EMERGING SCIENCE

Synthetic biology offers extraordinary opportunities and challenges for conservation

By Kent H. Redford

HUMANS HAVE ALWAYS sought to reshape nature to meet their needs: taming fire, domesticating animals and plants, building dams and nuclear power plants, and shaping and reshaping nature in countless other ways. We have been largely interested in how humans benefit from our actions with little attention to how nature is affected. To be sure, our species has affected nature in many significant ways such that historical extinction rates far exceed those in the geologic past. For example, on average, humans appropriate about 25% of potential net primary terrestrial productivity, mostly from agricultural land use and harvests (Haberl et al. 2007); we use more than half of all accessible freshwater; we apply more ammonia and nitrate than are fixed naturally in all terrestrial ecosystems; and we are changing the atmosphere through the dramatically increased production of methane and carbon dioxide (Crutzen 2002). Clearly humans are the dominant ecological and evolutionary force on the planet (Palumbi 2001).

The Anthropocene, the geological epoch we have entered, is named for this pervasive impact humans are having on the earth. But the impacts are not just pervasive; they are also increasingly novel. Humans are breaching boundaries that have held throughout human evolution. Species have been moved purposefully and accidentally, resulting in new ecosystems; climate change is threatening to produce a set of novel climates; species boundaries are being breached as humans move genes about; and organisms are being created that incorporate machines and electronics as part of their bodies.

Synthetic biology arrives

Part of this new age of human impacts is the developing field of synthetic biology, or "synbio." Synthetic biology is a hybrid of engineering and biology with an emphasis on reliably and predictably engineering the genomes of living cells to produce goods and services of use to humans. There is no universally agreed-upon definition of synthetic biology but one that is commonly referred to is (1) the design and construction of new biological parts, devices, and systems and (2) the redesign of existing natural biological systems for useful purposes (syntheticbiology.org).

Key elements of synbio in the field are (1) its engineering approach to natural systems (designing and fabricating "components" and "systems" using standardized and automated processes; (2) an emphasis on novelty: fabricating parts and systems that do not exist in the natural world (or redesigning and fabricating those that do); and (3) doing so to address human needs (ECNH 2010; Presidential Commission for the Study of Bioethical Issues 2010). Synthetic biology can be applied to a broad range of fields, including food production, new materials and manufacturing, waste processing and water purification, ecological restoration, and human health (see http://www.parliament.uk/mps-lords-and-offices/offices/bicameral/post/post-events/future-environmental-impacts-of-synthetic-biology/).

Synthetic biology is a rapidly developing field because of the rapid decrease in the cost of reading and writing DNA. Technologies that enable the manipulation of DNA are changing at a rate faster than the developments that led to cell phones and today's computers, suggesting that we could see in synthetic biology a rate of change faster than that in the last decade of smartphone and associated technologies (Carlson 2013). Billions of dollars are being invested annually in synthetic biology; developments of novel applications or improvements of existing ones emerge weekly. For example, only recently we read an announcement of the creation of the first custom, synthetic chromosome using synthetic biology tools (Mosendz 2014).

The practice of synthetic biology

Media coverage about the future that synthetic biology will enable has included a great deal of hype, but significant scientific advances show some of the potential that synthetic biology may bring. Trees have had their genomes altered so that they are easier to process for pulp; vanilla and other flavorings are now being produced in factories by algae and bacteria; ACT, the most significant drug used in treating malaria, no longer must be grown from the *Artemisia annua* plant but is produced in factories by yeast; bacteria have been reprogrammed to construct electronic and optical materials; and a new species of fruit fly has been created specifically by altering the genes responsible for its reproduction. There are thousands of other fronts across which synthetic biology is pursued, from fuels and medicines to foods and the reanimation of extinct species.

Unlike that of many other technologies, the philosophy underlying synbio development, as practiced at least in the United States and Europe, is open access, with new techniques and approaches being put into the public domain. Associated with this philosophy is widespread experimentation with synbio by community labs, teams of undergraduates, and now even high school students. Community labs are set up by interested synthetic biologists and made available for a nominal fee to anyone who is interested in experimenting with the new technologies (see diybio.org). The easy accessibility of equipment and genetic sequences (many can be ordered over the Internet) has extended the practice of synbio to students in high school, college, and graduate school. A great deal of synbio work is being done in university and commercial labs, but this is a technology that is open to many segments of society, including do-it-yourself biologists.

Despite all the work on and investment in synbio, next to no attention has been given to the relationship between this emerging field and conservation. Synthetic biologists have formed collaborations to look at the implications of their work for the social sciences, law, and arts and humanities (Marris and Rose 2012), but not with the protected area community or any other type of conservationist. This lack of engagement is equally stark from the conservation side, as the conservation and global change communities have paid virtually no attention to synthetic biology. These two fields are taking steps, though only in small ways, to talk to each other. A recent Wildlife Conservation Society meeting held in 2013 brought together the two groups (Redford et al. 2013; Redford et al. 2014), and some follow-up discussion on the intersection of the two communities is beginning to take place.

And what about biodiversity?

Synthetic biology may have a range of potential negative impacts on biodiversity: novel organisms may escape containment and cause negative impacts on natural ecosystems; land conversion for crops that were developed using synthetic biology may cause immediate, direct effects on species, ecosystems, and protected areas; and complex secondary effects on society and economy may also result (e.g., land conversion by people displaced or impoverished by first-order changes). Of equal significance, synthetic biology could provide conservationists with more effective methods of conservation, including the creation of biological tools that could help to gather and process field samples affordably or monitor for the presence of particular threats. Synthetic biology could be used to restore lost genetic variation to extant but diminished and threatened populations. Or it could be used to engineer microorganisms to create approaches to solving intractable problems facing humans, including providing clean water, restoring degraded lands, and developing better medicines—outcomes that might also have positive effects for conservation.

The two fields have a great deal to discuss:

- How should conservationists think about the novel species being developed by synthetic biologists?
- How will these species interact with existing species and ecosystems?
- Will or could these new technologies be used to re-create extinct species—a process called "de-extinction?" (The Long Now Foundation 2014)
- What will it mean if extinction is no longer forever?
- What will happen to our definitions of "natural" when human-made species are created and begin to interact with "natural" species?
- What threats will synbio bring? Will the organisms produced through synbio escape industrial facilities and become invasive? Will high school students purposefully release organisms they made as part of a class? What would happen if engineered organisms developed to fight an invasive disease evolved to attack agriculturally beneficial organisms?
- Conversely, what threats might synbio alleviate? Can it be used to develop solutions to known risks to biodiversity, such as the fungal diseases that threaten many amphibians and bats with extinction (Fisher et al. 2012)? Could we engineer disease resistance into species like the Tasmanian devil that are threatened with extinction because of a highly contagious disease?
- What would happen to the ecosystems into which new life-forms are introduced?
- Will species created through synbio be privately owned? What will this privatization do to conservation efforts?
- What will happen if synbio is used to deliver services more efficiently and at lower cost than "natural" systems?

Finally, synthetic biology organisms could directly affect existing protected ecosystems in a variety of ways by:

- Becoming invasive or otherwise affecting populations of protected species, or disrupting protected ecosystems
- Changing the economic value of land (and hence demand for land) within protected areas (e.g., making crop production possible on land currently regarded as marginal for agriculture and hence allocated as a protected area)
- Changing the way land surrounding protected areas is used and hence affecting species composition in the protected areas because of species immigration or extinction
- Accelerating (or slowing) the rate of ecosystem conversion outside pro-

tected areas and hence the relative importance of existing protected areas (e.g., reducing pressure on habitats like tropical forests and making protected areas less necessary and therefore uneconomic to run)
- Changing demand for products currently illegally harvested from protected areas (e.g., meat, timber, nontimber forest products, illegal drug crops)

Need to engage

We do not know what impacts synthetic biology will have on biodiversity and park-based conservation. Some experts are convinced the effects will be positive and an equal number are convinced they will be catastrophic. What is clear is that the future will feature synbio in many forms. One of synthetic biology's pioneers, George Church, has written glowingly of the promises this new technology will bring, including improving human and animal health, extending the human life span, increasing intelligence, and resurrecting extinct animals, even hominids (Church and Regis 2012).

Inevitably, synthetic biology will proceed in developing new products based on new or modified organisms, despite the frequent calls for more oversight and the desire by some governments to establish regulations specific to this field (AAAS 2012). Institutions to put such restrictions in place simply do not currently exist, so the strong sense by many synthetic biologists of the imperative to create open-source architecture has led to strong calls for self-policing by practitioners. Finally, synthetic biology will not be stopped: investments in the field are huge, the potential applications are numerous, and the technology is accessible to too many.

Conservationists may choose to ignore synthetic biology, but they do so at their own risk and the risk of the natural biodiversity they are devoted to conserving. Synthetic biology is a fact and, because it is being pursued throughout the globe by governments, industries, academics, and individuals, it will be with us for a long time. But given the early stages of its development, this is a key time for the conservation community to engage and try to influence the practice and outcomes.

This scenario creates an opportunity for the National Park Service to begin to engage with the synbio community and the public about the issues raised by synthetic biology. To achieve this engagement, at a minimum the National Park Service needs to understand what is happening in the field of synthetic biology and begin to educate its key constituencies. Better still would be engagement with the synbio community to influence the development of the industry in ways that are at least benign to conservation efforts and at best beneficial to protecting national park resources and values. Perhaps there are intractable—wicked—problems that are facing the National Park Service that could be addressed with synbio solutions. Or the Park Service could consider undergoing a scenario planning exercise related to synthetic biology as it has been doing with climate change.

A sea change?

Despite local successes, conservationists have not been succeeding at their objective of conserving greater biodiversity (Butchart et al. 2010). Numerous measures have been applied to quantify this lack of success, and a general air of despair has settled over the field. The conservation community has been quick to adopt new technologies, including camera trapping or monitoring of wildlife, GPS collars, and environmental DNA capture and analysis. But by and large the community is disinclined to adopt new technologies, saying as one person said to me: "Technology is responsible for getting us into the mess in which we find ourselves. You are crazy to think that technology will do anything but make the situation worse." In the last few years strong voices have demanded a new approach to conservation (e.g., Kareiva and Marvier 2012). But these voices have not talked about truly extraordinary changes—ones like careful and discriminating inclusion of synthetic biology approaches in our conservation toolbox such as discussed above.

The future world will not be a slightly older version of the one we currently inhabit. Rather it will have a significantly altered climate, changed sea levels, novel pests and diseases, nonanalogue ecological communities, and a human population with less interest in conservation. The costs, benefits, and risks of synthetic biology need to be considered against this backdrop, not against a projected version of the world as we now understand it.

Much of conservation is predicated on the core ideals of wilderness and nature. However, recognition of the increasing role humans play in structuring ecosystems and thereby shaping the lives of wild species has led practitioners to realize that human management may be a paradoxical but necessary part of conserving the wild. Synthetic biologists propose to further equip humans to actively and consciously engineer the living world. Aldo Leopold famously said, "To keep every cog and wheel is the first precaution of intelligent tinkering." But what if we could make new cogs and new wheels? What would this mean for our attempts to mend centuries of nonintelligent destruction? The transformed world of 2050 will demand new strategies and new approaches in conservation. Should some of them involve creation of new pieces? Synthetic biology can be incorporated into these as a powerful new tool to face the powerful new challenges facing conservation. It is time to consider such extraordinary measures.

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