, instead, invoking initial development and testing phases even before specific problems arise. The shifting-values objection holds that by the time a specific problem arises, investment in an enterprise will have produced a commitment to continue it, and sunk costs could override legitimate concerns. Cryopreservation technologies could play a valuable logistical role in this scenario. Where there is a push to deploy new interventions quickly and a countervailing precautionary tug, cryopreservation technologies offer the possibility of storing biomaterials if a pause in implementation is required to reassess risks. Thus, the availability of cryopreservation technologies can support a third option between rapid rollout and project cancellation. They may make it possible to adjust the timing of management projects to handle barriers and constraints with less loss of resource investments. In addition, biobanking viable cells has the possibility to buffer or mitigate misjudgments should wild populations or their genetic diversity be lost.

Something common to all of the listed roles for advanced cryopreservation technologies, whether

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through biodiversity banks or scaling up ecosystem management activities, is their integration with conservation research and practice. By facilitating travel through space and time, including strategic delays to improve cautious but effective interventions, cryotechnologies build connections and aim to renew relationships between humans and global environments. Focusing on biodiversity banks primarily as long-term storage rather than as a passage, bridge, or means of travel risks misunderstanding or underestimating their conservation role. Biodiversity banks, many of which are associated with zoos and museums, are integrated with a range of conservation initiatives, including not just scientific research and management initiatives but also public education. As social institutions, they are situated to communicate about the biodiversity crisis and may have a positive effect on cultural relationships with nature.[33] Rather than detached, quixotic ventures focused only on highly technological interventions,[34] conservation biodiversity banks see themselves as participating in initiatives that are coupled with management activities, whether now, in the near, or in the more distant future. Currently, these include captive breeding and release programs such as the US Fish and Wildlife Service black-footed ferret initiative[35] and others that advocate for a mix of traditional conservation strategies, such as increasing protected areas, and novel interventions, such as assisted gene flow, that are supported by cryopreservation technologies.[36]

Procrastination: The Thief of Time

One serious concern about the development and use of advanced cryopreservation technologies remains. Biodiversity banking and novel management interventions, including assisted reproduction, assisted gene flow, and translocation, do nothing to address the root causes of biodiversity loss. What is worse, they may encourage the perception that our environmental future is secure so long as these rescue techniques can be developed. Writing about the full range of uses of cryopreservation, including biomedical and conservation contexts, Joanna Radin and Emma Kowal raise the concern that freezing biomaterials creates hope for the future that distracts us from attending to problems in the present. They write, "This is the most striking temporal dimension of cryopolitics: The abdication of responsibility for action in the present made possible by recourse to the promise of an ever-receding, and technoscientifically enabled, horizon of future salvation."[37] This describes cryopreservation and related management interventions as a moral hazard: they may legitimate or excuse society's propensity to risk biodiversity loss, in this case by failing to address climate change and habitat destruction, because there is some reason to believe that future generations will be able to recover from incurred damages.

Thus, a belief in technofixes can be seen as reducing motivation to address the causes of biodiversity loss. Biodiversity banks, in this view, are a technology of procrastination rather than a technology of logistics. If it is true that these approaches delay or undermine efforts to mitigate climate change, then they exacerbate rather than relieve environmental problems. For the last decade or so, coral scientists have been split between those who favor reef protection efforts exclusively and those who favor experimentation with other tools and techniques. For example, Irus Braverman describes the views of a leading coral scientist who holds that reef gardening is "the very opposite of preemptive action; it is an attempt to depoliticize the contemporary crisis by masking it with temporary fixes."[38]

Not all conservationists believe that technological approaches to conservation management present a moral hazard, and not all believe that there is a true dichotomy between pursuing traditional versus novel conservation strategies. Proponents of novel conservation strategies do agree with skeptics that preserving our environmental future requires addressing climate change and habitat loss. However, proponents take exception to the diagnosis that refraining from novel approaches will have a causal effect on reversing the causes of biodiversity loss, since the structures that maintain fossil fuel economies derive their power from global markets and are not responsive, for example, to coral reef management strategies. While critics have argued that "the act of freezing or suspending life in anticipation of future salvation is an impediment to an actually sustainable future brought about through decisive action and accountability to the present,"[39] proponents of novel conservation tools and techniques have countered that active conservation management using techniques such as genetic rescue may be essential to save many populations and species.[40] Expanding the portfolio of conservation strategies may also bring new sources of funding to the biodiversity crisis while expanding public awareness and support for ecosystem conservation.[41] This seeming gulf between presumably equally well-intentioned and motivated groups is itself an impediment to effective and timely action. Identification and reinterpretation of wedge issues such as these are needed to enable opposing groups to find ways to focus on agreement and cooperate synergistically.

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Time is Relative: Who Frames the Future?

When considering the future of conservation that might be facilitated by biodiversity banking and cryopreservation-supported ecosystem management, we can see that it is important to consider frameworks for future decision-making. We have argued that conservation biodiversity banking and the management strategies supported by cryotechnologies might be thought of as buying time that can accomplish strategic delay; at the same time, we see these methods as encouraging flexible but active planning rather than as a technology of procrastination. Rather than deferring responsibility and decision-making, it is more accurate to think of them as sharing responsibility and collaborating on decision-making with future people. Their goal is to provide options for future restoration by preserving genomic materials. This requires that we also nurture and preserve decision-making opportunities.

Discharging this shared political responsibility raises issues that have only recently come to the forefront in environmental ethics. For example, we could consider as a cautionary case a debate over genome sequencing. Over the objections of Anishinaabe tribal leaders, a group at the University of Minnesota completed sequencing of *Zizania palustris* (manoomin or wild rice). The project was justified on grounds of scientific interest and potential use in future plant breeding.[42] It was opposed on the ground that the Anishinaabe people had both moral and treaty rights to maintain control over manoomin. The Red Cliff Band of Lake Superior Chippewa viewed the sequencing effort in the context of previous efforts to develop cultivated strains of wild rice for commercial production. Their opposition to the project pulled together strands of argument ranging from their practice of harvesting and protecting manoomin as a form of cultural identity to concerns about patenting and commercialization arising from the capabilities and intellectual property regimes associated with molecular techniques.[43] Robert Streiffer's analysis holds scientists and administrators leading the sequencing project at fault for treating the tribe's arguments as unworthy of serious consideration. Tribal arguments were unfairly judged as reflecting an "unscientific" worldview that fell short of the epistemic standards of modern science.[44]

While more work remains to be done in research ethics on the relationship between epistemology and power in community-engaged research,[45] progress has been made in producing guidelines for scientists and engineers whose work bears on natural and cultural resources of interest to Indigenous and local communities.[46] In addition, Traditional Ecological Knowledge often has the potential to support conservation research and practice.[47] As a matter of justice, in accord with the Kunming-Montreal Global Biodiversity Framework, and as a matter of effective conservation, protocols for conservation biology research should include plans for respectfully engaging with Tribal groups and, with their permission, incorporating local environmental knowledge into research.[48]

> Shifting the imaginative frame for understanding the potential of advanced cryopreservation from the existential to the logistical reduces the attention put on the status of frozen entities and heightens our awareness of their time-spanning possibilities to support ecological processes and build collaborative relationships with future people. Flexible but deliberate coordination and planning are required to conduct research that starts now but extends for decades as we attempt to stop and reverse biodiversity decline, an endeavor that may ultimately take centuries. This shift in framing to active, innovative planning for the future reveals the importance of attending to justice and extending respect to diverse worldviews in the here and now.

A detailed discussion of measures for engaging with philosophical viewpoints and traditional knowledge systems lies beyond the scope of the present paper, but consideration should be given to making techniques for biodiversity conservation accessible to people who have suffered the most from habitat loss and who are dependent on resilient local ecosystems. Protocols for collecting samples, building infrastructure, and siting projects should include plans for soliciting local knowledge and sharing control over decision-making.

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Tomorrow's Another Day: Countering Climate Despair with Ingenuity

Although most of the preceding discussion has addressed development of advanced engineering approaches, other mechanisms exist to place effective capabilities into the hands of diverse communities through emerging open technologies.[49] Much as the conceptualization of open-source software ushered in a new age of decentralized cooperation in computing science, other modalities for internet-based sharing of consumer-level fabrication, electronics, and computer hardware can decentralize biopreservation. If we consider that the genetic resources of many thousands of aquatic species require conservation biobanking and germplasm repository development, it is evident that a few elite institutions cannot hope to meet the sheer volume of the impending need. Inexpensive, standardized, but customizable devices can be made widely available through web-based sharing of open hardware. Such devices can be produced at low cost by methods such as 3D printing and can assist research, sample processing, quality management, training, teaching, and outreach.[50] This decentralization can be integrated with powerful central facilities that incorporate repository capabilities to establish networks within and among user communities to produce an overall amount of support for restoration and management well beyond the reach of individual centers. However, as identified above, technological advances do not operate in a vacuum, and their emergence, while addressing current problems, can also raise or exacerbate other problems. In this case, greatly expanded global biopreservation capability and participation could fuel wider issues with access and benefit sharing as genetic resources are locally collected and transported through time and space, especially if existing treaties and agreements, such as the Nagoya Protocol, are not suited as governance structures for decentralized materials as they interact with the inevitable unexpected events of the future.

Advanced cryopreservation technologies have the potential to change how research, conservation, and medicine are practiced. Building out the necessary infrastructure will require considerable investment. It is likely not to be built solely at existing research stations, and there may be a compromise between siting where the work has the highest ecological value and where it has the most secure access to infrastructure, such as airports, power generation, liquid nitrogen, and political economies. These and other issues may raise equity concerns with these technologies and their products. Moreover, there could be conflicting concerns about economic benefits, especially if conservation becomes more profitable than it is currently. The potential for conflict over such matters only underlines the need to consider novel options for constructive exchanges that respect the rights of affected parties, including other species and their ecological continuance.[51]

Shifting the imaginative frame for understanding the potential of advanced cryopreservation from the existential to the logistical reduces the attention put on the status of frozen entities and heightens our awareness of their time-spanning possibilities to support ecological processes and build collaborative relationships with future people. Flexible but deliberate coordination and planning are required to conduct research that starts now but extends for decades as we attempt to stop and reverse biodiversity decline, an endeavor that may ultimately take centuries. This shift in framing to active, innovative planning for the future reveals the importance of attending to justice and extending respect to diverse worldviews in the here and now.

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Paul B. Thompson serves on advisory boards for the American Veterinary Medical Association, American Humane Association, and United Egg Producers. All other authors have no relevant disclosures.

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