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opinion

From dinosaurs to dodos: who could and should we de-extinct?

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Abstract. Reviving extinct species with new synthetic biology tools is as exciting an idea as it is controversial. Genomic manipulation of extinct species' close relatives and/or cloning suitably preserved cells are the two main ways synthetic biology could be used to revive species. Discussions of where to target initial revival efforts have focused on species' charisma (e.g. Woolly mammoth, Passenger pigeon) with less emphasis on feasibility or the ecological, ethical and legal considerations. Here I discuss who we could and should de-extinct, focussing on these latter criteria. Given the current devastating anthropogenic pressures on biodiversity, I suggest that a better use of de-extinction technologies would be to focus them on preventing species extinctions by restoring populations of critically endangered species. For example, this could be through increasing population numbers through cloning or genomic manipulation to better enable susceptible species to adapt to global change or by restoring genetic diversity by reviving extinct sub-species (e.g. Quagga, Barbary lion). This idea circumvents many of the criticisms of de-extinction from conservationists, whilst retaining public interest in de-extinction.

Keywords. candidate species, cloning, conservation, critically endangered, ethics, ecological impact, prioritization, synthetic biology

Extinction is not forever

The idea of bringing back extinct species has always elicited wide public interest (Crichton 1991) but until recently 'de-extinction' was thought to be confined to fiction. However, new technological advances in synthetic biology have made the revival of extinct species a real possibility (Church and Regis 2012) and discussions of this idea have generated roughly equal amounts of excitement and controversy (Pimm 2013, Redford et al. 2013, Sherkow and Greely 2013, Zimmer 2013). New synthetic biology tools have the potential to be used for reviving extinct species in two main ways: genetically manipulating closely related species and/or cloning individuals from suitably preserved cells (Church and Regis 2012). Whilst cell cloning may be limited to very recently extinct species (which are more likely to have viable cells preserved), genetic manipulation may be possible for a wider range of extinct species. Techniques to genetically engineer species by selective breeding are well established, but new synthetic biology tools allow more precise genomic manipulation (Wang et al. 2012). For example, some ideas being discussed include inserting extinct Passenger pigeon (*Ectopistes migratorius*) DNA into closely related Band-tailed pigeons (*Patagioenas fasciata*), Woolly mammoth (*Mammuthus primigenius*) DNA into Indian elephants (*Elephas maximus*)[1] (Zimmer 2013) and, perhaps not seriously, Neanderthal (*Homo neanderthalensis*) DNA into human embryos (Church and Regis 2012).

Who could we de-extinct?

The discussion of where initial revival efforts should be targeted has so far focused on charismatic species that resonate well with public interest, for example the Thylacine (*Thylacinus cynocephalus*), Woolly mammoth and Passenger pigeon[1]. There has so far been less emphasis on biotechnological feasibility or the ecological, ethical and legal considerations. Feasibility currently severely limits candidate choice; for example the half-life of DNA (521 years) means that even in

1 http://tedxdeextinction.org/, last accessed 05 March 2014 ideally preserved conditions DNA becomes effectively unreadable after 1.5 million years (Allentoft et al. 2012). Recovering DNA from specimens older than 1.5 million years seems unlikely, meaning no dinosaurs unless you count trying to build one out of a bird by expressing ancestral traits[2]. The rate of DNA degradation suggests that, all other things being equal, time since extinction decreases the likelihood of de-extinction success. For example, Yangtze River dolphins (*Lipotes vexillifer*), last seen in 2004 (Turvey et al. 2007), might be easier than Woolly mammoths (extinct around 2,000 BCE; Barnes et al. 2007). Estimating how (possibly very degraded) fragments of DNA are arranged is much easier if the extinct species has close relatives to act as a reference genome. The integration of a closely related reference genome with extinct DNA is also more likely to succeed. For example, the Quagga (*Equus quagga quagga*), an extinct sub-species of the extant Plains zebra (*Equus quagga*) according to the IUCN Red List[3] is an easier prospect for de-extinction than the Thylacine which has no close relatives and represents millions of years of unique evolutionary history.

Generation times would also impact de-extinction feasibility, where longer generation times would mean slower growth and presumably a more expensive process per individual. For example, Passenger pigeons may have many eggs per clutch and more than one clutch per year, while Woolly mammoths have only one baby per pregnancy every three to four years (extrapolating data from closely related extant species; Jones et al. 2009). Other constraints on feasibility are also important considerations; for example, birds with their eggs coated in hard shells have as yet never been successfully cloned. Species with simpler genomes such as extinct amphibians (e.g. gastric-brooding frogs *Rheobatrachus silus*; see Zimmer 2013) or extinct invertebrates (e.g. Polynesian tree snails *Partula spp.* and Xerces blue butterfly *Glaucopsyche xerces*) may be less charismatic to some, but more feasible de-extinction candidates.

Who should we de-extinct?

If the end goal of a de-extinction effort is the release and establishment of a viable population, then the likelihood of individuals establishing viable populations is another important consideration in candidate choice. Extinct species are more likely to be able to establish successfully if their existing native habitat is protected from future anthropogenic global change and the original threatening process has ceased. For example, the Yangtze River dolphin would be an unlikely candidate species because its original habitat (Yangtze River in China) is highly polluted, a situation that is getting worse (Turvey et al. 2007). On the other hand, Thylacine habitat in Tasmania and Australia is still present and the hunting pressure which drove this species to extinction might be controlled in any reintroduction. However, only a small proportion of extinct species were over-hunted to extinction[3], so selecting large numbers of de-extinction candidates under this criterion might not be feasible. Even then, these hunted extinct species might not be safe from anthropogenic impact, given the controversy which 'rewilding' causes, especially of large carnivores (Donlan et al. 2006, Navarro and Pereira 2012).

Generation times would also impact the establishment of viable populations because species with longer generation times would be slower to establish and would recover more slowly after any chance perturbation (Cardillo et al. 2005). Complexity of social behaviour would be an important criterion to consider; for example Passenger pigeons were highly social and it is unclear how emergent social behaviours would survive the de-extinction process. Finally, the potential impact on the environment of the release of these newly de-extinct species is also critical. Although unlikely to become pests, could such revived species be considered Genetically Modified Organisms (albeit very fancy ones) and come under that legal framework curtailing release? Understanding which species would be suitable candidates for de-extinction would benefit from examining crite-

2 www.ted.com/talks/jack_horner_building_a_dinosaur_from_a_chicken.html, last accessed 05 March 2014.
3 www.iucnredlist.org, last accessed 05 March 2014.

ria for reintroduction success in extant species such as in the most recent guidelines from IUCN (IUCN/SSC 2013). These guidelines could be adapted to investigate which extinct species would be more or less viable as candidates for de-extinction and subsequent re-introduction. On the other hand if the end goal of de-extinction is permanent captivity, then candidates would be favoured that could be kept successfully, for example species with smaller home ranges and social groups, to avoid behavioural problems and poor health (Mason 2010).

Maintenance of taxonomic, functional and genetic diversity of species within ecosystems has been shown to provide resilience to disturbance as well as a number of important ecosystem services—for example, pollination, clean water, carbon sequestration (reviewed in Cardinale et al. 2012). This provision of ecosystem services is often used as a rationale for conserving extant biodiversity (e.g. UK National Ecosystem Assessment 2011). Similar arguments for reviving extinct species could be made where a species had a particular ecosystem function. For example, Woolly mammoths acted as keystone species in the Pleistocene tundra (Gill et al. 2009) and Dodos (*Raphus cucullatus*) as seed dispersers on Mauritius. Perhaps targeting those species with a high potential to restore a lost ecosystem function should be prioritised. Restoring lost phylogenetic diversity could also be a consideration for candidate choice, as in other conservation prioritization schemes (e.g. EDGE; Isaac et al. 2007). Phylogenetic diversity of extinct species that have extant close relatives is to some extent already represented, so prioritization could be made for extremely phylogenetically unique species, although this may be unfeasible.

We are facing huge challenges on this planet as our population grows and we appropriate more and more of Earth's resources for our use, destroying species and the ecosystems they live in and the services that they provide us (Butchart et al. 2010). Given this extinction crisis, it is perhaps challenging to justify large amounts of resources being funnelled into de-extinction itself. Perhaps the most appropriate use of technological advances in synthetic biology is to assist extant species likely to go extinct in the next few years, by increasing their genetic diversity, increasing population numbers or genomic manipulation to better enable susceptible species to adapt to global change (Ryder 2002, Redford et al. 2013). For example, Javan rhinos (*Rhinoceros sondaicus*), assessed as Critically Endangered and with fewer than 40 living individuals, are likely to go extinct in the next few years[3]. This species seems an excellent candidate, scoring highly on technological feasibility (living cells), on the likelihood of establishing viable populations (adding to an existing one), and on having a low impact on the environment (already present). The biggest challenge for success with these species would be the continued presence of threatening processes causing their declines (poaching, habitat loss). Although these species are currently extant and the 'wow' factor would not be as high, many conservationists would argue that preventing an imminent extinction would be a better use of these new de-extinction technologies (Redford et al. 2013).

Still, the concept of de-extinction has an undeniable appeal and targeting extant species might not grab public interest and funding in the same manner. I argue that by dismissing de-extinction entirely, the conservation community would miss opportunities to increase the public and corporate interest in conserving wild nature. De-extinction, instead of deflecting resources away from conservation, may open up entirely new ones, such as from biotechnology companies (creating a bigger pie not slicing up smaller pieces of the same pie). One possibility that could assist conservation efforts, further develop the synthetic biology toolbox and inspire the public might be to restore the populations and genetic diversity of extant species by targeting extinct sub-species for de-extinction, such as the Quagga, Barbary lion (*Panthera leo leo*) and Bali tiger (*Panthera tigris balica*)[3]. Although these are only sub-species, public will for conservation is by no means restricted to the species level and branding a species as a local, regional or country "mascot" has a powerful effect on conservation will and spending, as evidenced by wide interest in the Florida panther (*Puma concolor coryi*) and American peregrine falcon (*Falco peregrinus anatum*) in the USA (Meuser et al. 2009). The prioritization of these sub-species as de-extinction candidates would obviously have to incorporate ecological, ethical and legal considerations, as discussed previously. Sub-species de-extinction capitalizes on the huge amount of public interest and wonder generated by the concept of de-extinction and the tools developed and resources raised would aid in extant species conservation.

Conclusions

Given the new synthetic biology tools, level of public interest and the growing number of independent biotechnology companies, I think that there is an inevitability about species de-extinction, whatever the opinion of the conservation community. Engaging with de-extinction to maximise the conservation potential of these tools and moving the discussion of species' prioritisation beyond charismatic species is now vital. Careful thought needs to be paid to the ecological, ethical and legal impacts of candidate choice and this will be influenced by the motivation behind the species de-extinction effort (e.g. zoo specimens, potential re-release, scientific study). However, to best make use of technology and to help and not hinder conservation, I believe efforts should be focused on critically endangered extant species possibly using de-extinction of their sub-species as a public and corporate engagement tool.

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