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The added value of real options analysis for climate change adaptation

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Abstract

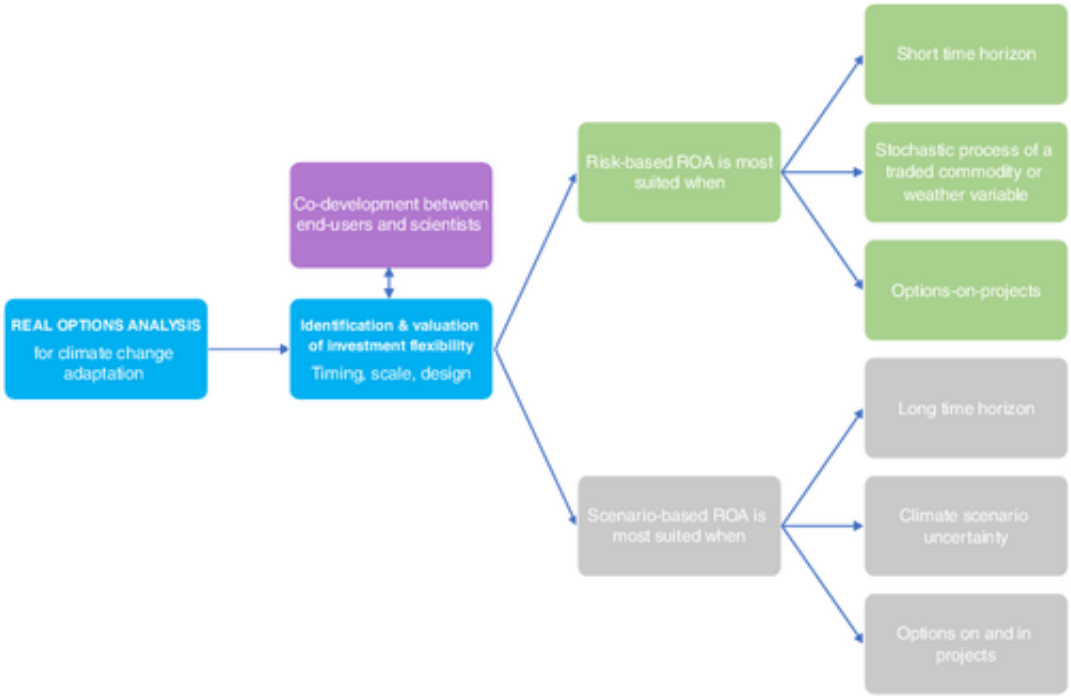
Climate change adaptation investment decisions can be made more efficiently if uncertainty and new information are considered in their economic appraisal. Real options analysis (ROA) is a robust decision-making tool that allows for the incorporation of both uncertainty and new information. In this opinion article, we argue that ROA is a valuable tool, providing the analysis is designed to reflect the real-world characteristics of the decision context. We highlight the differences between traditional risk-based ROA, and scenario-based ROA, and discuss the relative merits of the approaches from the perspective of their assumptions and use of climate information. We also emphasize the need for increased co-development of ROA design and applications with end-users. Given the large climate uncertainties for long-term adaptation planning, we suggest that an emerging strand of scenario-based ROA methods offers ways to help identify and conditionally value flexibility without aggregating values into precise expected values across states of the world.

This article is categorized under:

Climate Economics > Iterative Risk-Management Policy Portfolios

Abstract

Real options analysis (ROA) can enable economically efficient adaptation investment decision-making. Through identifying and valuing flexibility, ROA can support decisions in an uncertain future.



1 INTRODUCTION

Today's climate adaptation planning decisions need to anticipate future climate-related changes, even while the exact timing and magnitude of climate change impacts remains uncertain (Wilby & Dessai, 2010). Uncertainty stems from a range of sources (e.g., knowledge or epistemic uncertainties, as well as social and economic uncertainties), but in this article we refer to it generically to mean “any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system” (Walker et al., 2010). In the context of climate change, with many plausible futures, deterministic approaches to long-lived decisions are insufficient (Shepherd et al., 2018). As a consequence, there is increasing interest in approaches to support decision-making under uncertainty (IPCC, 2019). Using techniques from economics and finance, mathematics and social science, these approaches can handle uncertainty and changes in information over time better than more traditional economic appraisal tools (Dittrich, Wreford, & Moran, 2016). Principles such as flexibility, learning, and diversification are used in the design of practical adaptation plans and projects, helping to ensure adaptation remains “robust” across a range of potential futures. Robust decision-making principles recommend avoiding irreversibility and favoring “soft” measures, such as managerial or institutional changes, over “hard” engineering measures where possible (Hallegatte, 2009). Yet, in many cases the latter are unavoidable.

Infrastructure often involves large and irreversible investments, including power plants, sea walls, water storage, and wastewater treatment facilities. Such investments have lifetimes of several decades or longer. Ensuring that investments remain functional into the future is essential to avoid wasted expenditure or future vulnerability. The pace and magnitude of changes that climate change presents, require a similar magnitude of change in our decision-making processes and methods. However, predicting exactly what the climate will be in future is impossible, due to unavoidable uncertainties both within and across scenarios (IPCC, 2013).

There are a wide range of robust decision-support methods and approaches for the economic appraisal of adaptation (Dittrich et al., 2016; Watkiss, Hunt, Blyth, & Dyszynski, 2015). Moreover, complementary approaches from beyond economics can be applied, such as the adaptation pathway approach (Haasnoot, Kwakkel, Walker, & ter Maat, 2013). Each approach has strengths and weaknesses and suitability for particular contexts. In this paper, we focus on one robust decision-making approach, real options analysis (ROA), which extends the principles of cost–benefit analysis (CBA) by allowing for learning over time. ROA is particularly suited for the appraisal of an adaptation investment that will be long-lived and irreversible. Unlike traditional CBA, ROA provides economic information about real options, which can be loosely defined as conditional investment actions, for example whether to invest now, delay investment, or invest partially now and retain the option to invest further into the future, or to abandon the project. The ROA umbrella is not restricted to the analysis of the efficient timing of a single project or of one particular type of action, but can also encompass several options staged over time in logical sequences. ROA can therefore also be applied in a more general context to investigate the value of new information and cost and flexibility tradeoffs in an adaptive plan. Due to sunk costs and future lock-ins, option valuation is essential to assess the economic performance of investments with a long life time in the context of climate change uncertainty. This explicit incorporation and valuation of uncertainty and new information in the economic appraisal is the added-value of ROA.

In this opinion article, we maintain that the advantages of ROA for large, long-lived investments in the presence of uncertainty are critical, and that ROA is an essential part of a toolbox of approaches to support decision-making under the “wicked” problem of climate change. We assert that some of the barriers to more widespread adoption by decision-makers can be overcome by developing simpler approaches to ROA, ideally in conjunction with end-users. As the ROA umbrella encompasses a range of differing approaches with varying levels of complexity and types of uncertainty, we discuss the origins of ROA and describe the traditional approach. In Section 3, we discuss the recent growth in ROA studies in the academic literature, and examine the potential for scenario-based ROA to overcome

some of the limitations of the more traditional applications. Section 4 provides a discussion of potential ways to enable greater adoption of ROA and some concluding observations.

2 REAL OPTIONS ANALYSIS: ORIGINS, APPROACHES AND APPLICATIONS

2.1 Origins of ROA

With its origins in financial economics, ROA is the extension of financial option pricing theory (Black & Scholes, 1973; Merton, 1973) for managing real assets. In ROA, options are left open in the future, assuming a gradual resolution of uncertainty. The solution of real options models is based on different techniques, such as Monte-Carlo path dependent simulations and binomial or multinomial trees (Kontogianni, Tourkolias, Damigos, & Skourtos, 2014). The method selected will depend on the available data, the type of option and the desired simplicity.

With an increasing application in the literature and more general interest in different approaches to handling uncertainty, ROA is referred to broadly and used in many contexts, with some ambiguity over what constitutes a ROA. In part this is caused and exacerbated by the range of approaches falling under the ROA umbrella. Here, we distinguish between what we refer to as “traditional” ROA, which applies risk-based models from the financial options pricing literature (Dixit & Pindyck, 1994; Trigeorgis, 1995), and “scenario-based” ROA, which values investment flexibility within or across scenarios. Examples of the latter are scenario tree analysis (Conrad, 1980), which assign probabilities to climate scenarios as if these are probabilistic states of the world (e.g., Abadie, 2018). Other examples that we will classify as scenario-based approaches are probability threshold analysis (Lempert, 2014), or the recent economic evaluation extension of the adaptation pathway method (Haasnoot et al., 2019). We introduce both traditional and scenario-based methods and provide examples of applications to discuss their usefulness for climate change adaptation.

2.2 Traditional risk-based ROA

Traditional risk-based ROA approaches assume that expected values and conditionally optimal actions can be computed over time. This setting is typically applicable if the future states of the world are known, and if their realizations are probabilistic and observable, an assumption that has led to criticism of ROA for climate change analyses (e.g., Kalra et al., 2014). We discuss this limitation further in the paper. The majority of traditional ROA studies are found in the energy and infrastructure domain (Fernandes, Cunha, & Ferreira, 2011), but here we focus on climate change adaptation applications of the binomial tree model of Cox,

Ross, and Rubinstein (1979). This model has been frequently applied in the climate change adaptation literature, and does not use difficult mathematics (for which ROA is generally notorious (Dittrich, Butler, Ball, Wreford, & Moran, 2019)).

The binomial model was originally designed to value financial options. As the model name indicates, there are only two possible state changes at each point in time, so it is a discrete state-discrete time model. In finance, ROA works through a "call option," which gives the right, but not the obligation, to buy a stock at a specified price, the "exercise price," before or at some specified date in the future: the "expiration date." If the stock price is lower than the exercise price at the expiration date, then the option has no value. If the stock price is higher than the exercise price at this date, then the option value is equal to the difference between the stock price and the exercise price. To determine the option value at any other moment, option values are computed backwards in time (Cox et al., 1979). For example, one period before the expiration date the stock price can still go up or down once. The option value is computed from a probability that the stock price goes up or down with a multiplication factor. These up and down factors, in turn, are estimated from the price volatility of the underlying asset: the stock price.

With this structure of the binomial model in mind, its technical application to climate change adaptation projects is simple. For example, decision-makers may need to know whether it would be better to invest in an adaptation project now, or to delay the decision into the future. Examining the parameters of the binomial model for the adaptation problem at hand can help inform this decision. The expiration date corresponds to an appropriate specification of a relevant finite time horizon for the adaptation problem. The exercise price amounts to the costs to invest in the project, for example, building a protection measure, and the current price of the underlying asset is defined by some variable that explains the stream of the revenues of the project, for example, the damage avoided from flooding from the measure. Lastly, its volatility is estimated from the available observations or climate change scenarios, for example, changes in rainfall intensity over time that lead to flooding. Other examples of variables used to represent the volatility of the project revenues are derived from annual flood damage data in Park, Kim, and Kim (2014), probabilistic sea level rise scenarios in Abadie, Galarraga, and de Murieta (2017), and minimum and maximum annual flood frequency values computed among climate projections (Ryu, Kim, Seo, & Seo, 2018).

Many ROA applications of binomial tree models exist in the climate change adaptation literature. This includes the wait option, also called "deferral option," to improve an urban drainage system under climate change (Park et al., 2014), the deferral option to invest in a canal to reduce flood risk (Abadie, Sainz de Murieta, & Galarraga, 2017), and deferral and

abandon flood mitigation options under climate change uncertainty (Ryu et al., 2018) as well as compound options in the upgrading of a hydropower plant (Kim, Park, Bang, & Kim, 2017). Another application explores investment in research and development for a drought tolerant crop (Wynn, Spangenberg, Smith, & Wilson, 2018).

A number of ROA applications assume a stochastic process similar to the stochastic process in the binomial model but in continuous time, a Brownian Motion with drift, which is also used in finance applications, to describe the underlying climate variable. Examples include the estimation of coastal flood impacts (Abadie, Galarraga, et al., 2017) or flood protection decisions (van der Pijl & Oosterlee, 2012) under rising sea levels.

2.2.1 Ensuring the model is appropriate for the context

Ideally, models should be designed to fit the characteristics of the problem and decision context and not vice versa. ROA will not be suitable in all contexts, and the traditional ROA model will also not always be appropriate. The problem context should be carefully considered, including questions such as (1) which model features are more or less realistic and how can they be modified?; (2) is the uncertainty representation suitable for the adaptation problem at hand and if so, in what way?; (3) are the options that can be analyzed with the real options method actually relevant for the adaptation decision?; and (4) are the institutional arrangements capable of managing a decision sequence over potentially long time periods?

Option valuation with traditional ROA methods generally requires an observable variable explaining the stream of benefits, revenues or cashflow of an investment, and whose changes over time can be described by a stochastic process. Ideally, this will be a market price of a traded commodity, for example energy or water prices, such as in the case of hydropower plants (Kim et al., 2017) or profits linked to irrigation dams (Michailidis & Mattas, 2007). In other cases, such as in the flood risk adaptation applications (Dittrich et al., 2019), rainfall or water level observations can serve as a starting point, but for these examples there is clearly more noise between those observations and option valuation.

Other features in the binomial model can be relaxed or changed, for example risk neutral valuation may be useful in a corporate adaptation context where the investment revenues depend on the price of a financial asset, but is less useful in a context of public adaptation investment where a wider range of values are considered. Also, there is an assumption about constant volatility in the binomial model that may or may not be realistic, as distributions can be updated based on observations over time. However, other stochastic processes or endogenous probabilities can be considered depending on the underlying variable that is relevant for the adaptation project.

The latter brings us to the second and more fundamental question: traditional ROA methods are risk-based methods, which may seem impossible to reconcile with many climate change adaptation decisions that involve deep uncertainty, where probabilities cannot be assigned (Kalra et al., 2014). Traditional ROA assumes that uncertainty reduces probabilistically, for example as time series of data grow longer, and model uncertainties in climate and hydrological models are reduced. The need for agreement on probabilities means the technique can be vulnerable to bias, gridlock and brittle decisions (Kalra et al., 2014). Most applications of ROA make simplifying assumptions regarding the probabilities of future climate scenarios to avoid estimating the likelihood of different climate scenarios. In the construction of a binomial tree, probabilities of each path need to be assigned to the transition "nodes," for example based on the Global Circulation Models and RCPs (Representative Concentration Pathways). Other studies assume the climate scenarios are equally likely (e.g., Gersonius, Ashley, Pathirana, & Zevenbergen, 2013).

We would however like to propose a more nuanced perspective. First, the time horizon of the adaptation problem being considered and the relative importance of scenario uncertainty within this time horizon is of critical importance. For example, if an option to delay an investment in coastal infrastructure will only last for a few decades, then sea level rise projections in this time frame do not differ meaningfully across RCP scenarios in most places (e.g., Kopp et al., 2014). Probabilistic projections that are used in traditional ROA are then a natural starting point. In a context of deep uncertainty with long time horizons, this is not the case, but stochastic process assumptions for ROA can still be applied, for example within RCP scenarios, such as in Abadie, Galarraga, et al. (2017) to study long run flood impacts.

Finally, traditional ROA is predominantly useful for climate change adaptation cases where the options for flexibility are known, and where these options are options "on" projects. For example, we have seen applications of the binomial tree model to analyze options to wait, as well as scale or extension options, abandon options, and compound options, that is, options on options. The latter were valued in Ryu et al. (2018) and Kim et al. (2017) for example. If options for flexibility still have to be identified, or if these involve structuring decisions over time, such as valuing design options such as adding air conditioning in a building at a later date or flood defense designs that can be more easily upgraded (flexibility "in" projects), then other RO methods may be more suitable (Wang & De Neufville, 2005), as we will discuss in the following section.

3 FROM SCIENCE TO PRACTICE: THE BENEFITS OF ROA FOR DECISION-MAKING

3.1 The increasing number of ROA studies in the academic literature

From planning flexibility for flood risk reduction to investment options of research and development spending on drought resistant crops, literature applications of ROA have grown into a developed niche of the climate change adaptation literature, with the large majority of climate adaptation publications on ROA appearing since 2010. For example, a Google Scholar search with "water" + "real options" + "climate" generates more than seven thousand hits, from which three quarters have been published since 2010. Yet, whereas there are many CBA applications in, for example, the flood risk domain that have been used to inform real-world decisions (see for example, Bos & Zwaneveld, 2017), ROA approaches have yet to reach a similar level of real-world decision-support. This begs the question: To what extent can ROA assist with adaptation decision-making in a practical sense? In this paper, we discuss a range of studies in the literature to draw out the contexts in which ROA could provide the greatest benefits to decision-making.

We searched Scopus and Web of Science for the terms "real options," "climate," and "adaptation" and identified 65 studies. Mitigation or other applications than climate adaptation were excluded. Papers with a theoretical discussion of ROA rather than an application, and conference proceedings and other gray literature were also excluded. From this sample, we identified 39 peer-reviewed studies that have been published since 2011. Figure 1 illustrates the publications on ROA over the last eight years, demonstrating a marked increase over time.

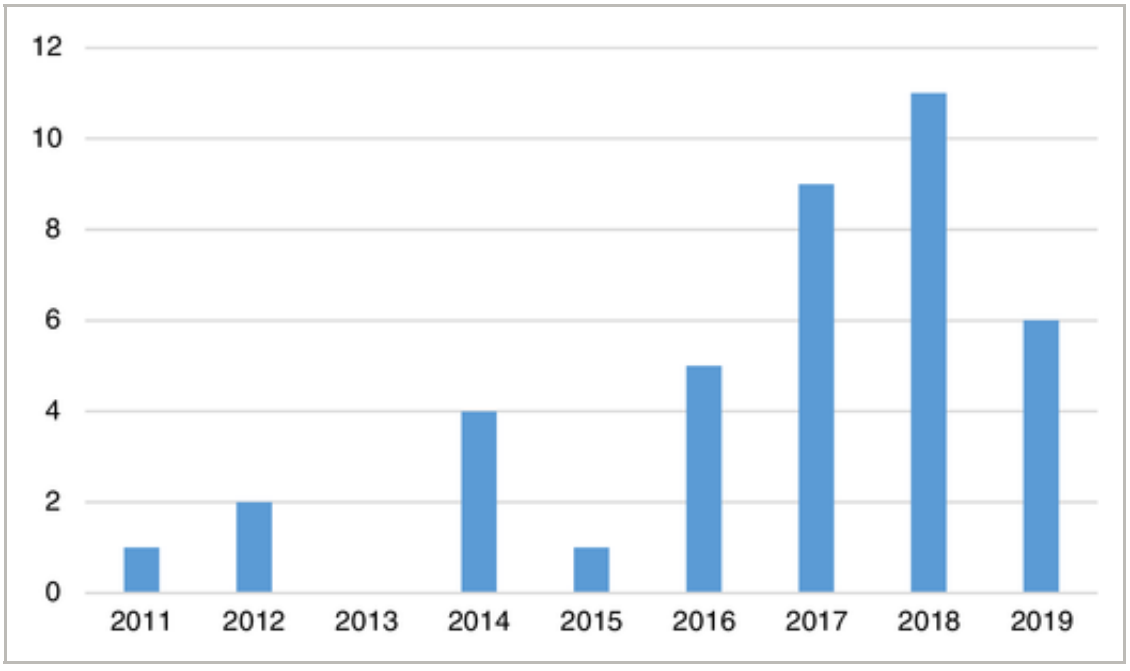


Figure 1

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Findings from the literature demonstrate a range of benefits from applying ROA instead of a more traditional CBA. Many studies find that incorporating flexibility and the value of information over time can lower the overall cost of adaptation projects (e.g., Dittrich et al., 2019; Gersonius et al., 2013; Woodward, Gouldby, Kapelan, Khu, & Townend, 2011; Woodward, Kapelan, & Gouldby, 2014). Depending on the situation, ROA can result in more efficient decisions. In the case of dam construction in Ethiopia (Jeuland & Whittington, 2014), no single efficient plan existed across plausible futures, because no probabilities could be assigned to key uncertainties (in that case deep runoff and water demand uncertainties). To overcome this problem, a ROA was combined with a robust decision-making approach. ROA enables the potential value of flexibility to be determined, by comparing lowest downside and highest upside NPV for different investment sequences across scenarios, which leads to the identification of a dominant starting point where dam construction is always most attractive, that is, the location where the option to build would be exercised first. Further, by investigating an extreme case of perfect learning, ROA is used to show that delaying investment for one dam would be inefficient no matter the conditions due to the size of the forgone benefits from waiting. In other cases, however, for example the case of farmer production regimes in the South Australian wheat belt (Sanderson, Hertzler, Capon, & Hayman, 2016), there is a positive value to delaying a regime switch until the expected benefits of the switch are sufficiently large.

Despite the demonstrated economic advantages in the literature, examples of ROA applied in practice are still limited. Explanations for this include the relatively high complexity and resource-intensiveness (Herder, de Joode, Ligtvoet, Schenk, & Teneja, 2011), although recent applications identify simplified approaches that overcome many of these barriers (e.g., Dawson, Hunt, Shaw, & Gehrels, 2018; Dittrich et al., 2019). In the following sub-section, we describe “scenario-based ROA” which has the potential to overcome some of the limitations of traditional ROA approaches, and complement other processes for acting under uncertainty.

3.2 Scenario-based ROA

As the name suggests, scenario-based ROA methods apply scenarios, which can be both about plausible futures as well as about plausible changes in the current understanding of a system (“learning scenarios,” Hinkel et al., 2019). Scenario-based ROA methods provide imprecise monetary information about individual options, the value of new information or pathway flexibility. The requirement to derive imprecise monetary information is clearly less

demanding than to compute precise expected values over time and circumvents some of the criticisms about traditional ROA: The states of the world do not have to be fully known, and the future does not have to evolve in a well-defined probabilistic manner. Examples of scenario-based ROA are methods that do not interpret scenarios as states of the world, but assign imprecise probabilities to them or use them to study probability thresholds, and methods that only compute conditional option values or costs under different scenarios, decision tree branches or pathways but do not (probabilistically) aggregate them.

A wide range of scenario-based ROA have been applied to climate change adaptation problems, some of which overcome the inability to assign probabilities to long-term climate futures. Some methods apply a scenario of perfect learning at a given moment in time to investigate the value of flexible designs, for example a dike with a wide base that can be upgraded according to the sea level increase in 2040 (Woodward et al., 2011), or a scenario of gradual uncertainty resolution to analyze trade-offs between a more and a less flexible adaptation measure, for example a hard versus a soft coastal flood protection measure (de Bruin & Ansink, 2011). Other scenario-based ROA sample from climate change scenarios or assign probabilities to the scenarios (Abadie, 2018; Woodward et al., 2014), or use observed changes between two rounds of sea level rise projections to estimate option values (Dawson et al., 2018). The latter apply subjective probabilities to simulate alternative attitudes to uncertainty of the decision-maker, an approach that may provide a more user-relevant way to engage with ROA. More generally, in the scenario-based approach, options are computed for scenarios (narratives), for example by interpreting them as probabilistic states of the world or by computing conditional option values for learning scenarios.

Moreover, recent methods have begun employing imprecise probabilistic concepts, for example by the analysis of scenario probability thresholds that would change the choice of an adaptation alternative (Lempert, 2014) or by using a set of probability distributions or multiple sets of probabilities (Dawson et al., 2018). Although named differently, scenario-based real option valuation has recently also entered the adaptation pathways method (Haasnoot et al., 2019), which has become widely used in the climate change adaptation literature in recent years.

By using scenarios rather than probabilistic states of the world, scenario-based ROA is more appropriate for deep climate change uncertainties than traditional ROA. Scenario-based approaches generally tend to make fewer restrictive assumptions than traditional ROA which makes them more defendable, because they do not assume a single set of probabilities or a single probability distribution for climate futures. Also, they can be applied in cases where there is a fuzzy relationship between a mix of sources of new information, such as new observations and new climate change studies, and the value of flexibility. Other

advantages of this type of ROA for climate change adaptation is that they are generally easier to communicate and more useful in interaction with stakeholders. Indeed, there is significant value to decision-makers in learning about story lines, path dependencies, lock-ins, and the various options to increase flexibility, including design flexibility, with scenario trees or similar instruments as a first step before the actual ROA. Moreover, these methods may also support decision-making by building consensus and may be more closely connected to existing cost–benefit practices.

4 DISCUSSION AND CONCLUSION

Currently, despite the potential of ROA to save costs, avoid costly lock-ins, and to increase flexibility, CBA practices that disregard investment flexibility valuation continue to dominate in practice. This may be in part due to the complexity of implementing and communicating the more common traditional ROA, and in part because it takes time for public authorities to adopt new techniques (Schedler, Guenduez, & Frischknecht, 2019). This was also once true for CBA, although it is now applied ubiquitously (for background, see Pearce, 1998). However, there is also anecdotal evidence that flexible adaptation solutions are implemented without a formal real options valuation tool, which may pave the way for ROA the future. For example, in the case of the Dutch IJssel lake area, flexibility was achieved through additional pumping capacity (Centraal Planbureau, 2014) and in Schleswig Holstein, Germany, dikes have been made wider to allow for a relative cheap increase in height in the future if needed due to sea level rise (Melur, 2013, p. 45). Moreover, some CBA guidelines include ROA. For example, the UK Greenbook includes a section on ROA (HM Treasury, 2018). Other countries, such as the Netherlands, reject the use of some risk-based ROA methods, such as the binomial model of Cox et al. (1979), but are open to other valuation methods (Bos & Romijn, 2017).

To further bridge this gap, we suggest that co-development of ROA design and applications between decision-makers and researchers is critical. Engaging with the users of the researchers from the beginning of the process and embedding their requirements into the research is much more likely to result in adoption and implementation of the research (Wreford et al., 2019). For example, Lawrence, Bell, and Stroombergen (2019) applied simplified ROA concepts in a real-world sea-level rise adaptation decision context in New Zealand, resulting in a greater appreciation by the stakeholders of the value of incorporating flexibility into longer term decisions. In addition, climate change adaptation, like any other interdisciplinary field, tends to suffer from an isolation of the parts of analysis. Rather than beginning with the needs of the end-user, a policy-maker or a business, top-down “science first” or “predict then act” (Lempert, Nakicenovic, Sarewitz, & Schlesinger, 2004) approaches are often applied: the physical science is the starting point but may not necessarily provide

the information which would be needed for application. We believe there is considerable scope of extending interdisciplinary work to address this.

A summary of the approaches discussed in this opinion article is presented in Figure 2, beginning with co-development in the first instance. The conditions under which the traditional and scenario-based approaches are most suited are identified on the right of the figure.

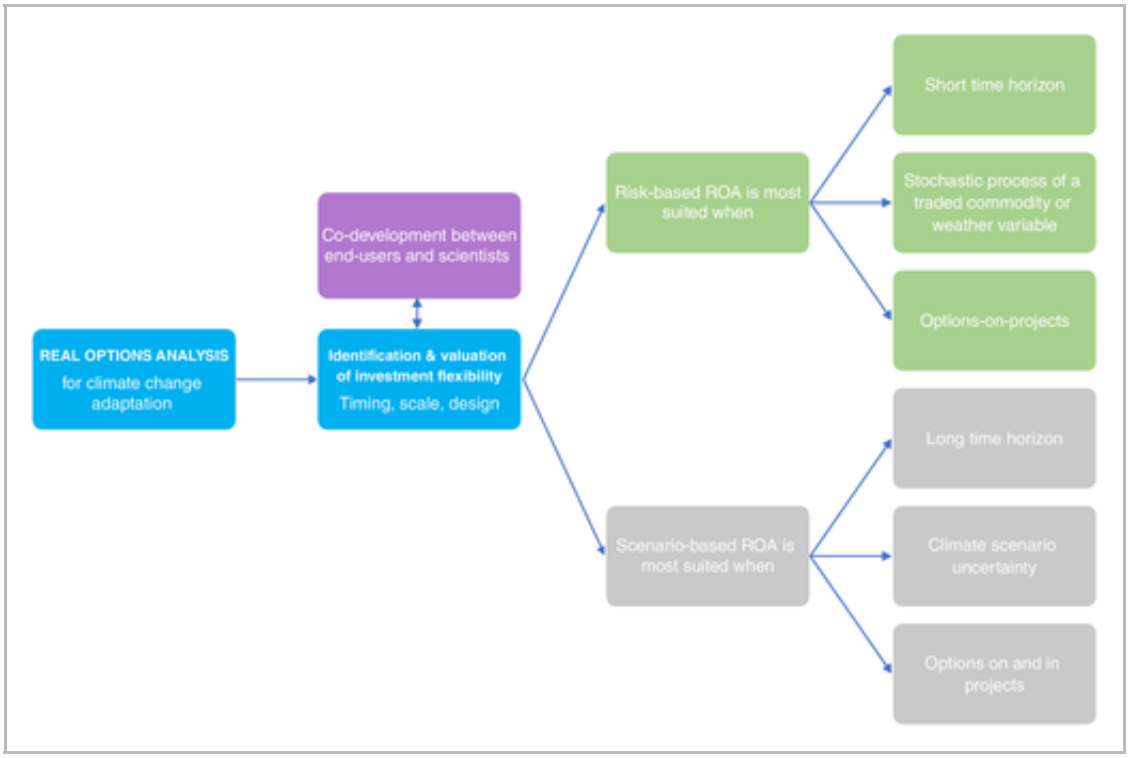

Figure 2 Open in figure viewer | PowerPoint

Identification of the appropriate ROA approach in different contexts. ROA, real options analysis

We have argued that ROA can provide significant added value for climate change adaptation if the analysis carefully considers the real-world characteristics of the decision context. We highlight that a range of approaches exist under the label of ROA, and some are less useful for informing adaptation than others. Transferring traditional ROA directly from financial theory by using assumptions that likely do not apply in a climate change context, or by the assignment of probabilities to scenarios, will in many cases not yield helpful guidance for decision-makers. In addition, such models can be hard to grasp, may fail to connect to CBA practice and make decision-makers reluctant to embrace them.

A range of scenario-based ROA methods offer ways to help in identifying flexibility and also conditionally valuing flexibility, without aggregating these values into precise expected values across states of the world. Such methods offer a promising way forward: thus far, on

a policy level, if CBA is applied as a scenario-based (what-if) tool, then scenario-based ROA is a logical extension (what-if option values or imprecise probabilistic assessment) for adaptation decision-making to identify under what conditions flexibility can be valuable, and to clarify its potential value under these conditions. Increasing co-development between researchers and decision-makers could lead to many more and better implementations of ROA.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Anita Wreford: Conceptualization; funding acquisition; investigation; methodology; writing-original draft; writing-review and editing. **Ruth Dittrich:** Conceptualization; investigation; methodology; writing-original draft; writing-review and editing. **Thomas van der Pol:** Investigation; methodology; writing-original draft; writing-review and editing.

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