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Of mongooses and mitigation: ecological analogues to geoengineering

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Abstract
Anthropogenic global warming is a growing environmental problem resulting from unintentional human intervention in the global climate system. If employed as a response strategy, geoengineering would represent an additional intentional human intervention in the climate system, with the intent of decreasing net climate impacts. There is a rich and fascinating history of human intervention in environmental systems, with many specific examples from ecology of deliberate human intervention aimed at correcting or decreasing the impact of previous unintentionally created problems. Additional interventions do not always bring the intended results, and in many cases there is evidence that net impacts have increased with the degree of human intervention. In this letter, we report some of the examples in the scientific literature that have documented such human interventions in environmental systems, which may serve as analogues to geoengineering. We argue that a high degree of system understanding is required for increased intervention to lead to decreased impacts. Given our current level of understanding of the climate system, it is likely that the result of at least some geoengineering efforts would follow previous ecological examples where increased human intervention has led to an overall increase in negative environmental consequences.

Keywords: climate engineering, biological control, ecological intervention, climate change

1. Introduction

The accelerating use of fossil-fuel energy over the past century has led to growing concern over the effect of carbon dioxide and other greenhouse gas emissions on the Earth's climate. Progress on mitigating greenhouse gas emissions has been frustratingly slow, leading some scientists to call for a need to consider direct climate intervention as a means to avoid or decrease dangerous climate impacts. We are now aware that our actions have led and will continue to lead to climate change, but this is nevertheless an unintended consequence of our global energy use. By contrast, direct climate intervention, or geoengineering, would represent an explicitly intentional intervention in the climate system, with the purpose of slowing or reversing the rate of global temperature change (Royal Society 2009).

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Humans have been interfering both intentionally and unintentionally with the Earth system for a very long time, though it is only recently that these interventions have led to global-scale impacts. In particular, there are many examples of intentional human interventions in ecological systems that represent deliberate attempts to mitigate or reverse the effects of a previous unintentional intervention. Such examples are in many ways analogous to the current discussion surrounding the use of climate intervention as a response strategy to anthropogenic climate change. In this letter, we examine the recent history of ecological intervention, with an eye to the ways in which these past experiences may parallel current geoengineering proposals. Where possible, we draw analogies between geoengineering and other types of ecological interventions, and in so doing seek to infer what lessons may be learned from past experience.

2. Classical biological control

In 1883, the Indian mongoose (*Herpestes javanicus*) was intentionally introduced to the Hawaiian islands in an effort to control damage in the sugar cane industry caused by invasive rat (*Rattus norvegicus*) populations that had arrived uninvited in the Hawaiian Islands along with European settlers (Baldwin *et al* 1952). The mongoose introduction followed from seeming success in controlling rats in the sugar cane industry in Jamaica and other islands in the West Indies (Hill 1897). Since then, mongooses have also been introduced to control rats in Fiji, Mauritius, and to Amami-Oshima Island in Japan (Watari *et al* 2008). There are conflicting reports as to the effectiveness of mongooses, as a diurnal predator, in controlling a primarily nocturnal rat population (Hill 1897, Baldwin *et al* 1952). It is clear, however, that since their introduction, mongooses have represented an extremely effective general predator and have contributed to the decline of populations of many native and endemic species, including ground-nesting birds, sea birds, snakes, lizards and sea turtles (Hill 1897, Nellis and Small 1983, Honegger 1981, Morley 2004, Watari *et al* 2008, Coblentz and Coblentz 1985).

The mongoose is an example of an early attempt at biological control of an invasive pest species. Classical biological control, or biocontrol, is often employed as a pest-management strategy to control invasive species by introducing additional predator species. The approach is based on theories of predator–prey dynamics: invasive species often thrive and become pests in their new environment without the natural predatory and parasitic controls on their populations that existed in the ecological context of their evolutionary origin. Biocontrol programs seek to introduce these natural enemies into the new environment in order to mitigate agricultural, ecological, or economic damages, and are often seen as an alternative to more detrimental or difficult methods such as pesticide/herbicide application or eradication by poisoning or hunting (Van Driesche and Van Driesche 2000). In the case of the mongoose, a problem caused as an unintentional side effect of human activities (rats) was sought to be corrected by an additional, but intentional species introduction (mongooses). More than a century later, it is clear that mongoose introductions were both limited in their success in controlling the rat populations, and presented additional unintended environmental impacts that have far exceeded any possible economic or ecological benefit of their introduction (Baldwin *et al* 1952, Watari *et al* 2008).

There are many other examples from the field of biological control in which species introductions have been attempted to control the spread of a previously unintentionally introduced pest species, leading to unforeseen ecosystem consequences that in many cases have been worse than the original problem (Howarth 1991, Pearson and Callaway 2003). Another well-publicized example is that of the cane toad (*Bufo marinus*) which was introduced to Queensland, Australia in 1929 in an attempt to control the gray-backed cane beetle (Lampo and De Leo 1998); the cane toad, which is toxic to potential predators, was not successful in this insect control, and has since established itself as a pest species in its own right, posing a direct threat to a number of native species (Covacevich and Archer 1970, Lampo and De Leo 1998). A further example is that of the predatory snail, *Euglandina rosea*. Beginning in the 1950s, *E. rosea* was introduced in multiple locations to control the giant African snail (*Achatina fulica*), which after spreading to several locations in Asia, the South Pacific islands and the West Indies had become a threat to both agriculture and human health (Civeyrel and Simberloff 1996). However, *E. rosea* has not remained confined to the primarily agricultural target areas of introduction, is not generally effective at controlling the target snail species, and has spread and preyed on non-target native snails. *E. rosea* has been credited with the decline and probable extinction of a number of other snail species, including the well-document example of a species of Moorean *Partula* snail, which had been the subject of population and genetic studies at the time of the *E. rosea* introduction (Simberloff and Stiling 1996, Civeyrel and Simberloff 1996, Howarth 1991, Clarke *et al* 1984).

Efforts to suppress invasive species through biological control can be seen as analogous to the current discussion surrounding intentional climate intervention, as a response strategy to the problem of global warming. Global warming is an inadvertent environmental consequence of our global fossil-fuel energy system. Geoengineering would represent an additional intentional human intervention in the climate system, aimed to decrease net climate impacts. As in the case of the above examples from biological control, removing the source of the problem (whether continued greenhouse gas emissions or continued introduction of rats to Hawaii) is seen as either too expensive, too difficult or too impractical. As in the case of biological control, there is a strong potential for unforeseen impacts from geoengineering, which may well be worse than the original problem. Such undesirable impacts are increasingly likely in the case of complex systems where scientific understanding of system processes is limited.

3. Biological control as an analogue to climate control

The idea of climate control as a response strategy to the problem of anthropogenic climate change goes back several decades (Keith 2000). Kellogg and Schneider (1974) presented a thoughtful analysis of the possibility of climate control, emphasizing that the costs of miscalculation (or indeed the perception of miscalculation) would be immense. Marchetti (1977) was the first to use the term ‘geoengineering’ in a proposal that CO_2 emissions could be curbed by capturing and injecting CO_2 into the deep ocean. In 1992, the US National Academy of Sciences reviewed the feasibility and risks associated with a variety of geoengineering ideas, including reforestation, ocean fertilization, cloud albedo modification, stratospheric aerosol injection, and the use of space-based reflectors (National Academy of Sciences 1992). While they did not seek to recommend specific options over others, this report is notable as one of the first comprehensive reviews of a wide range of geoengineering proposals.

Much of the current debate surrounding geoengineering was initiated by an editorial published by Crutzen (2006), who proposed that stratospheric aerosol geoengineering could be employed as a way to allow a reduction in lower-atmosphere aerosol burdens without the accompanying loss of the cooling influence that these aerosols currently afford. Wigley (2006) proposed a combined approach to climate stabilization whereby aerosol geoengineering could be used to provide additional time to achieve the necessary decreases in greenhouse gas emissions. Barrett (2008) pointed out that geoengineering may be remarkably inexpensive compared to emissions reductions (see also National Academy of Sciences 1992), and that this potential ease of implementation is both attractive and dangerous. Carlin (2007) argued that geoengineering may in fact be a preferable response strategy to emissions cuts, on the grounds that decreasing emissions to the extent necessary would be too costly and difficult to achieve. Keith (2009) rejects the view that geoengineering should be considered as an alternative to emissions reductions, and suggests instead that it may be used as a temporary measure to avoid catastrophic climate impacts, in effect, as a kind of climate change insurance policy.

In drawing analogies between geoengineering and other types of human interventions in natural systems, it is important to be clear that there are a wide variety of perspectives among proponents of geoengineering as to both when, and on what scale it would be appropriate to consider these kinds of climate interventions. The opinion that geoengineering might be employed as an alternative to mitigation (e.g. as suggested by Carlin 2007), or even as strategy to buy time to allow mitigation to proceed more slowly (Wigley 2006), is arguably an extreme position within current geoengineering discussions. A similarly extreme analogy would be a case in which biological control was attempted without any attempt to minimize the re-introduction or spread of the target species. A more nuanced view on the appropriateness of geoengineering (e.g. that put forth by Keith 2009) is that geoengineering should be considered only in the case that other options for preventing catastrophic climate change are unsuccessful, and even then should be only regarded as a temporary measure to avert dangerous climate impacts.

The question of when and how we might know when other attempts to avert dangerous climate impacts have been unsuccessful is clearly a central issue in the current discussion of when and how geoengineering may represent an appropriate response strategy. Here, there may be important differences between the use of geoengineering as a last-resort response strategy, and similar past uses of biological control. Biological control is often implemented as a response strategy to control comparatively specific ecological or economic damages from invasive species. In the case of climate control, we face substantial uncertainty in our understanding of the very impacts that climate intervention would be intended to avoid. It is not at all clear at what point we might know that the climate impacts associated with non-intervention may be either dangerous, or worse than, the combined known and unknown impacts of climate intervention. We also may not know which impacts are reversible and which are irreversible, or to what extent a reversible intervention may be possible to avoid an irreversible consequence of inaction. Any decision to implement a geoengineered climate intervention would have to be made in the face of substantial uncertainty of the consequences of both action and inaction; it seems likely that this uncertainty will prevail regardless of the amount or rigor of prior study and risk assessment.

Biological control has often also been considered only as a last resort when other control strategies have failed and the perceived costs associated with doing nothing or waiting would be severe. However, the use of last-resort biological controls has been criticized on the grounds that it can lead to a kind of 'fire-fighting' approach that leaves little time for extensive and involved risk-analysis and trial research, and can result in interventions being implemented without a clear understanding of the ecological implications or risks (Thomas and Willis 1998). There are also many instances where the outcomes of biological control have not been adequately evaluated, or where the environmental impacts of biological control are either not researched, not reported, or only identified accidentally by other researchers (Caltagirone 1981, Howarth 1991, Thomas and Reid 2007, Simberloff and Stiling 1996). In cases where impacts have been assessed, negative ecological consequences of biological control often emerge; for example Simberloff and Stiling (1996) reported that in every case of fish species introductions where detailed research has been carried out, there was found to be substantial harm inflicted on non-target native species. Indirect effects such as food web subsidies and interactions and functional replacement of native species are often hard to detect or quantify, and until recently, have generally remained unconsidered (Pearson and Callaway 2003).

It is important to recognize that biological control has been practiced extensively in a wide variety of contexts and environments, and there are many examples of elegantly successful biocontrol programs with few or no recognized negative impacts (Caltagirone 1981, Van Driesche and Van Driesche 2000, see also review by Howarth 1991). Biological control as a scientific field has been active for more than a century (Thomas and Willis 1998), and many of the most notorious examples of failed (and often ecologically disastrous) interventions occurred early in the field's development. The mongoose example is more than 100 years old, and many have pointed out that a generalized vertebrate predator such as the mongoose would not be introduced to control an invasive species today (Thomas and Willis 1998, Van Driesche and Van Driesche 2000). The practice of biological control has certainly improved over time due to the experience of early mistakes, as well as with improved scientific understanding of how both naturally and artificially introduced invasive species adapt to and impact novel ecosystems.

The idea of geoengineering has been in the scientific literature for decades (Keith 2000), but has only recently been seriously considered as an option for responding to the problem of global climate change. In many ways the current state of scientific understanding of the climate system and the possible effects of geoengineering are more analogous to the early developments of the field of biological control than to current practices. Both biocontrol and geoengineering represent efforts to manipulate complex systems in the presence of substantial

Table 1. Summary of possible ecological analogues to the use of geoengineering as an intervention to counter anthropogenic climate change.

Problem	Cause	Intervention
• Invasive species	• Inadvertent species introduction	• Biological control
		• Introductions of host-specific viruses
		• Immunocontraception
		• Pesticides, herbicides, poisoning, hunting
• Endangered species	• Multiple causes: e.g. habitat loss	• Assisted colonization
		• Translocation
• Habitat destruction/degradation	• Multiple causes: e.g. resource extraction	• Ecological restoration
• Lake/forest soil acidification	• Acid rain/deposition	• Liming
• Water contamination	• Industrial and agricultural pollution (various)	• Permeable reactive barriers
		• Constructed wetlands
		• Phytoremediation
• Coastal eutrophication	• Agricultural fertilizers	• Large-scale seaweed cultivation

scientific uncertainty in our understanding of system structure and function. Like biological control, we can draw on knowledge of natural climate processes such as large volcanic eruptions for information's about how the climate system may respond to geoengineering interventions (e.g. Trenberth and Dai 2007); however, unlike biological control, we do not have any real-world examples of past geoengineering attempts from which to inform and refine our practice. In this sense, it seems likely that we are still at the 'mongoose stage' of the science of climate control and that geoengineering proposals, which may seem like elegant solutions to a global problem based on current understanding, seem likely to be missing crucial facts and connections. The specific risks associated with geoengineering schemes can only, as yet, be hypothesized based on current knowledge and understanding, and the potential for actions that appear to be well thought out to lead to unintended and disastrous consequences is high at this early stage.

4. Other ecological analogues to geoengineering

Biological control is in many ways an instructive analogy to geoengineering, but there are a number of other possible analogous types of interventions in ecological systems. There are numerous examples of environmental problems created as a result of human activities, and it is not uncommon for solutions to be attempted that involve additional intervention, rather than (or in addition to) efforts to decrease the original source of the problem. Several such possible analogous interventions are listed in table 1.

In the case of invasive species, biological control is clearly a top–down intervention that is aimed at controlling the spread of the original exotic species. There are other approaches to the problem of invasive species control, which may also be considered as partial analogies to geoengineering. These include the use of pesticides and herbicides (which have their own rich history of unintended consequences (e.g. Carson 1962)), direct target bating and poisoning, hunting and culling, immunocontraception (the introduction of agents to render a target species infertile), the introduction of infertile males, and introduction of viral diseases (Simberloff 2009, McCallum 1996, Henzell *et al* 2008, Jacob *et al* 2008). Such approaches have had both successes and failures, and carry their own risks (Simberloff 2009, Nogales *et al* 2004, Howald *et al* 2007, Priddel *et al* 2000, Fayrer-Hosken *et al* 2000, McCallum 1996, Nuñez 2009), but are also likely to be largely ineffective without measures to control the possibility of ongoing or re-introduction of the invasive species (Myers *et al* 2000, Howald *et al* 2007).

The planned movement of individuals or populations of a species has also been widely proposed and attempted as an endangered species conservation strategy (Young 1999, Minckley 1995, Ricciardi and Simberloff 2009). Species are at risk around the world for a multitude of human-caused reasons including habitat degradation, destruction and pollution, resource extraction, over-hunting and over-fishing, or indeed by previously introduced invasive species. Translocations are aimed at re-introducing a species to an environment where the species previously existed, but has become extirpated (Ricciardi and Simberloff 2009). Assisted colonizations are interventions aimed at introducing a species to a potentially favorable habitat in which it may have a better chance of persistence, but which lies outside the range in which the species evolved. Many such proposals for species re-introduction or assisted colonization have been hotly debated on account of both the high financial cost of this type of intervention, as well as the ecological risks associated with introducing any species into a changed or novel environment (Ricciardi and Simberloff 2009). As an extreme example of species movement intervention, some ecologists have proposed what has been called 'Pleistocene re-wilding', in which we might introduce proxies for extinct North American mega-fauna in order to recreate ecological conditions, evolutionary processes and selection pressures that existed before human colonization (Caro 2007). These interventions, though diverse in intent and feasibility, provide an interesting analogy to geoengineering by raising the question of to what extent it is possible or desirable to recreate ecological conditions that existed in the past but have been lost due at least in part to human activities. In the case of climate control, it is also critical that we consider whether the intent is to slow the rate of climate change, to maintain current climatic conditions, or to return global temperatures to some previous state.

A similar issue is also central to the field of ecological restoration, which provides another potential analogy to geoengineering. Restoration activities are clearly a direct human intervention aimed at correcting a past problem caused by human-induced habitat degradation and destruction (Higgs 2003). Ecological restoration is a diverse field; some large-scale technologically intensive restoration efforts may mirror geoengineering proposals fairly well, while small-scale community-involved efforts such as those described by Higgs (2003) as 'focal restoration' are less analogous.

Interestingly, restoration efforts have sometimes failed because of interaction between biotic and abiotic agents that were not adequately considered (Byers *et al* 2006); this may provide a partial analogy to geoengineering, which would also need to address complex and difficult-to-predict interactions between physical climate systems and the global biosphere. More generally however, although in a global context restoration is carried out amidst persistent degradation pressures, it is rarely the case on a local project level that restoration is attempted in a circumstance where active degradation is ongoing (though see Epstein *et al* (2001) for a report on strategies for coral reef restoration in the face of continued degradation from pollution and human recreational activities). We argue that geoengineering could only be accurately termed 'climate restoration' were it to be attempted after human emissions of greenhouse gases had been eliminated, for the purpose (for example) of returning global temperatures to past levels.

There is also an interesting analogy to be drawn regarding the effect of the simple existence of the possibility of post hoc technological fixes that both ecological restoration and geoengineering seem to provide. Early discussions surrounding ecological restoration included concern that conservation efforts would be diluted by the potential for restoration, since this potential might help sanction the continuation of ecologically destructive behaviors. Restoration ecologists reject this argument as erroneous, and argue instead that successful restoration can complement (rather than detract from) conservation goals by involving local communities, integrating an ethos of respect for natural systems, and engendering long-term commitments from stakeholders (Higgs 2003). In the case of geoengineering, some climate scientists have expressed concern that the possibility of geoengineering as a viable strategy to control global temperatures may divert attention, effort and incentive from the more important (and arguably more difficult) challenge of decreasing emissions of greenhouse gases (e.g. Matthews *et al* 2009, Robock 2008). However, unlike the focal restoration ecology described by Higgs (2003, 1997), most geoengineering schemes would by necessity occur on large geographical scales, and would require intensive technological investment. The requirements for advanced and specialized technological skills, as well as the large-scale nature of these potential projects carry ramifications rendering them much more difficult to integrate at the community level.

Another relatively simplified analogy to geoengineering can be found in efforts to remediate acidified lakes and soils by adding acid-neutralizing agents such as calcium carbonate to lake or forest ecosystems. Success has been reported in both field experiments and in practical applications, with the caveat that careful monitoring and a good understanding of soil and water chemistry is required so as to minimize adverse ecosystem impacts, and that repeated application is necessary in the context of continued acid deposition from atmospheric pollution (Huettl 1989, Henrikson *et al* 1995, Weatherley 1988). A similar analogue can be found in efforts to decontaminate polluted waters and soils by the use of permeable reactive barriers, constructed wetlands or other methods of phytoremediation (the use of plants to remove organic contaminants) (Blowes *et al* 2000, Cheng *et al* 2002, Susarla *et al* 2002). Seaweed cultivation has also been successful as a strategy to mitigate coastal eutrophication that has resulted from agricultural nutrient runoff (Troell *et al* 1999, Fei 2004). Like the case of geoengineering, these examples represent engineered solutions to environmental problems caused by diffuse pollution sources that are hard to regulate directly, and do not represent long-term solutions to the source problem. However, unlike geoengineering, these examples are localized in scale or occur in controlled areas, and generally occur in systems with relatively well-understood chemical and ecological mechanisms. As such the primary costs associated with these interventions relate to the required investment of money, time and continued monitoring, with relatively little potential for unforeseen ecological risk.

5. What can we learn from these ecological analogues?

A critical consideration surrounding any intentional human intervention is whether the actions taken are likely to increase or decrease net undesirable environmental impacts. This is illustrated conceptually in figure 1, which shows two possible outcomes of a decision to intervene in a hypothetical environmental system for the purposes of managing the unintended impacts of previous human activity. The dashed line represents the point of intentional intervention, after which this intervention may lead to either increased (A) or decreased (B) negative environmental impacts. We hypothesize here that a high degree of system understanding, combined with a relatively contained spatial scale or limited level of system complexity, is required to be reasonably confident that the trajectory of impacts following the decision to intervene will follow case B. Conversely, we argue that in the case of a global-scale system with both a high degree of system complexity and limited system understanding, environmental impacts are likely to follow case A and increase in proportion to the degree of human intervention.

There is also evidence from the range of examples that we have discussed here that the most successful and least environmentally detrimental interventions tend to be those that are both localized in scale and occur within the context of relatively well-understood systems. Using artificial or enhanced wetlands to decontaminate polluted water, or using seaweed cultivation to decrease coastal eutrophication represent localized and spatially contained interventions with relatively low potential for adverse impacts

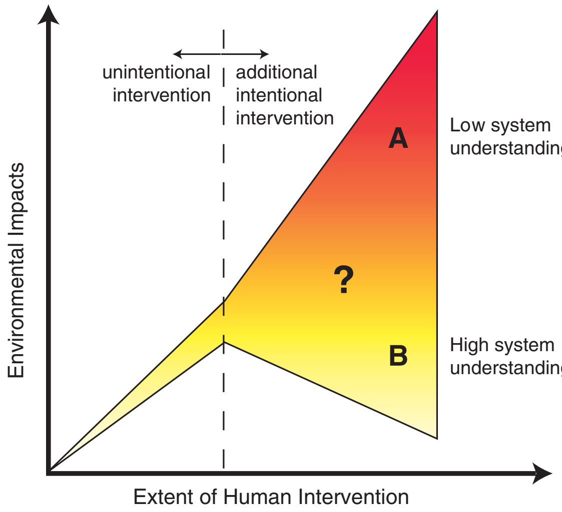

Figure 1. Conceptual relationship between human intervention and resulting environmental impacts. Where system understanding is low or incomplete, we hypothesize that additional human intervention in environmental systems leads to a net increase in undesirable or unforeseen environmental impacts. With increasing system understanding, it becomes increasingly possible that additional intervention in a system can lead to overall decreased negative impacts.

beyond the immediate local area (Blowes *et al* 2000, Cheng *et al* 2002, Troell *et al* 1999). Similarly, the use of reproductive technologies such as sperm storage and captive breeding programs carry a risk in terms of time and economic investment, but arguably carry relatively low ecological risk, especially for species that are already on the brink of extinction (Foose and Weise 2006, Wildt and Roth 1997, Fickel *et al* 2007).

By contrast, biological control, assisted colonization and species translocations involve complex and highly dynamic ecological systems, with the potential for the introduced species to migrate both spatially and ecologically beyond the intended location or ecosystem function, to carry pathogens to novel environments, to decrease overall biodiversity, and to have impacts on seemingly unrelated components of the ecosystem (Moore *et al* 2009, Pearson and Callaway 2003). For example, freshwater shrimp (*Mysis relicta)* were introduced to Flathead Lake in Montana, USA as an intended supplemental food source for kokanee salmon, which were themselves introduced as fishery stock. However, since kokanee feed diurnally in shallow water, and shrimp emerge from the deep-water sediments into the water column primarily at night, the shrimp proved not to be a viable food source. Instead, the shrimp competed with kokanee for a common zooplankton food source, leading to a dramatic decline in kokanee population numbers. As a result, this led to a decline in the local eagle population that was dependent on the salmon as a major prey species (Spencer 1991, Ricciardi and Simberloff 2009). Ricciardi and Simberloff (2009) argue that assisted colonization is 'tantamount to ecological roulette'.

There is also evidence within the field of biological control that where system understanding is limited, it is likely that the adverse consequences of intervention will exceed the benefits accrued (or costs avoided) from intervention. It is less evident at what point system understanding reaches a sufficiently advanced level to avoid disastrous ecological consequences of interventions. Mongoose and cane toads introductions, in hindsight, were clear mistakes, though some have argued that such errors would not be made today given much improved understanding of ecosystem ecology and the potential consequences of predator introductions (Thomas and Willis 1998, Van Driesche and Van Driesche 2000). There is a recent report, however, of the consequences of a mongoose introduction that occurred on a small island in Japan in 1979, underlining our ability to repeat past errors even with foreknowledge of the potential consequences (Watari *et al* 2008). Similarly, the predatory snail *E. rosea* has been introduced as recently as 1992, with arguably equally disastrous consequences (Civeyrel and Simberloff 1996) and the freshwater shrimp introductions described above occurred between 1968 and 1975 (Spencer 1991). These more recent cases may reflect a less advanced scientific understanding of invertebrate and aquatic population dynamics, but also question the argument that severe consequences of intervention are avoidable with increased time and experience.

Classical biological control can arguably be an effective and relatively low risk approach to controlling invasive species in cases where the system has been well researched and the risks have been weighed carefully against those associated with alternate approaches (Van Driesche and Van Driesche 2000, Simberloff and Stiling 1996, see also review by Howarth 1991). In practice, however, biological control has often been primarily motivated by economic concerns, such as damage to crops or fisheries, with less attention or value placed on the potential for adverse ecological impacts. There is a clear risk that decisions about implementing geoengineering may also be motivated by the perceived financial benefit of geoengineering, given the potentially larger economic costs associated with decreasing greenhouse gas emissions (e.g. Barrett 2008). A critical lesson from biological control may be that financially motivated interventions are more likely to follow the trajectory of increasing environmental impacts than those that are enacted based on a clear and well-informed analysis of the balance of environmental risk, and that place value on ecological processes, biodiversity, and long-term ecological sustainability and risk reduction.

Another recent critique of deliberate species introduction and translocation comes from Ricciardi and Simberloff (2009) in which they argue that a cost-benefit analysis of a proposed intervention is unlikely to provide an accurate estimate of the potential ecological costs of action, given insufficient understanding of the science of assessing and predicting environmental consequences of actions. They submit that even a careful assessment of costs and benefits is likely to result in attempting interventions that carry both a high potential for impact on the target system (highly effective interventions) and also a high potential for adverse consequences (high potential for risk). They argue further that this is precisely the circumstance in which intervention should not be attempted due to a likely underestimate of the potential negative environmental consequences relative to

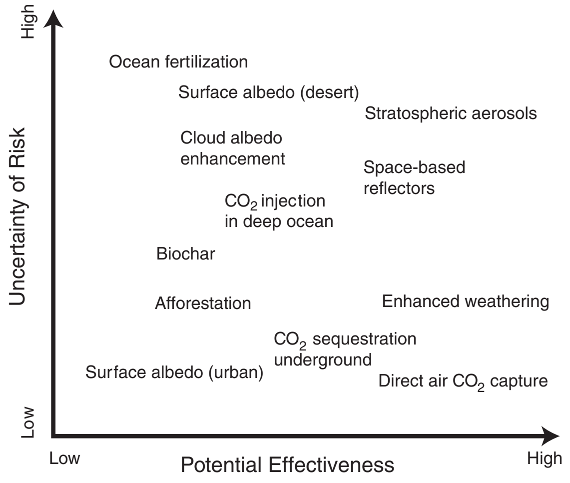

Figure 2. Proposed geoengineering schemes plotted according to their potential effectiveness (representing the potential benefit of a proposed intervention) and their risk uncertainty (representing the potential environmental cost of intervention). Many planetary-scale genengineering schemes fall at the upper right, carrying the potential for both high impact and also high uncertainty of risk (figure adapted from Ricciardi and Simberloff (2009); risk classifications based on Keith (2001) and Royal Society (2009)).

the more easily quantified economic benefits of intervention. Based on this, Ricciardi and Simberloff (2009) suggest that interventions should only be undertaken in cases where the potential effectiveness and risk uncertainty are both small.

This argument can be equally applied to proposed geoengineering interventions. In figure 2, we have adapted figure 2 from Ricciardi and Simberloff (2009), and have overlaid a qualitative estimate of the potential effectiveness and risks associated with various geoengineering proposals, based on table 1 of Keith (2001) and table 5.1 of Royal Society (2009). Planetary geoengineering schemes (e.g. aerosol geoengineering) can be considered to be in the category of high risk/high effectiveness interventions, whereas some local schemes like urban surface albedo modification could be considered to be at the opposite extreme (low risk/low effectiveness). Some schemes (e.g. direct air CO_2 capture and underground CO_2 sequestration) can be considered to be highly effective but relatively low risk, whereas others (e.g. ocean fertilization) have relatively high risk, but limited proven effectiveness or impact.

A typical cost-benefit analysis may conclude that proposals at the upper right of figure 2 (high effectiveness, high risk uncertainty) have more net benefits than costs and therefore may warrant consideration as a reasonable response strategy. However, Ricciardi and Simberloff (2009) argue that in the case of ecological interventions, such analysis is unlikely to predict the true environmental cost of the proposed intervention and that high risk/high effectiveness interventions are those most likely to have unforeseen and potentially disastrous consequences. We suggest here that this same argument can be applied to proposed climate interventions, and that high risk/high effectiveness interventions must be approached with both caution and an awareness that we are unlikely to be able to fully predict the risk of potentially serious adverse consequences.

6. What conclusions can we draw?

The ecological literature provides a rich source of examples of human intervention in complex systems, which have resulted in complex and unanticipated consequences. Biological control is a close analogy to geoengineering in that: (1) interventions are often undertaken to correct past impacts that have resulted from previous inadvertent interventions; (2) controlling the source of the original problem is often considered to be too difficult or costly; (3) interventions can carry a high risk of adverse ecological impacts; and (4) the target systems are typically complex and often not well understood, leading to increased potential for unpredictable consequences of intervention. Unlike geoengineering, biological control: (5) is usually—though not always—localized in scale; and (6) is often repeated in multiple similar systems over time, enabling the potential for testing theory and learning by trial and error.

Biological control and other similar interventions also carry several characteristics which at present represent only partial analogies to geoengineering proposals, and which could serve as possible lessons that could be applied to the current geoengineering discussion. In particular: (7) interventions have often been implemented for primarily economic reasons, rather than out of concern for environmental impacts, and such interventions have generally had more severe ecological consequences; (8) biological control has often been implemented at the last minute when other interventions have failed, leaving little time for comprehensive risk assessment; (9) interventions have usually not been accompanied by sufficient attention to or monitoring of potential non-target impacts; and (10) biological control has often been implemented in high risk/high effectiveness circumstances, which increases the potential for large negative consequences. These are all potentially avoidable mistakes, which we would do well to consider explicitly when discussing deliberate climate intervention as a response to anthropogenic climate change.

Anthropogenic climate change is a global-scale crisis with the potential for very severe consequences for both human and environmental systems. In this sense, climate change is clearly at a very different spatial scale from the ecological examples which we have considered in this letter, and as such the consequences of inaction are also potentially much more far-reaching. However, the physical climate system carries a level of complexity comparable to the complexity of ecological systems, and it is for this reason that we feel that there are appropriate analogies to be drawn with past attempts to control and manipulate complex ecological systems. Furthermore, the scale and complexity of the global climate system, which underlies the potential for harmful and unpredictable impacts of climate change, is also what makes the consequences of intervention both unpredictable and potentially severe. The evidence from past ecological interventions does not impart confidence in our ability to either predict or control the results of attempts at deliberate climate control.

Thirty-five years ago, Kellogg and Schneider (1974) speculated as to whether we would ever know enough about climate prediction to be able to predict the outcome of deliberate climate intervention. Climate science has seen phenomenal progress in scientific understanding in the past few decades, but each new step in understanding has also revealed new areas of uncertainty that were not previously considered. We know more, and also have a better sense of what we do not know, than was the case when Kellogg and Schneider wrote on this topic, but we are still very far from being able to predict with confidence the consequences of climate intervention. It is very difficult to know at what point we may reach a sufficient level of understanding of the climate system to be confident that deliberate intervention will have the desired effect; this is clearly a central question to consider in any discussion of geoengineering as a possible response strategy to global warming. It is also clear that we must approach the question of geoengineering with both caution and an awareness of the lessons from past ecological interventions, so that we do not put ourselves in a situation where in hindsight we wish that the mongooses had never been released at all.

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