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Optimal geoengineering experiments[☆]

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ABSTRACT

We characterize optimal investment in pollution control measures with uncertain effects that can be learned by experimentation. The anticipation of learning through experimentation introduces two effects. The Inquisitive Effect appears because the planner wants to invest in geoengineering to gather socially valuable information on its effects. This effect encourages investments in geoengineering and may justify field tests even where the expected benefits fall short of the costs. The Flexibility Effect stems from the planner optimally preparing for the post-learning stage, where the field test is either ramped up or scaled down, depending on the outcome of the experiment. This effect can encourage or discourage investments in geoengineering. We demonstrate this set-up through an economic analysis of an artificial oxygenation scheme designed to mitigate eutrophication in the Baltic Sea and find that while the expected marginal benefit falls short of costs, a field test representing some 10 percent of full deployment would be optimal.

1. Introduction

Recent years have seen increasing interest in measures designed to alter stock dynamics of polluting substances. Examples abound, including proposed climate engineering schemes, as well as measures that are already routinely used in other fields, such as biomanipulation of food webs and treatment of eutrophied water bodies using oxygen, aluminum or iron.[1] A distinctive feature of many such "geoengineering"[2] methods is the substantial uncertainty overshadowing their effectiveness. Unlike in the case of measures to reduce emissions, uncertainties related to large-scale geoengineering projects, almost by definition, cannot easily be resolved in controlled small-scale experiments. The true impact of these methods can only be learned through large-scale experimentation, that is, partial implementation of the method itself.

The relevant question in the case of geoengineering is not only whether they should be implemented on a large scale, but also under what conditions experiments should be undertaken prior to possible full-scale deployment. For instance, several recent studies have called for field tests in climate engineering (Buesseler et al., 2008; Keith et al., 2010; Long et al., 2015) and

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[1] For discussion and examples of biomanipulation of foodwebs and geoengineering in lakes, see the special issues of Freshwater Biology (Kasprzak et al., 2002) and Water Research (Lürling et al., 2016).

[2] The term "geoengineering" is sometimes used as a synonym for climate engineering, that is, manipulation of the climatic system in order to limit adverse effects of climate change. In this study, we follow the recent literature in adopting a broader definition of the term, used by Conley (2012) and Lürling et al. (2016), among others.

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experimental manipulation of entire ecosystems (Carpenter et al., 1995, 2011), but not everyone agrees with these suggestions.[3] The arguments against large-scale field tests can be broadly divided into three categories: (i) The expected benefits do not justify the costs and risks of the experiment (Robock et al., 2008; Blackstock et al., 2009); (ii) large natural variability precludes learning and forces any meaningful experiment to be almost the size of full deployment (Strong et al., 2009; Robock et al., 2010); and (iii) the effects of the experiments may not be fully reversible (Robock et al., 2008). The purpose of this paper is to provide a tractable model to address the following questions: What roles do the abovementioned reservations on natural variability and irreversible effects play in the design of optimal experimentation? Under what conditions is a field test the preferred choice and how large should the optimal field test be?

In our model, the social planner makes investments in geoengineering to maximize the social welfare while at the same time acquiring new information and revising policies as new information arrives. An immediate effect of the inclusion of learning is that it negates the usefulness of the standard cost-benefit rule, for the optimal investment is no longer based solely on expected benefits and costs, but also depends on the prospects of learning and the flexibility of the method. We derive an Euler equation describing the optimal investment in geoengineering and identify two additional effects that appear when learning is introduced: the Inquisitive Effect and the Flexibility Effect. The Inquisitive Effect appears because the planner wants to invest in geoengineering to gather socially valuable information. As it is easier to distinguish the effects of a large investment from natural stochasticity, a larger field test speeds up learning. This effect thus encourages investments in geoengineering and, moreover, may justify field tests even where the expected benefits fall short of the costs. The Flexibility Effect stems from the planner optimally preparing for the post-learning stage, where the field test is either ramped up or scaled down, depending on the outcome of the experiment. If geoengineering does not work as intended, or has serious side-effects that prevent large-scale deployment, all the previous investments are wasted or even harmful and the planner phases out the field test; to limit these sunk costs and irreversible side-effects, the planner prefers small field tests and this discourages investment in geoengineering. If geoengineering turns out to be effective and has no serious side-effects, the planner ramps it up, which is cheaper in the case of a larger initial investment; this favors larger field tests and encourages investment. The sign of the Flexibility Effect depends on the interplay of these two eventualities and is therefore generally ambiguous.

As an application of our model, we analyze a proposed scheme for artificial oxygenation of hypoxic sediments as a measure to mitigate eutrophication in the Baltic Sea, Northern Europe. The prospective use of this geoengineering method is highly disputed among academics (Stigebrandt and Gustafsson, 2007; Conley, 2012) and it serves as one example where large scale intervention in an ecosystem is seriously being discussed on the political level (HELCOM, 2014). In the application we consider two kinds of uncertainties related to artificial oxygenation: the effectiveness of oxygenation in reducing benthic hypoxia and the risk of hazardous side-effects. The model is calibrated statistically by making use of the variation caused by a natural event that decreased the size of the hypoxic area in the sea drastically in the beginning of the 1990s.[4] In an attempt to quantify the uncertainty within the scientific community, we have gauged prior beliefs using a survey carried out among researchers specialized in hypoxia in the Baltic. Our results indicate that it is not optimal to invest in oxygenation without learning, but investing becomes profitable when learning is taken into account. The expected marginal benefits of reduced eutrophication fall short of the marginal costs and the expected marginal damages due to hazardous side-effects of oxygenation (−15 MEur under the optimal policy). Notwithstanding the negative expected welfare effects, the inclusion of learning introduces the Inquisitive Effect (121 MEur) and the Flexibility Effect (−100 MEur), which make a field test representing some 10 percent of the full deployment optimal.

Most economic analyses of geoengineering carried out to date have focused either on known or expected benefits and costs, and have primarily sought to determine whether full geoengineering schemes are socially beneficial (Nordhaus, 1992; Carlin, 2007; Gramstad and Tjøtta, 2010; Moore et al., 2010; Goes et al., 2011; Bickel and Agrawal, 2013; Aaheim et al., 2015; Bahn et al., 2015; Ollikainen et al., 2016). We contribute to this literature by introducing the possibility of resolving uncertainty by experimentation. As argued above, and as will become clear in the course of our analysis, the inclusion of learning is more than merely a technical consideration, for it introduces new effects that may overturn the results of the standard cost-benefit analysis. A few studies have analyzed passive learning, that is, the effect of an exogenous learning process on the optimal investment in geoengineering (McInerney et al., 2012; Moreno-Cruz and Keith, 2013). In a recent study, Quaas et al. (2017) considers an inter-generational setting where a decision maker can choose to invest in research that always reveals the true effects of geoengineering but may choose not to do so in the presence of time-inconsistent preferences. The present study focuses on a different question, namely, the optimal design of field tests where the planner is assumed to be time-consistent, and focuses on the trade-off between the speed of learning and irreversibilities.

More generally, our study is connected to those of Kolstad (1996) and Pindyck (2002) who analyze the role of sunk investment costs in pollution abatement capital in a setting where learning is passive. Following the concepts and ideas introduced earlier by Arrow and Fisher (1974), Henry (1974) and Dixit and Pindyck (1994), the planner dislikes irreversibilities such as sunk

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[3] For instance, perhaps the largest field experiment in geoengineering to date – the dumping of 100 tons of iron sulfate into the Pacific Ocean off the west coast of Canada by private businessman Russ George in 2012 to reduce atmospheric CO_2 levels and to restore the depleted salmon stocks – was widely condemned by lawyers, environmentalists and civil society groups (Lukacs, 2012). Similarly, the LOHAFEX iron fertilization experiment in 2009 was heavily criticized by nongovernmental organizations (Van der Zwaag, 2011).

[4] Natural phenomena can help to estimate critical parameters related to geoengineering methods; for example the eruption of Mt. Pinatubo has been used to estimate the effectiveness of solar radiation management (McCormick et al., 1995). In the present study, we make use of a delay between salt pulses from the North Sea into the Baltic, which weakened the halocline and naturally reduced the size of the hypoxic area.