Research Output Journal of Biological and Applied Science 3(1):63-67, 2024

ROJBAS Publications ISSN: 1115-6120

https://rojournals.org/roj-biological-and-applied-science/

Ecological Restoration Using Synthetic Biology

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ABSTRACT

Ecological restoration seeks to reverse the damage caused by human activities to natural ecosystems, aiming to return them to a close approximation of their pre-disturbance structure and function. Traditional methods of restoration have evolved over the years, but challenges persist, particularly in the introduction and management of novel species. Synthetic biology offers new tools and approaches to enhance ecological restoration efforts by designing and deploying genetically engineered organisms tailored for specific restoration goals. This interdisciplinary approach holds promise for improving biodiversity, ecosystem services, and resilience. However, it also raises significant ethical, regulatory, and ecological concerns that must be addressed to ensure responsible implementation. This paper explores the integration of synthetic biology into ecological restoration, examining its potential benefits, risks, and future directions.

Keywords: Ecological restoration, Synthetic biology, Genetic engineering, Biodiversity, Ecosystem services.

INTRODUCTION

Technological developments constantly influence traditional practices. Synthetic biology is transforming ecological restoration. The term restoration refers to the attempt to change the damaged or the altered ecosystem so that it looks like an earlier version of itself. It has been defined as well as a process of assisting the recovery of an ecosystem that has resulted from disturbance, was damaged, degraded or destroyed. Ecological restoration has been debated and expanded in recent years. The way ecologists restore ecosystems has evolved through a hundred years of practice. The most complicated and contentious phase of restoration is the act of deploying novel species. Genetic and synthetic technologies provide further choices to advance the goals of the restoration [1]. Ecological restoration is done for landscapes that are degraded by the actions of people. There are five elements of restoration. First, the aim is to return an ecosystem to a close approximation of its pre-disturbance structure and function. Second, the intention of restoration is to reintroduce keystone species, especially mutualists, to rebuild necessary ecological links. Third, the earlier inhabitants are prioritized. Given the depth of human impacts, the focus on native species means additional emphasis on pre-human conditions. Fourth, ecosystem restoration is sensitive at spatial, temporal, and genetic scale because of habitat management practices. Finally, the restoration is driven by the restorationist-perceived needs and to advance management goals. There are a number of challenges and practices in ecological restoration that are the subject of ongoing debate because of the complicated relationships between humans and other beings [2].

DEFINITION AND IMPORTANCE

Ecological Restoration Using Synthetic Biology 2 Ecological Restoration Using Synthetic Biology 1.1. Definition and Importance [3]. Ecological restoration is conventionally understood as "returning an ecosystem to its original (pre-disturbance) trajectory". (Note that "trajectory restoration" is not the only possibility; see Ladle & Whittaker, 2011.) The Society for Ecological Restoration Europe (SERE) goes further, purporting that "restoration is an action that assists the recovery of an ecosystem that has been degraded, damaged or destroyed". They further state that restoration implies ecological and transformative goals: The fundamental objective of ecological restoration is to reverse ecological degradation and regenerate an ecologically healthy and self-sustaining ecosystem that is integrated into the surrounding landscape. Restoration is a complex ecological and socio-ecological process that aims to create functional and structural elements necessary for the long-term maintenance of biodiversity and ecosystem services at the species, habitat, and landscape/ecosystem level. This philosophy forms the basis for European ecological restoration standards, whereas recent work in the US emphasizes explicitly transformative calls for addressing injustices born of colonial historical processes situated in biophysical environments. The clearest importance of ecological integration is that ecological restoration has frequently yielded us new systems that were different from the original and that embodied different (or at least jointly higher) economic values, distinct agential assemblages, and novel symbiotic combinations. Although the measure of an ecosystem's value is contested, even in economic terms, ecological restorations are of major value that not only produce ecologically sensible landscapes to be enjoyed but yield a tangible economic return: healthy ecosystems provide the societal benefits of clean water, soil protection, carbon storage, aesthetic landscapes, and trophic support by comparison to non-restoration practices such as minimal management, in toto replacement as an agricultural or built environment, etc., albeit via some temporal delay and indirect causative mediation. This is not to say that ecological integration is always successful: many efforts at ecological integration are labeled as failures because they do not accurately represent that which was lost or desired. EVE. Competitive interlopers compromise the otherwise spontaneous Folk values and organizational order which EVE supports and prompts costly management. Moreover, defenses of ecological restoration's practical importance can invariably be deployed in defense of other normative restorative efforts. For instance, regulation, taxation, and use of financial incentives to mandate a social ecological palliative or uphold conservation of historical 'authenticity' and 'originality' answerable in a similar justificatory way. The practical importance of ecological integration varies depending upon one's normative choice: that which makes the restored landscape valuable is that it is ecologically rich, that it is suffused with the signs of its stripped-out history, or that it serves only to bolster economic prosperity. Crucially, to attempt to bolster the place value for the latter is likely to have negative moral and ethical impacts on those who call it home [4, 5].

CHALLENGES IN ECOLOGICAL RESTORATION

Ecological restoration is the practice of actively changing ecosystems in response to human-driven changes, aiming to make ecosystems more diverse, connected, and resilient to future environmental changes. This practice is most often put into action by government agencies, non-profit organizations, and individuals. Many individuals, including property owners and land managers, are motivated by a desire to restore native landscapes that function as they did before the effects of humans. Other motivations include conserving native species for their intrinsic value, restoring cultural landscapes as part of tradition or national heritage, improving ecosystem services such as food or water supply, and mitigating the negative effects of development and pollution. While practitioners' empirical guidance and scientific results about an array of pests are immense, this guidance is ultimately a much smaller percentage of the ecological restoration literature [6]. Ecological restoration is a social and economic process as well as a scientific endeavor, and practitioners often have disparate goals and consider many factors when managing ecosystems, including non-native species. Moreover, restoration is limited by political will, social justice, and the unintended social and ecological consequences of even the most principled actions. Funding for long-term monitoring or plant that does not directly lead to more plants compete with more politically popular short-term actions or the filling of basic human needs. Few areas hit hard by ecological damage are given money for science to study the damage, rather than for reparation. Overall, the challenge of achieving successful ecological restoration lies within many different areas, from the scientific to the operational. Only by understanding and working within these challenges can synthetic biology contribute to a successful genetic restoration [7].

INTEGRATION OF SYNTHETIC BIOLOGY IN ECOLOGICAL RESTORATION

Synthetic biology or synbio is a scientific discipline that takes engineering principles and applies them to biology. This allows the creation of biologically based systems, organisms, and products to achieve particular outcomes. The standard organization of synbio involves a linear engineering cycle to design, build, and test, which results in a biologic part, device, or system. These constructs are then used and combined to create synthetic organisms and eventually contribute to applications. Early or traditional synbio has mainly been designed for very direct and industrial applications. A shift is now occurring to work on other problems that have industrial significance, but are historically subject to sustainable development and/or policy debate [8]. One area where synthetic biology might make such a contribution is ecological restoration. That is, addressing degraded environments to get them back to a previous state. Such can involve habitat and conservation management such as using FireRegime for bush recovery, and water quality treatment plant management. While basic research and application of synthetic biology as a tool for eco-engineering or for working directly with biodiversity does exist, it is now starting to overlap with the field of ecological restoration. Open source systematic software for GMP, for instance, might be useful for ecological engineers or others working with active living materials. Databases of socially engaged synthetic biology might be used to inform landscape professionals or council workers in biodiversity habitat restoration designs. Overall this overlap is seen to be potentially very beneficial, but all current literature is speculative in nature with the outcomes of such an overlap untested and unknown. There are of course also associated risks, which are also yet to be fully addressed [9].

BENEFITS AND POTENTIAL RISKS

Despite its potential to transform ecological restoration, there are doubts about the benefits and drawbacks of synthetic biology. The advantages of introducing these new technologies are numerous. They can offer ways of reducing production costs and fund management of environmental values, which might be more effective and more professionally delivered than non-profit conservation activities. This might also harness processes of economic globalization, generate new industries with a stake in environmental conservation, offer new amenities and options for current and future generations, and help promote the aim of sustainability through labeling or exclusion of products causing negative environmental impact as eco-unfriendly [10].

However, it is also possible that the unrealized promises of genetic technologies, and the negative impacts upon sustainability of these enterprises, might result in rapid transcendence or eclipse of these technologies in ways suggesting irrelevance or triviality rather than an ongoing stewardship role. The potential risks of synthetic biology are therefore significant and are difficult to measure. For instance, if profits generated by synthetic biology-based ecological restoration result in an expansion of Australian agricultural and mining industries, then the ecology of Australia will continue to be transformed by this industry into market values. This is likely to contradict the goals of ecological restoration, which seek to restore landscapes according to management plans developed by humans. Developing a capacity for evaluating these different and vague contingencies is constrained by complexity and uncertainty, but it is fundamental to the development of practical guidance for decision-making in the field of ecological restoration [11].

CASE STUDIES

Synthetic biology ingredients are increasingly part of new genetic control technologies for invasive species. One of these is gene drive, which is used to broadly spread lethal phenotypes and fertility inhibitors targeting organisms that are causing devastating and potentially irreparable harm to biological communities and ecosystems. These are also found in the targets set out within the framework of GBIRd's case for a Green Freedom approach, where the aim is not only to facilitate ecological restoration but also actively participate in the process of restoration and rehabilitation itself across multiple biomes [12].

Case Study: Ischia Study Summary The setting for this study, Ischia, is Italy's third-largest volcanic island and one of the most populous of the 113 active volcanic islands that exist. Fauna and flora are classified by many as exhibiting various states of endangerment. Here, the restoration of ecosystem function by the improvement of pest control is actively facilitated by the planned GM modification of Musca domestica vicina - an invasive species known locally as "Mosca della stalla o mosca del cavallo" translating into "stable fly" or "horsefly." The insecticidal strain of the fungus Metarhizium rileyi is also proposed for development. The dispersal process of this transboundary study was stopped by the COVID-19 worldwide pandemic. Nevertheless, the practical part of the societal consultation has been terminated on the Italian island of Ischia [13].

ETHICAL AND REGULATORY CONSIDERATIONS

There has been limited attention given specifically to integrating the practice of ecological restoration and the emergent field of synthetic biology from an ethical and regulatory perspective. It is important to recognize that European Union (EU) regulations, at least concerning the release of genetically modified organisms (GMOs), have moved well beyond 'designed nature' and 'complexity/oversight tradeoffs' as framing principles. Present GMO regulations assess the environmental risk posed by the specific characteristics of genetically modified organisms rather than how the specific organisms were manufactured. But it is also not the time to abandon oversight and reflectiveness as oversights or unnecessary speed might lead to misconceptions and failures just as easily as those we might experience from undue reluctance to intervene. As a relatively new field, synthetic biology itself is, of course, only just beginning to develop agreed-upon best practices. Once best practices are achieved and put in place, they contribute to the responsible development of science and technology [14]. A main ethical issue is the moral acceptability of using synthetic biology. It is important to take account of public opinion and to make sure that the public is informed about the benefits, risks, and social implications of the use of synthetic biology. The public's ethical preferences are important because science and technology are not pursued in a vacuum, but by and for societies, premised on the values held in common by the publics served by the technology. While the debates in Europe have so far not been very broad or deep, there have already been some discussions of the topic, some including synthetic biology specifically. Several questions, concerns, and hopes have emerged [15].

FUTURE DIRECTIONS AND EMERGING TECHNOLOGIES

Future directions and emerging technologies. Bottom-up synthetic biology applies principles of standardization, modularization, and rational design to the generation of biological systems with novel functions - from biosensors and microbial cell computing, to new drugs, materials, and energy sources. This approach has the benefit of predictability and control precision. Thus, one direct application of synthetic biology to ecological restoration may be a bottom-up design and build of ecological communities from their component parts. This has direct application in the creation of high-diversity, multi-level model systems that are suited for community ecological experiments. For example, improving metal bioremediation capacities of a hydrocarbon-degrading consortia to support land-based crude remediation, or creation of a methane-consuming model community for the development of a methane-based bioelectricity economy using carbon capture and storage technologies [16]. A leading area in the future is self-organization technologies for ecosystem restoration. It is possible that a new generation of bio-based remediation and restoration technologies might involve the engineering of naturally occurring self-organizing behaviors in biological systems. These experiments can be understood as the reshaping of existing biological systems that can be exploited for ecological purposes and 'hacked' for in situ ecological remediation. The challenge is to figure out what aspects of these emergent, self-organizing properties should be designed or managed to achieve better ecological outcomes. Whether self-organization redesign or synthetic communities are successful or even used will depend on assessments of their ecological, economic, and social desirability. These could be expensive or require large-scale 'in situ epidemiology' studies to ensure these biological products are safe. These questions will, in part, depend on whether or not novel bio-based approaches can be harnessed for ecological benefits and what advantages they offer over current approaches [17].

CONCLUSION

The integration of synthetic biology into ecological restoration represents a promising frontier in environmental science. By harnessing the precision and innovation of synthetic biology, it is possible to address some of the most challenging aspects of restoration, such as the reintroduction of keystone species and the enhancement of ecosystem resilience. However, the deployment of these technologies must be approached with caution, given the potential ecological risks and ethical concerns. Comprehensive regulatory frameworks and robust public engagement are essential to ensure that synthetic biology contributes positively to ecological restoration efforts. Future research should focus on developing safe and effective synthetic biology applications, monitoring their long-term impacts, and addressing societal concerns to foster sustainable and resilient ecosystems.

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CITATION: Bizimana Rukundo T. Ecological Restoration Using Synthetic Biology. Research Output Journal of Biological and Applied Science. 2024 3(1):63-67